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Model of the Cognitive Aspects of Air Traffic Control

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Abstract

This document is a report on the development of a Cognitive Model for Air Traffic Control (ATC) which has been contracted out to the "Institute of Evaluation Research" (Institut für Begleitforschung, IFB) by the Human Resources Domain of the European Air Traffic Harmonisation and Integration Programme (EATCHIP).

It is intended to provide the reader with a basic understanding of the cognitive processes involved in ATC and will be useful to those involved in training, selection, automation, task analysis and job design for ATC.

Keywords

Input/Output (I/O)-system	Long-term Memory	Mental Model	Mental Picture
Process Control System	Situational Awareness	Working Memory	

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EXECUTIVE SUMMARY

This document is a report on the development of a Cognitive Model for Air Traffic Control (ATC) which has been contracted out to the "Institute of Evaluation Research" (IFB) by the Human Resources Domain of European Air Traffic Harmonisation and Integration Programme (EATCHIP).

It is intended to provide the reader with a basic understanding of the cognitive components and processes in ATC and will be useful to those involved in task analysis, job design, selection, training and the development of Human Machine Systems (HMS), and for ATC.

The cognitive model assumes that ATC is an information processing activity which is governed by rules, plans and the acquired knowledge of the controller. Memory functions are of central importance in this process. According to the cognitive model, ATC is a goal-directed activity (action) which can be described as proactive and planned.

The model includes four structural elements and one basic functional principle. An information processing system was selected to deduce the structural elements of the model. The functional principle is derived from action-oriented psychological models and stresses the role of anticipating situations.

The model permits an understanding of how situational awareness develops and how the traffic picture is formed by the controller. The results of stress research and error analyses can easily be integrated into the model.

Chapter 1, *Introduction*, outlines the scope of the project and describes the methods used to develop the model.

Chapter 2, *Basic Concepts and Definitions*, gives an update of the main terms of a cognitive model of ATC (mental model, mental picture, situational awareness, decision-making, and information processing model).

Chapter 3, *Structural Model of the Cognitive Processes of Air Traffic Control (ATC),* describes the basic elements of the model (long-term memory, working memory, Input/Output (I/O)-system, process control system).

Chapter 4, *Process Model*, describes the basic assumption of a top-down approach, outlines the basic processes of ATC, and describes the functional principle of anticipatory regulation of action. The chapter finishes with an illustrative example.

Chapter 5, *Relevant Situational Factors*, addresses the problem of changes in cognitive functions under stress and provides a brief listing of additional factors and effects.

Chapter 6, *Validation and Conclusions* gives a summary of the results from validation interviews with operational controllers, and includes some concluding remarks.

The appendix contains references, definitions, abbreviations and the interview guide.

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1. INTRODUCTION

1.1 Purpose

ATC is primarily a cognitively-guided activity. The receipt of information, information selection, information search, information integration, decision-making, information communication and the providing of feedback are all basic elements of air traffic control officers' (ATCOs) tasks. Guidelines for the task analysis, selection and training of controllers and the design of Human-Machine Systems (HMS) should be developed with a thorough understanding of the cognitive processes involved in ATC. The purpose of this report is to present a comprehensive model of air traffic control which allows the basic processes to be understood as well as the strong and weak sides of the controller's cognitive system.

1.2 Scope

In this context the term model is used as a set of interrelated diagrams, descriptions and explanations of the main cognitive components and processes involved in air traffic control. It can be used to advance theory and form hypotheses and implications for application in task analysis, selection, training and design of HMS.

The development of the model has been based on current research and publications on cognitive psychology, psychology of knowledge and expertise, psychology of teamwork, decision-making, attention, and working memory, as well as relevant applied research in aviation psychology, traffic psychology and engineering psychology.

The model will describe and link the most relevant cognitive processes of air traffic control and will allow the interplay of different components to be understood. The model aims to integrate the relevant cognitive and decisional processes involved in ATC. At the same time current concepts such as situational awareness, shared mental models in teams, communication and human-machine interaction will be linked to the model. Special emphasis will be placed upon

(a) Mental models;
(b) Situational awareness;
(c) Shared mental models and
(d) Decision-making processes.

Situational factors affecting the concepts listed above (such as psychological stress, time pressure and shift work) will be listed. As a final step, results from validation interviews with six experienced controllers will be outlined. The concluding remarks will describe the differences between the assumptions of the model and the current studies and findings in this area of research.

The work has benefited from continuous feedback through presentations to members of the EATCHIP Human Resources Domain. In addition, the model was presented and thoroughly discussed at the first EUROCONTROL Human Factors (HF) Workshop in May 1996. The results of this workshop were integrated into the model. Finally, cognitive interviews were held with operational Air Traffic Controllers (ATCOs). This final validation ensures that the model can be applied to different areas of ATC.

1.3 Methods

Three different methods were employed to conduct the project.

First of all, preliminary observations and task descriptions were obtained from an inspection of different ATC units at the Deutsche Flugsicherung (DFS) in Frankfurt/Main. These observations were spread over three consecutive days. The areas of Tower Control (TWR), Approach (APP), and Area Control (ACC) or en-route control were reviewed by two experienced members of the scientific team. Following these observations brief interviews were conducted with ATCOs for each of the three areas. In the final session all areas were represented both by an experienced and a novice ATCO, and a series of questions on mental representation and related topics were answered in a group-interview-situation.

The identification of relevant publications was the second step of the procedure. This included requests on relevant psychological data banks, a screening of references from relevant publications, and a review of reports of unpublished data obtained from the DED5 team. As the information from data banks is incomplete in most cases, nine of the most relevant journals were screened manually. This screening included references from 1982 to 1995 and was conducted by visiting six different university libraries. A reference data bank was created from the original 2500 entries; 400 of the most relevant are listed in a separate bibliographic annex of this report as a background for the development of the cognitive model of ATC.

As a third step, group discussions were facilitated at the first EUROCONTROL HF Workshop in May 1996, and an enlarged team from the Institute of Evaluation Research completed the methods employed for the development of the structural and process model of ATC. Finally a validation interview was developed and six ATCOs from the Frankfurt/Main ATC centre (DFS) were interviewed twice.

2. BASIC CONCEPTS AND DEFINITIONS

2.1 Mental Model - Mental Picture

Mental models are the cognitive representations whereby humans are able to generate descriptions of system purpose and form, explanations of system functioning and observed system states, and predictions about future system states. This definition is closely related to Rouse and Morris (1986).

Actual **mental pictures** of a situation represent moment-to-moment snapshots of the actual situation based on the mental model and the actually perceived external cues. A series of mental pictures represents the actual mental model including the actual parametrisation. Note that mental pictures are sometimes defined as more general mental models (cf. Wilson & Rutherford, 1989). The current definition is in harmony with the use of the term (traffic) picture in the ATC community. The mental picture is based on the mental model and the environmental information. Situational awareness is given as long as the mental picture and the information about the situational conditions from the environment correspond adequately.

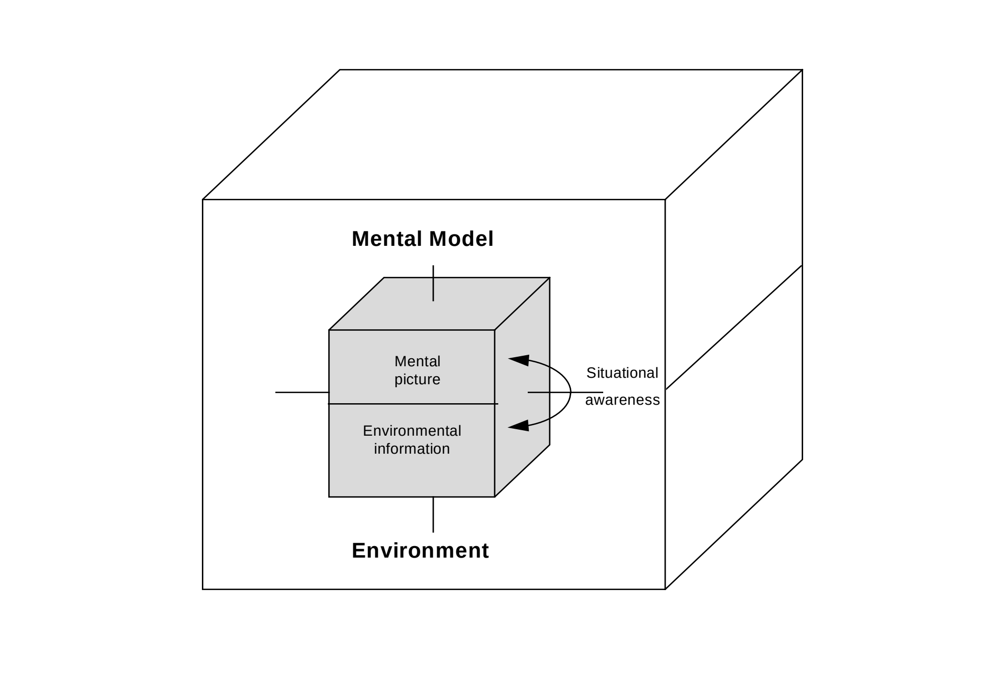

Figure 1: Mental Model

2.2 Situational Awareness

According to Domingues *et al.* (1994), situational awareness can be defined as the result of the “continuous extraction of environmental information, integration of this information with previous knowledge to form a coherent mental picture, and the use of that picture in directing further perception and anticipating future events.“

Maintaining situational awareness is regarded as one of the cognitive core tasks of ATCOs (EATCHIP, 1996a). Loss of situational awareness is equivalent to loss of the mental picture, which is one of the most critical situations in the process of ATC.

Endsley (1995) discriminates different levels of situational awareness: "It does not only encompass an awareness of specific key elements of the situation (Level 1 situational awareness) but also a Gestalt comprehension and integration of that information in the light of operational goals (Level 2 situational awareness), along with an ability to project future states of the system (Level 3 situational awareness)."

2.3 Decision-making

Decision-making is an active cognitive process which selects one out of a set of possible courses of action. Decision-making requires a weighing of the pros and cons of different alternatives. An unbiased decision-making process requires a medium level of vigilance. Hypervigilance or lacking activation can result in deficient decision-making (Janis & Mann, 1977). Activation and the quality of the decision-making process are linked by an inverted-U-relationship (cf. the so called Yerkes-Dodson-Law (Yerkes & Dodson, 1908). Edlund (1982), Janis and Mann (1977), and Kallus (1982) confirmed declines in decision-making quality with increasing stress.

Full situational awareness in combination with a medium level of vigilance will result in optimal decision-making. Decision-making takes place at different levels of automaticity, just as other forms of cognitive activity.

Active decision-making takes place at the knowledge level of Rasmussen’s (1983) hierarchy. The choice of action is often a kind of rule-based behaviour, and the selection of certain responses triggered by cues is often automatic and corresponds to the skill level of action.

In most cases, the ATCO’s decision-making process can be described as a three-step process. The three decision steps answer the following questions:

(1) Is a control action necessary or is monitoring sufficient?

(2) What kind of control actions will have to be conducted to reach a specific goal?

(3) When is the control command to be delivered?

2.4 Information Processing Model

ATC can be conceived as one of the standard examples of information processing tasks. Information processing models have become very popular in our time. The core components of an information processing system can be inferred from the analogy of a computer system. In the case of human information processing some special strengths and weaknesses have to be taken into account.

One of the leading engineering psychologists who has described an information processing system is Wickens (1992). Input of his information processing system are environmental stimuli which are perceived via the sensory system. Which stimuli are perceived is dependent, among other things, on the allocation of attentional resources.

Attentional resources also explain how decisions are made and response selection is conducted within the information processing system. Decision-making and response selection determine the execution of responses.

The execution of responses is also dependent on attentional resources. Responses are always fed back to the receptors, and in many instances responses change environmental input (e.g. by directing attention selectively).

Of course, Wickens' information processing system includes human memory functions.

The human memory is divided into a short-term sensory store, a long-term memory and a working memory (cf. Atkinson & Shiffrin, 1968). These interact continuously while processing environmental information.

The first memory system (short-term sensory store) is related to the perception of information in the different receptor systems. While the short-term sensory store and the long-term memory have a very large capacity, the working memory is a system with a limited capacity. This limited capacity of the working memory system is an important feature of psychological information processing systems.

While Wickens includes a system which allocates attentional resources to different components of his information processing system, other authors include a kind of process control systems into the information processing system. A kind of central processor with evaluative and controlling properties is necessary to explain the strengths and weaknesses of human information processing.

A basic information processing system was selected for the structural model of the cognitive processes of ATC.

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3. STRUCTURAL MODEL OF THE COGNITIVE PROCESSES OF ATC

3.1 Outline of the Model

ATC requires an extensive theoretical knowledge study (statutory information), simulation training (practical application of knowledge) and 'life' practical training (acquisition of experience and expertise). Initial expertise is measured via a comprehensive checkout and licensing procedure and must be maintained on a continuous basis. Following periods of absence (vacations, sickness) or on changing to a new sector further training (theoretical and practical), acquisition/re-acquisition and checkout of expertise are necessary. It is not possible to do a specific ATC job based purely on a data-driven cognitive representation.

Instead, a model with a strong top-down component is necessary to explain these phenomena. In accordance with a top-down model is the fact that it is possible to take over the job in well-trained teams within a few minutes (though taking over seems to be a major source of error and risk). As a consequence, this implies some kind of learning-dependent cognitive structure which reflects the real air space and the real traffic flows at hand in a certain control area.

A possible construct which accounts for such effects is the concept of cognitive schemata and cognitive scripts. Expectations and anticipations can easily be derived from these schemata or scripts.

The structural model of ATC is based on four core elements of an information processing system. These four elements are depicted in Figure 2.

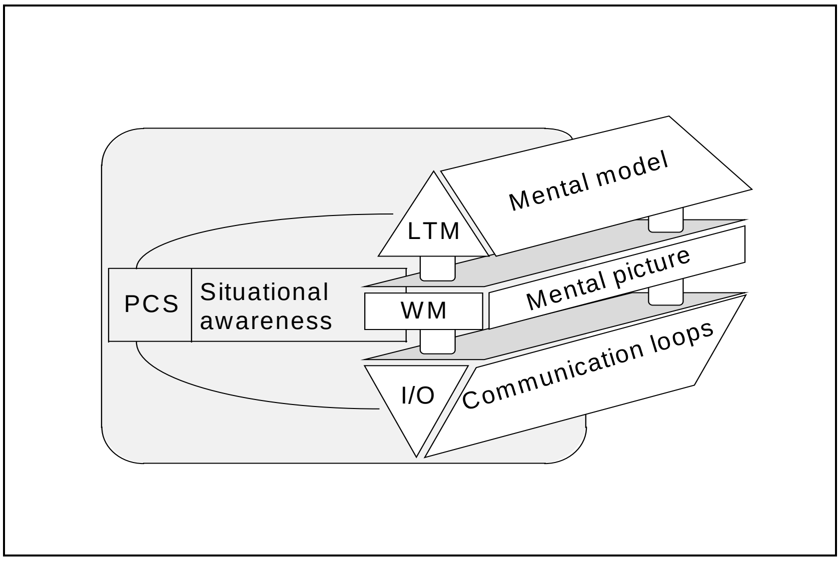

Figure 2: Structural cognitive model of ATC

3.2 Long-term Memory

A long-term memory structure allows information, information-processing routines and programmes to be stored. The hard disk of a PC shows that one of the basic problems of long-term memory is the organisational structure of information which should allow for a fast and direct retrieval.

The mental model of an ATCO is stored in the long-term memory. This mental model can be conceived as a system of schemata (Norman & Rumelhart, 1975) and scripts (Schank & Abelson, 1977). The selection of a specific script can be viewed as the activation of a network of action-related knowledge (Oesterreich, 1994).

Long-term memory structures can be subdivided into different structures. One should differentiate between knowledge about things, events and rules (epistemic knowledge, "WHAT"-knowledge), and the knowledge that enables us to solve problems and to adapt to new situations (heuristic knowledge, "HOW TO"-knowledge). Epistemic knowledge encompasses at least three important domains:

(1) Language-based knowledge about things.
(2) Rule-based knowledge of how to do things and how things work.
(3) Knowledge related to specific episodes from experience.

Knowledge based on episodes is primarily represented visuo-spatially. This kind of episodic knowledge plays a key role in ATC expertise.

For the current model it is useful to differentiate between general knowledge structures and ATC-specific knowledge structures:

(a) In ATC-specific WHAT-knowledge structures, rules and conventions of ATC, sector-specific rules and the like are represented;

(b) ATC-specific HOW TO-knowledge structures contain rules and procedures as to how to find solutions for new, unexpected traffic situations.

It has been shown that the capacity to derive these solutions depends on the experience of the controller (Vingelis, Schaeffer, Stringer, Grolemski & Ahmed, 1990).

The ATC-specific knowledge structures are closely related to the mental model. They could be viewed as propositions in a propositional network or as concrete episodes in the controller's episodic memory.

The mental model is a dynamic, primarily visuo-spatial time-space cluster. It has to account for changes in at least four dimensions. This can be accomplished either by a high dimensional mental model or by multiple projections of the changes in time and space.

The mental model can further be characterized by WHAT-background-knowledge and strong episodic influences. It also encompasses general as well as sector/task specific components. It includes preformatted action routines and situational scripts. The mental model is the mental basis for the traffic picture of the controller.

3.3 Working Memory

The central element of the technical information processing system is the central processing unit or, in more psychological terms, the working memory.

The working memory idea was introduced by Baddeley and Hitch (1974) based on the short-term memory conception of the Atkinson & Shiffrin (1968) model of human memory.

The working memory limits the capacity of the human information processing system. In other words, the working memory represents the bottleneck of the information processing system.

The human working memory according to Baddeley and Hitch (1974) consists of three parts:

(a) The central executive;
(b) The visuo-spatial sketch-pad;
(c) The phonological loop.

The working memory is a short-term buffer with a limited capacity for new incoming data and information. It can only handle a set of about five to nine elements or combined elements (chunks) at the same time. The capacity seems to be even less with visio-spatial input. Without active rehearsal procedures, memory traces fade within a few seconds.

The limited capacity of the working memory along with a high susceptibility to interferences explains why there is a wide range of deficiencies in the human information processing system. "Losing the traffic picture", one of the most important concerns of an ATCO, may also be attributed to the limited capacity and/or the proneness of the working memory to interferences. The mental picture of the air traffic situation in a sector contains more informational units than "seven +/- two". Thus, a close interaction between working memory and active long-term information processing has to be considered. The central executive plays a role in the attentional control of long-term information processing. The central executive of the working memory had to be specified for the cognitive model of ATC.

It can easily be deduced from a task analysis of ATC that there is great strain with many interferences on the phonological channel. Thus, the use of an articulatory loop to update the mental picture in working memory is either impaired or has to “draw back” on very strong selection mechanisms.

The loop for visual update (visuo-spatial sketch-pad), on the other hand, is supported by the radar screen and the flight strips. A consistent finding across different experimental tasks points to the fact that the visuo-spatial sketch-pad is very sensitive to interferences.

3.4 Input/Output (I/O)-System

The third component of an information processing system is the I/O unit.

In the case of the computer keyboard, mouse, printer and screen serve as I/O devices. Systems with a high capacity use I/O units which do not operate passively but have their own intelligent organization. So it is with the I/O system of the model.

The I/O system possesses a short-term sensory store and is organized in functional feedback loops. Functional loops direct the behaviour of perceptual systems. The eye has to move in the direction of the anticipated input. Otherwise we would miss the input from the situational surroundings like someone sitting in a high-speed train trying to focus on a situation outside the train.

The same is true for our motor responses. Without a correct anticipation of the situation we would hardly be able to grasp moving objects. At the same time, correct motor activity is fed back instantaneously. In simple information processing systems input and output are separated. The organization of the I/O system in functional feedback loops is hardly taken into account.

Thus, the assumption of functional loops is a deviation from classical situationally determined information processing models. One important aspect of different functional I/O loops is that these can be found at different levels of mental processes ranging from automatic subconscious processes to conscious communication.

Most of the activities of the I/O system can be conceived as top-down processes. These top-down processes are determined by the mental model and the mental picture. The I/O system is structured in feedback-loops according to the principle of reafference (v. Holst, 1950). Higher level activity of the I/O system, i.e. the active selection of information and the active selection of responses, is monitored in the working memory and is controlled by the process control systems. Thus, the I/O system is closely connected with the working memory and the process control systems.

The I/O system is not only organized according to the sensory system and the corresponding motor systems (like the oculo-motor-system and the eye). Cross-modal loops are also very important (e.g. hand-eye co-ordination). Thus, the I/O system is equipped with information transformation capabilities which allow cross-modal activity to be done quasi automatically.

3.5 Process Control System

Finally, the information processing has to be controlled by programmes and an operator or operating system: the process control systems. The process control systems of our model is a functional extension of the central executive proposed by Baddeley. Taking the continuous (self)-monitoring of ATC processes into consideration and including situational awareness at the same time in the model, we decided to extend the central executive to a process control systems. The extension of the central executive to a separate system can be justified by the parallels between the central executive and the supervisory attentional system (SAS, Norman & Shallice, 1982). These parallels were outlined by Baddeley himself.

This process control systems of the cognitive model of ATC allows us to include situational awareness, different aspects of attention, decision-making, planning processes and concepts of goal-directed action into the model.

The process control systems organizes the interaction of working memory, long-term memory, and I/O system. It is closely connected with the working memory. The process control systems receives input from different sources. One important source is a mismatch-comparator in the working memory compartment.

A second important input is the information on the actual state of the different I/O groups of the I/O system. Thus, insufficient conditions of the Radio/Telephone-communication (R/T-communication) loop or of the receptive functions of the controller are fed back to the process control systems.

A further input source for the process control systems is a feedback regarding the actual state of the controller. Signals of tiredness, hunger, thirst and changes in motivation are needed to conduct an adequate process control. Self-monitoring and self-evaluation are important functions of the process control systems.

Finally, there is a large amount of input to the process control systems from long-term memory functions. These allow experience-based activity of the process control systems to be integrated in the actual control actions. The most important feature of the process control systems is to ensure situational awareness.

While the I/O system has to conduct many automatic (skill-based) activities, the working memory is primarily concerned with rule-based activity, and the process control systems is the region where knowledge-based activity is initiated.

The different levels are in accordance with Rasmussen (1986), as depicted in Figure 3 overleaf.

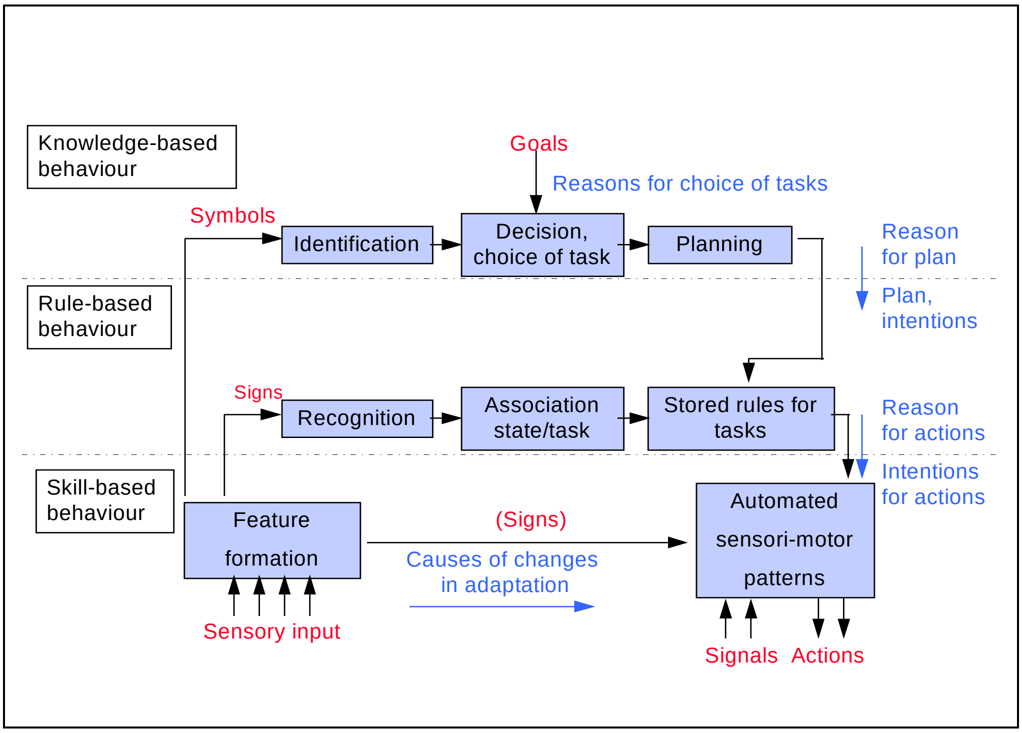

Figure 3: Levels of behaviour (drawn from Rasmussen, 1986)

4. PROCESS MODEL

4.1 Top-Down and Bottom-Up Processes

A process model of ATC has to integrate two different views on human behaviour in complex Human-Machine Systems (HMS). These different views have been termed "bottom-up" or "data-driven" and "top-down" or "theory-/model-driven" approaches by Norman (1983).

Bottom-up processes are those activities which are controlled by external cues and commands. This term is also used to describe behaviour which is primarily driven by incoming information. Ad hoc trouble-shooting in an unexpected conflict situation of two or more aircraft can be used as an example of primarily bottom-up behaviour of a controller. Behaviour governed by plans, mental models, intentions and rules are typical representatives of "top-down" behaviour.

A long list of arguments can be stated in favour of a top-down conception of ATC. An integration of bottom-up and top-down processes, with a strong dominance by top-down processes, will be achieved by the current process model of ATC. Even in a top-down governed mode of behaviour the controller has to be responsive to emergency signs and other situational cues. Thus, data-driven reactions must always be taken into account. On the other hand, one can find good arguments to describe complex behaviour in terms of top-down-oriented processes.

The mental workload from handling highly complex traffic situations with continuous timing could also be reduced by the use of scripts. Scripts allow priorities to be derived which are reflected by the sorting of flight strips, and they allow the load to be reduced from continuous routine decision-making. Specific scripts in long-term structures also explain the distinct selection of relevant information from each flight to be controlled.

Additionally, ATCOs can “draw back” on a series of preformatted action routines to do their job. These are stored in the long-term memory and can be activated readily under certain conditions. Thus, there are "if ... then"-rules which activate certain action routines.

According to this view, the process of ATC is a special case of goal-directed behaviour (action). Goal-directed behaviour is organized hierarchically. Elements of action can be described by so-called test-operate-test-exit-loops (TOTE-units; Miller, Galanter & Pribram, 1960).

A theoretical concept which allows the process of ATC to be described as goal-directed behaviour is the model of anticipatory regulation of action (Hacker, 1986; Hoffmann, 1993). The core element of the anticipatory regulation of action can be termed "Anticipation-Action-Comparison Unit" (cf. 4.4).

4.2 Basic Functions of the ATC Process

ATC has a lot in common with the control of goal-directed behaviour in general. The main difference between ATC and the cognitive control of one's own actions is that the controller has to direct external activity which has to be co-ordinated with others. Four different processes should be considered in the description of ATC. These are termed "monitoring", "controlling", "checking" and "diagnosing".

Monitoring refers to the continuous or intermittent comparison between the anticipated traffic situation and the actual system state. Controlling in the narrow sense of the word denotes an intervention, which tries to change the traffic situation actively. Checking is a process of situational scanning, which takes place intermittently or as a consequence of unexpected events. Diagnosing is an active process of information search, which tries to explain unexpected or new traffic situations.

As long as the traffic situation develops as anticipated and planned, the controller either has to monitor the situation or he has to execute control actions. In technical terms (control engineering), one can describe this as open-loop-activity which is directed towards future states of the system. As long as the situational conditions remain normal, i.e. as expected, and the control actions result in the expected changes, the mental picture corresponds to the subjective reality and the mental model is confirmed.

From time to time the controller has to reaffirm that the situational conditions really are as expected by checking the whole situation including the less attended areas. A comparably low rate of checking activity in comparison to monitoring activity will be observable in a well controlled situation. In the case of unexpected events, new stimuli or a misfit between planned and observed situation, the mode of action changes from monitoring and controlling to checking and diagnosing. Control is no longer conducted in an anticipatory proactive way but in a more situationally-determined reactive way. The cause of unexpected events has to be inferred from the mental model or the knowledge base of the controller (diagnosis). Where there is no obvious explanation, further checks have to be conducted to re-establish an adequate picture of the situation. The basic mental processes of ATC are depicted in Figure 4.

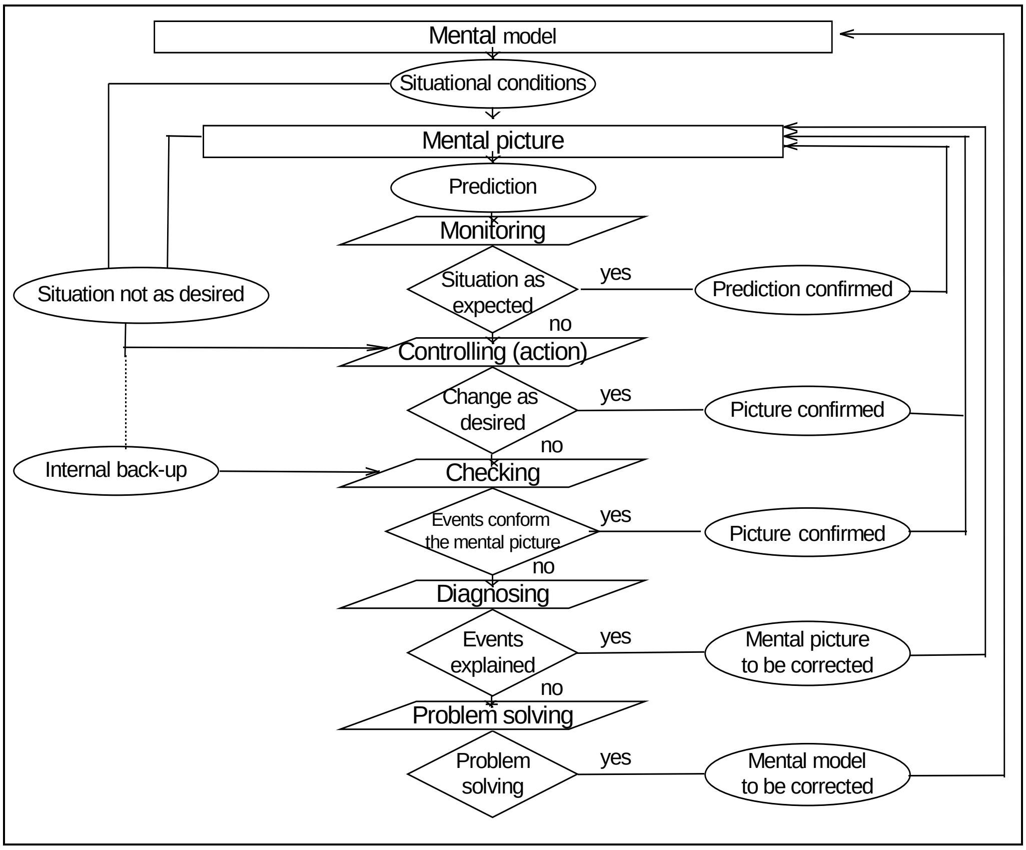

Figure 4: Basic functions of ATC

Figure 4 shows a sequence of functional steps which are organised hierarchically in feedback loops. After the mental picture (traffic picture) has been established monitoring takes place as long as no active intervention is necessary. If the traffic situation is not as desired and action is necessary the next step „controlling" is initiated. Monitoring and controlling are continued as long as no unexpected events occur and the controller needs no internal backup of the mental picture.

In case of internal backup or unexpected information, checking of the whole situation takes place. If checking confirms the mental picture, the process steps back to monitoring and control. Otherwise active information search and active retrieval from the long-term memory starts to diagnose the situation. If the mental model does not allow explanation of the current situation, the controller starts active problem solving. Each of these basic functions include more fundamental cognitive functions like perception and decision-making. In addition, decision-making takes place between the different steps.

Monitoring and controlling are driven by the mental model of the controller, checking and diagnosing as a process are geared by events. Diagnosing is directed to re-establish the mental picture. Therefore this process has to be interactive. It will allow the reactive activity to be switched to proactive control.

Switches between the two modes of activity are governed by the process control systems.

Monitoring

Monitoring is a process of continuous or discrete comparison between the actual state of the system and the expected state of the traffic situation. Monitoring is a top-down process governed by the expected state of the system. Thus, predictions as to the state of the system are the primary process of monitoring. The second important step is a judgement of the match between the expected and actual state of the situation.

Controlling

Controlling is a process of intervention. The ATCO directs single aircraft or groups of aircraft to obtain a desired traffic situation according to the principles of ATC. According to Nelson's (1995) description of control, it includes:

(a) The selection of a strategy;
(b) The allocation of time, and
(c) The decision to terminate.

The outcome of control actions has to be monitored in the sense stated above. Thus, control includes phases of monitoring activity. In other words, control and monitoring overlap closely. Controlling and monitoring are directed towards future states of the system (i.e., what action will cause what result?).

Checking

Checking occurs in novel situations as part of the basic orienting reflex. It also occurs in situations which indicate a misfit between the expected outcome and actual outcome of an activity. Finally, checking is triggered by situational inputs which signal the risk of undesired states of the system, e.g. emergency signals. A psychological state of anxiety is a classic example of the dominance of the checking mode of behaviour control.

Diagnosing and Decision-making

Assimilation of new, unexpected situational conditions into the actual mental picture of the traffic situation, or changing the mental picture to account for the new evidence (accommodation of the mental picture), takes place as a consequence of mental operations which can be termed "situational diagnosis". Diagnoses are often accompanied by an information search or by checking the situational conditions.

As long as the mental picture does not conform to the actual situation, information processing switches to a backward-oriented mode (i.e. What happened? What was caused by what?). The diagnostic steps have to re-establish a coherent mental picture and full situational awareness.

In some instances non-conforming information can be assimilated into the actual mental model. In these cases the model remains unchanged and no changes in the course of action will occur, despite changes in the situation. This can be a major source of error. Let us consider repeatedly experienced technical errors or repeatedly experienced false alarms in a technical system. False alarms and as-normal conceived technical problems will result in a kind of "mental error model", which is part of the controller´s mental model. Error models can be an easy means of assimilating non-conforming information.

Diagnosis can be faulty, and consequently, diagnostic errors have been studied at length. In many cases a wrong or faulty diagnosis results in erroneous decision-making. Human information processing has some weaknesses in the area of diagnosis. In many instances these weaknesses contribute to a highly efficient basis for action. In some cases, especially if emergency situations have to be dealt with, these shortcomings in human information processing can result in highly risky decisions or simply in wrong actions. Some of these actions have been described in error analyses. The most important shortcomings in human diagnosis are:

(1) Bias to overestimate the probability of rare events (e.g. faulty readback).

(2) Biases in handling variability (variability estimates are inversely related to the mean, e.g. deviations in vertical separation at a high altitude are judged less than the same separation at a lower altitude); variability is biased by extreme values (e.g. aircraft landing at extremely low speed or extremely high speed).

(3) Linear extrapolation of non-linear processes (e.g. possible conflicts between pairs of aircraft with growing number of aircraft).

(4) Confirmation bias for a given assumption/hypothesis.

(5) Ignoring negative evidence. Negative evidence, i.e. the missing of signs is not treated like positive evidence even if negative evidence is of high diagnostic value.

(6) Salience bias: the importance of salient information is systematically overestimated (e.g. standing at the top of the display). Similar effects can be obtained by brightness, flashing, large displays, centrally located displays or rapid changes of a display. On the other hand, information that requires a great deal of attention or computational resources will tend to be underestimated or even ignored.

(7) Bias towards treating different sources of information as if they were equally informative, even if they are undiagnostic or unreliable. Insensitivity to differences in predictive validity possibly contributed substantially to the Vincennes incident in 1987 (shooting down of a civilian aircraft during the gulf war by the U.S.S. Vincennes; Klein, 1989).

(8) Bias towards ignoring base rates. Conditional probabilities are normally replaced by absolute probabilities.

(9) Bias against absent information. The diagnostic information of missing cues is systematically underestimated.

(10) Reversed causal reasoning. We often neglect the fact that we tend to assume bi-directional causes in the case of uni-directional relationships. This error has repeatedly been observed in troubleshooting situations.

(11) Over-confidence. People are wrongly over-confident in their forecasts of future states of a system and in their retrieval from their own memory.

Biases in human information processing contribute to incorrect diagnoses and, as a consequence, to incorrect decisions. These biases can increase in stressful conditions. One example is "tunnel vision“ which is functionally equivalent to an extreme confirmation bias. Other effects of stress on decision-making will be discussed in the context of situational factors.

4.3 Hierarchical Organisation of Action

The term "action“ is used to denote goal-directed behaviour. At least two basic assumptions are necessary in order to explain goal-directed behaviour of working people. The first is that it must be known explicitly or implicitly how to achieve the goal. The individual must know what has to be done, when it has to be done, and how it has to be done. Otherwise, a problem solving process has to start.

The second assumption is that goal-directed behaviour can be broken down into components. Each component can be described as a kind of goal-directed behaviour towards sub-goals. Sub-goal-directed behaviour can be broken down into components. The basic assumption is that all the components and sub-components of behaviour are governed by the same principle. The principle "test-operate-test-exit (TOTE)-unit" by Miller, Galanter, and Pribram (1960) has been extended to the anticipatory principle by Hacker (1986) and Hoffmann (1993).

Before we turn to the explanation of the Anticipation-Action-Comparison Unit, we will explain the hierarchical organisation of action using an ATC example.

Let us consider the sub-components of a rather simple ATC situation. The aircraft has to be directed to another flight level at about the same speed. This activity can be broken down into the following sub-components: contact pilot, give instruction, wait for feedback, wait for action, confirm new situation. Each of these steps again can be broken down into more simple sub-components: it is necessary to direct attention to the actual parameters of the aircraft, before you contact the pilot; you have to direct the voice to the microphone if you want to address the pilot, and so on.

Addressing of the pilot necessitates the retrieval of correct phrases from the long-term memory and they should be verbalised in the correct pitch and volume.

This action can be broken down to a more basic level in the consideration of the changes in muscle tension in different areas of the voice control system.

4.4 Anticipation-Action-Comparison Unit

Continuous orientation in space-time is only possible if individuals are capable of predicting changes in the environmental input as a consequence of their own changes in position and posture. The perceived changes and the predicted changes have to be compared. When there are deviations between expected input and actual input, corrections are necessary. This is a basic principle of the organization of behaviour. It was described by Von Holst and Mittelstaedt at the beginning of the 1950s (principle of reafference; Von Holst, 1950). Even very primitive organisms and very basic muscle contraction processes are governed by this principle.

In the following paragraphs, a model based on this functional principle will be used to describe the mental activity of ATC. A basic Anticipation-Action-Comparison Unit is depicted in Figure 5.

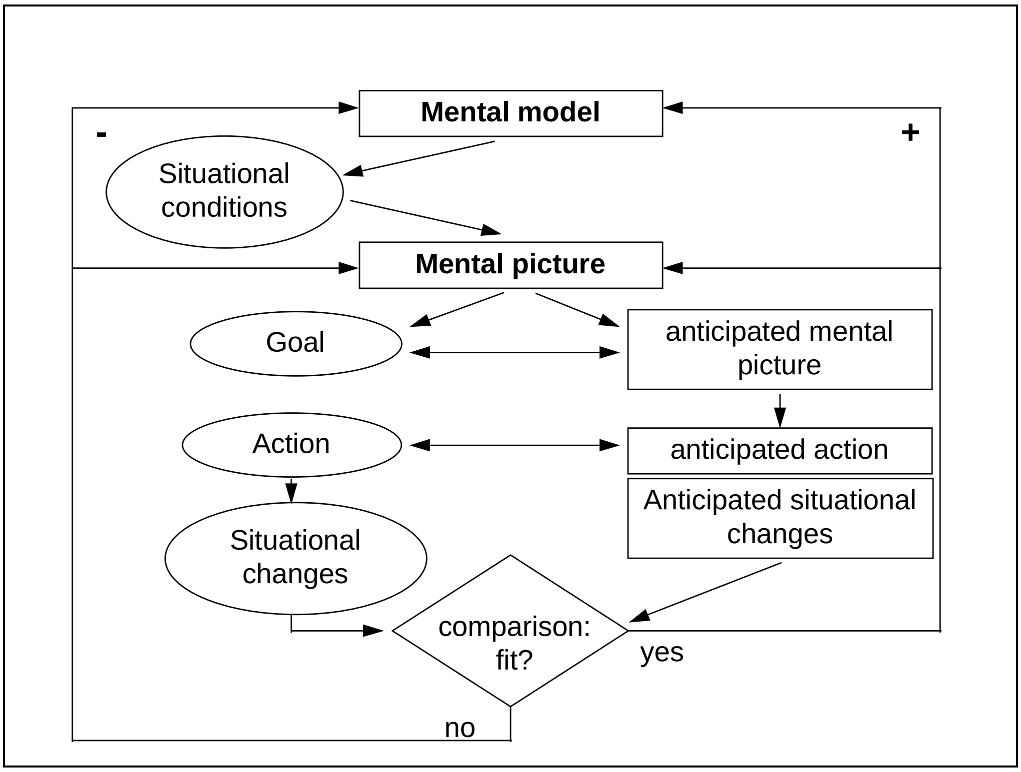

Figure 5: Anticipation-Action-Comparison Unit

The Anticipation-Action-Comparison Unit again stresses the importance of top-down processes in the course of ATC. The controller has to establish situational awareness before he can start to do his job. This means he has to generate a mental picture of the actual situation. To form a mental picture, he has to refer to his knowledge and his mental model from his long-term memory and has to integrate these knowledge factors with the actual situational conditions. The actual mental picture can serve as a basis from which to predict future system states. If the short-term predictions from the mental picture always come true, the controller knows that his picture is correct. This process of composing a mental picture and knowing that this mental picture correctly corresponds to the actual traffic situation means that situational awareness is maintained.

Based on his mental picture, the controller can predict the effects of control actions. In other words, he is able to anticipate the results of control actions. The anticipation process includes action and the resulting changes in the situation. Thus, the controller is able to generate mental pictures of future system states.

After executing the control action the controller compares the anticipated mental picture with the actual mental picture. If there is a match between the anticipated mental picture and the actual mental picture, the mental picture of the situation is confirmed. At the same time, the mental model and the mental representation of the situational conditions are reinforced.

In the case of a misfit between the anticipated system state and the actual system state, further action is necessary. If there is no obvious reason for the misfit between the anticipated mental picture and the actual mental picture, the mental model and the representation of the situational conditions are called into question. In this case, the process control systems will switch from the operating mode into the checking and diagnosing mode, and the controller will try to regain a correct mental representation of the situation.

4.5 Process Control

The process of ATC is directed by the process control systems and is based on the functions of the human working memory.

Working Memory Processes

The working memory is a short-term planning unit which integrates information from different sources. These sources are perceptual as well as internal, like long-term memory sources. Information integration and extraction in the working memory are directed by the process control systems by allocating attentional resources. The working memory keeps the actual mental picture and the actual parameters of the mental model in mind. It serves as a short-term planning function and allows anticipation of the action and the storage of the anticipated mental pictures.

At the same time, the working memory is a basic comparison unit which allows the comparison between the predicted mental picture and the perceived mental picture as well as fit/misfit-comparison in anticipation-action-comparison loops. The working memory has to provide the controller with an exact timing of actions. Furthermore, R/T-communication is based on information conducted through or derived from the working memory (phonological loop). As already mentioned, the information in the working memory will automatically be forgotten unless regular rehearsal or backup is conducted. The working memory is also involved in decision-making processes. Decision-making again takes place in close co-ordination between different structural components of the mental system. The core unit of the process control is the process control systems.

Process Control System

The process control systems is a kind of internal evaluation system which makes sure that action, in our case ATC, takes place as planned by the controller (protocol memory). Thus, the most important function of the process control systems is to maintain situational awareness.

The situational awareness is kept as long as the anticipated picture and the perceived picture show no intolerable discrepancies and as long as they are retained in the working memory. The process control systems continuously evaluates discrepancies and the relevance of new incoming information. This evaluation and judgement can be viewed as the basic psychological processes of the process control systems.

The switching of attentional resources from one focus to another is also directed by the process control systems. Incoming information is weighted and decision processes such as priority setting continuously take place. At the same time, the controller has to decide how many details from a traffic situation are necessary to make appropriate decisions and to conduct appropriate control actions. This can be termed the "selection of zooming parameters".

While conducting actions, the controller has to select interruption thresholds. This means that he has to select the threshold which determines whether he will switch from one task to another or direct his attention to a new environmental input, e.g. in critical situations or when perceiving a critical inner state such as fatigue.

The ongoing activity has to be checked by the process control systems. This means that the backup rate of the mental picture has to be selected, the sequencing of actions has to be controlled and the timing of the working memory and the time of action has to be checked as well as the correct execution of short-term planning.

If no preformatted solution for a conflict situation can be derived, the process control systems has to initiate active problem solving or at least active decision-making.

A further very important function of the process control systems is the self-monitoring function. Controllers need feedback about their internal state; they continuously have to evaluate their own performance and their decision-making (e.g. risk taking).

Process Parameters

The core elements of the mental processes of ATC can be conceptualised according to Dörner (1993). Dörner maintains that there are different levels of action regulation which can be termed according to Rasmussen (1983) as "skill-based behaviour", "rule-based behaviour" and "knowledge-based behaviour". Higher levels of organization can only be where the lower level action routines will not achieve their goals appropriately. Thus, a large part of the activity of an ATCO will be highly automated and remain sub-conscious (cf. Hayes-Roth, 1977). These subconscious elements of behaviour are hardly accessible via verbal reports.

An important element of the regulation of action is the extent of anticipated future situations and events. Detailed planning of future events and the exact timing of these events will result in a very detailed planning horizon. Flight strips are tools for the controller to extend his planning horizon.

According to Dörner one can describe the process of ATC using four basic parameters. These parameters are:

- the degree of differentiation,
- the selection threshold,
- the backup rate, and
- the speed of information processing.

High differentiation implies detailed scanning of the situation. This is very time-consuming. At the same time it will result in few wrong classifications of situations. The selection threshold determines the degree to which one adheres to a given course of action. Controllers who appear to do their job more rigidly have a high selection threshold while those with a low selection threshold very often seem to switch from one activity to another. A low backup rate is risky because situational changes may be overlooked. A very high backup rate can interfere with the continuous conduct of planned behaviour and the selection of relevant information from the situation. A very large amount of information processed within a given time will pose a great deal of strain on the controller, while a reduced amount of information will be accompanied by a saving of energy.

These basic parameters of the process are determined by different conditions. Two of these conditions are "importance" and "urgency" of actions.

The importance, for example, will change all modulation parameters. In the case of ATC the importance of activity is governed by a set of rules. Another basic condition is the urgency of actions.

Very urgent actions will shut down the backup rate for checking the total situation, increase the information processed per unit of time, increase the selection threshold and decrease the differentiation of information processing.

Subjective competence, motivation and stress are additional conditions which influence the conduct of the ATC process. The setting of these parameters is controlled or at least modulated by the process control systems.

Input/Ouput (I/O) System

The I/O system is organized in functional loops. At least six I/O loops can be separated and characterised:

(1) Radar screen information loop.
(2) Flight-strip information loop.
(3) Co-ordinating/tactical controller loop.
(4) R/T communication loop.
(5) Neighbour sector controller loop.
(6) Background information loop.

The I/O system is supported by diverse technical equipment. At the same time, there will be increasing workload on the working memory with increasing necessity to extract and integrate the relevant informational input from the devices and/or to actively request the relevant information. In addition, one should at least consider analogue and digital I/O formations and the coupling between them. Movements on the radar screen are quasi-analogue, while the numerical indications of height and speed are digital inputs.

The ATCO's informational output (in contrast to that of a pilot) is purely discrete using the verbal channel. Only side information (pitch of the voice) is given analogously. One implication of the analysis of the human I/O system used in ATC shows that much information transformation has to be carried out and that not all I/O options are used in the ATCO job. Note that changes in the I/O functions are often necessary when the equipment is changed, e.g. electronic fight strips have to be handled via keyboards and not via pens.

Long-term Memory

The mental model is stored in the long-term memory.

The core process is to provide the controller with a situational pre-adjusted mental model of the air traffic situation. Additionally, long-term memory provides the controller with different types of knowledge.

In the general mental model basic information has to be integrated:

– actual sector information/briefing,
– strategic plan information,
– global situational predictions (e.g. traffic density),
– unexpected peculiarities.

4.6 Illustrative Example

The example given in the following section demonstrates the "running of the mental model". The example is drawn from the tasks of the technical controller of an en-route sector. The subtasks are depicted from M. Cox (1994) who broke down the tasks of ATCOs into a set of interrelated subtasks. According to Cox (1994), the tasks of an en-route radar controller include:

(1) Pre-shift brief.
(2) Accept hand-over of sector from current controller.
(3) Conduct aircraft movements.
(4) Conduct hand-over of sector to relieving controller.

In the following section steps 1 and 2 will be considered (cf. Figure 6). Pre-shift briefing is conducted via the I/O system. The mental model of the traffic/sector situation receives a precise and reliable pre-parametrisation as far as weather, new procedures and equipment are concerned. The new information is stored in the working memory and transferred to long-term memory external storing devices. The process control systems is "fed" with special information which allows attentional resources to be allocated in accordance with the specific situational peculiarities.

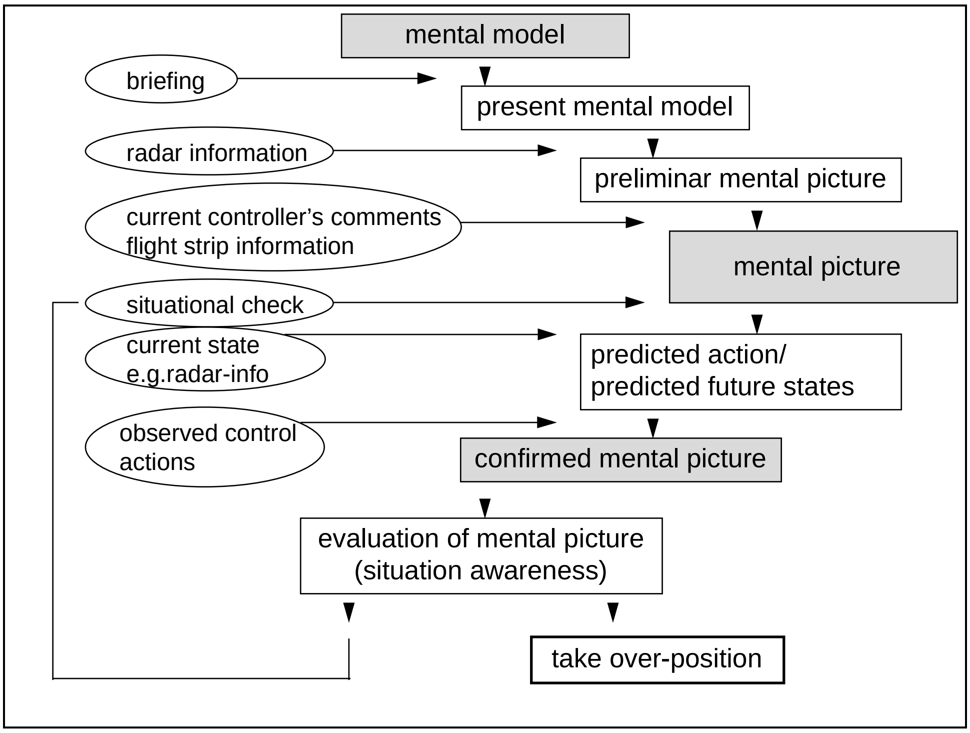

Figure 6: Take-over of a position

Before the relieving controller can take over his new position he has to establish a precise mental picture of the situation and the traffic situation. The mental picture is built up from three main sources:

(1) Usually the relieving controller's first source of information is the observation of the radar screen and the ongoing activity on the radar (radar-information-loop).

(2) The second source is the mental model. The mental model is pre-set in the briefing situation and continuously adjusted to the current procedures in the controller’s last shift.

(3) The third source is the current controller who informs the relieving controller about important events at hand. The information is acquired by the controller-controller-information-loop and supported by written information handed from controller to controller. Thus, at the moment of taking over the position, the phonological loop of the working memory is activated via speech and via read information.

One important implication of the cognitive model of ATC concerns the process of information integration. The mental picture is not established in the way of solving a puzzle without previous information. Instead, a copy of the mental model is set in motion by the information from the radar screen, the communicated details and the information from the flight strips.

Thus, the information is actively scanned from the available information sources. These first steps can be described as checking and diagnosing the situation.

The relieving controller has to answer the question, "Is there anything going on which has not yet been accounted for?" (checking). Next he tries to ascertain, "What events led to the current situation?". As soon as he has recognized the central event he will begin to predict the current controller's future action. The predictions are normally confirmed by the current controller's actions. If it is difficult to predict the situation, the current controller can be asked about his plans and strategies.

The anticipation of future system states is the most relevant process of the step "determine current controller's plans and strategies" in the analysis reported by Cox (1994). Of course, in many cases the prediction could be that the current controller will continue to monitor the situation.

To complete the composition of the mental picture, at least one complete anticipation-action-comparison-cycle has to take place. Where there is a match between predicted outcome and actual outcome, the model is confirmed. This is a process of internal feedback regarding the prediction. In many cases this internal feedback is supplemented by direct vocal feedback from the current controller.

According to our interviews the steps "discussion of the current characteristics of sector" and "discussion of the current controller's plans/strategies" (cf. Cox, 1994) are often omitted and replaced by an internal vicarious anticipation-action-comparison-process.

The relieving controller's main decisional process is to evaluate if his own picture is fully formed, accurate and complete. It will be necessary for him to check the whole situation and his own predictions.

After completing his mental picture and ascertaining the current controller's plans the relieving controller begins the take-over process. It should be noted that the mental picture future state will include aircraft to be received from adjacent sectors in the immediate future.

The final decision to take over is based on the activity of the process control systems. This must evaluate whether the picture is complete or not. At the same time, the process control systems has to evaluate whether the controller is ready and fit to handle the situation. If both questions are answered positively, the relieving controller's declaration of readiness to take over is communicated via the I/O system.

The actual hand-over of the sector will be mutually timed and achieved when there are no urgent messages to be sent. Complex control actions by the current controller should ideally be completed but in the case of complex situations, the current controller will stand by and ensure a smooth take-over. Once the relieving controller has assumed responsibility for the sector he may begin amending the departing controller's plans in accordance with his own mental picture, actual information and working methods.

5. RELEVANT SITUATIONAL FACTORS

As indicated earlier, the process of ATC can be modulated by different situational factors. Important situational factors of ATC have been listed by Redding and Seamster (1992). These factors could be termed task immanent situational conditions.

However, one can rule out situational factors that influence ATC in the sense of context factors. Some of these factors will be listed in the last part of this section (cf. Table 1).

Most important are those factors which affect the state of the controller and create a state of psychological stress, or at least some precursor of psychic and physical dysregulation. These effects of stress on ATC will be discussed in the next section.

5.1 Stressors and Effects

Some of the situational factors which contribute to the amount of stress imposed on the controller have already been mentioned in chapter 4. All those factors which increase stress on the cognitive system of the controller tend to evoke interferences in information processing and reduce compatibility between input and response, or between informational input, central processing and response (Wickens, Sandry & Vidulich, 1983).

Easily processed information will easily be forgotten, whereas deeply processed information will be better retained. At the same time, however, it will occupy mental resources, which increase workload.

The necessity to integrate rapidly changing informational input (e.g. in high density traffic situations) is one of the major sources of stress for ATCOs. At the same time, decisions have to be made under severe time pressure, and the ATCOs have to bear heavy responsibility.

High stress according to H. Selye (1982) is characterized by central and vegetative arousal, which is prolonged during a longer time period. The individual departs from his normal homeostatic equilibrium. Stress will also change information processing (see also *Human Factors Module Stress*, EATCHIP, 1996b).

First, the quality of information processing increases with increasing arousal until an optimal level is reached. The more difficult the task, the earlier this optimum will be reached (cf. Yerkes & Dodson, 1908). Beyond the optimal level of arousal, performance is degraded. The degrading of information processing has been characterized as a 'restriction in the range of cue utilisation' by Easterbrook (1959).

With increasing arousal we find a concentration on central aspects of the perceptual field. Peripheral cues are no longer processed. Extreme focusing of attention on a short range of cues has been characterised by the term 'tunnel vision', which could be observed in many studies concerned with the behaviour of operators, controllers and pilots in emergency situations. Hockey (1983) claims that speed of information processing will increase with growing stress, while working memory functions will be impaired by increased levels of stress. The inverted-U-relationship between stress and performance is thus decomposed into two additive linear components "speed of processing“ and "memory load“.

According to the ideas of Dörner (1993) outlined in part 4 of this report, stress will:

(1) Increase the speed of information processing.

(2) Reduce decision time.

(3) Increase the tendency to stick to the course of action (increase 'selection threshold').

(4) Increase the tendency of tunnel vision.

(5) Increase externalisation of behaviour (behaviour will be less dominated by internal plans).

(6) Enhance the tendency to switch from proactive goal-oriented behaviour (monitoring - control) to reactive behaviour (checking - diagnosis).

(7) Increase the probability of purely rule and skill-based behaviour in the sense of Rasmussen (1983).

According to Dörner (1993) urgency and the controller´s strain modulate information processing in predictable ways (cf. Figure 7).

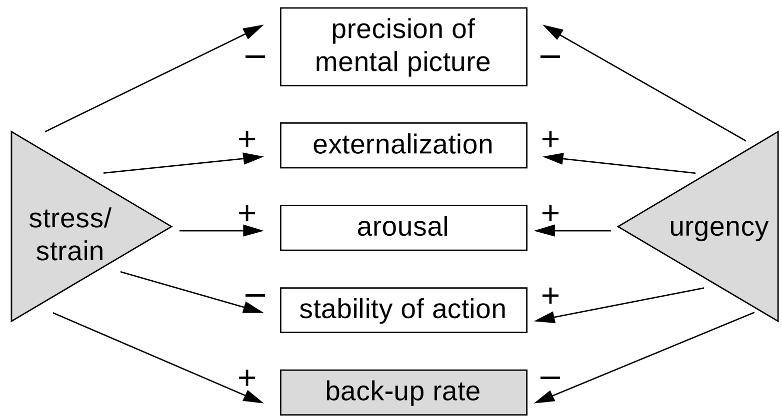

Figure 7: Effect of stress and urgency on process parameters of ATC (cf. Dörner, 1993)

Increasing strain (e.g. due to a less predictable high density traffic situation or delays and bad weather conditions) will be accompanied by a reduced precision in the mental picture. One reason is the increasing focus on conflict resolution. At the same time, it may happen that less important steps of the task or decisions are postponed, handed over to another person or even simply omitted.

With increasing strain, behaviour will switch from pre-planned action to more data-driven activities. At least the timescale of planning will be reduced. A comparable shrinkage of the planning horizon has been observed with changes from flight-strips to electronic flight strips. Externalisation implies a switch from cognitive controlled action with high situational awareness to more automated skill and rule-based action with reduced levels of situational awareness. At the same time decisions are less planned and more determined by routines or adapted from the actual course of action (e.g. flight level is kept in accordance with the neighbouring sector). Arousal is increased by stress and so is the information processing speed.

Up to this point effects of strain and time pressure or urgency change the information processing in the same direction. This is not the case as far as stability of action (or rigidity of behaviour) and the backup rate are concerned.

Stability of behaviour is increased by urgency and by emotional states like anger, in which unequivocal goals are set. Particularly in these stress states, which are characterised by increased uncertainty and reduced predictability of the situation, stability of action is reduced and frequent switches from one focus to another can be expected. High stability of behaviour is accompanied by a reduction in backup rate, while states of uncertainty speed up the backup rate. In extreme cases one can observe states of hypervigilant behaviour.

The changes caused by stress or time urgency are not positive or negative by definition. Stress and urgency enhance the economy of behaviour, especially when occurring at the same time. This positive shift can change into negative aspects, in cases of very complex situations, which cannot be handled without active problem solving and active decision-making.

Some important changes in decision-making were summarised by Janis and Mann (1977). Deviations from optimal, concentrated and vigilant decision-making can occur in cases of non-vigilant as well as in hypervigilant states. In non-vigilant situations the available information will not be thoroughly integrated and not all relevant alternatives will be scanned in an active planning process.

If there is only a limited amount of time to reach a decision, and if a sufficient solution for the situation is not at hand, there will be an extreme tendency to fall into a hypervigilant mode of information processing, which will result in non-optimal decisions. The controller will tend to vacillate from one alternative to another and restrict his view to a very few alternatives.

In addition, a state of hypervigilance drastically reduces the ability of co-ordinated team action (Kelly *et al.*, 1965).

On the other hand, he might keep to a given course of action, even if several disadvantages become obvious to the observer. According to Janis and Mann (1977), keeping to a given course of action (extreme selection threshold!) is the consequence if the controller does not see any chance of finding an adequate solution. In this case there is a strong tendency to hand over the responsibility to other people. Difficult situations with low time pressure are usually solved within the team (see *also Guidelines for Developing and Implementing Team Resource Management*; EATCHIP, 1996c).

The tendencies described above should be viewed as risks of stress for the controller. Normally, these tendencies are counteracted by training, experience, co-ordinated teamwork, and responsible self-monitoring. Experience in particular can effectively buffer the effects of stress on information processing and decision-making.

5.2 Additional Situational Factors - An Outline

Our literature review on situational factors revealed that less than 25% of the references were concerned with stress (e.g. noise, smoke, delay, workload). More than one third addressed personal states like illness, mood, fitness and drug consumption, which are related to stress in some instances but which refer to a far broader field (cf. Mohler, 1983). More than 40% of the studies tried to evaluate the role of factors directly related to the work of ATCOs (techniques, ergonomics, rostering, organization, team, standards, tasks).

Table 1 gives a survey of the different areas and the number of publications.

Table 1: Situational factors of ATC

	Situational factors of ATC	**Count* of empirical investigations (1972-1995)**
1	**Technical factors** i.e. electronic flight strips, old/new techniques, software bugs, technical equipment	15
2	**Ergonomic factors** i.e. temperature, illumination, size of display, work space	34
3	**Working hours** i.e. shift work, breaks, use of breaks, duration of work	9
4	**Organizational factors** i.e. planning controller, organizational structure, percentage of women at work, salary	23
5	**Standards** i.e. safety standards, amount of kerosene, secrecy	9
6	**Team** i.e. positive feedback, team combination, social conflicts	15
7	**Work flow** i.e. traffic density, sector size, briefing, weather, language, supervision	27
8	**Stressors** i.e. noise, smoke, delay, planning errors, monotony	71
9	**Alarm** i.e. emergency, breakdown of communication	13
10	**Person variables – states** i.e. illness, fitness, mood, drugs	100
11	**Person variables – traits** i.e. age, self awareness	5
12	**Private factors** i.e. vacancy, family, spare time, relationship, social status	7

** The count of investigations does not reflect the importance of the factors. Instead it shows the interests of researchers in different factors reflected in the number of research reports.*

One important result of the analysis of situational factors was repeatedly confirmed in our validation interviews. Surprisingly, periods of low workload after periods of very high workload or even periods of prolonged moderate or low traffic density are more error-prone than periods of high traffic density or periods of complex conflict resolution (cf. Stager & Hameluck, 1990).

Another important result concerns the topic of burn-out. Years spent in ATC do not only increase experience. At the same time, they bear the risk of burn-out, especially in cases of low social support from family or friends. Burn-out is related to changes in mood and behaviour, and therefore, it may even become safety relevant (see Dell´Erba *et al.*, 1994).

Finally, the study by Vortac and others (1993) should be mentioned. These researchers tried to assess deleterious and positive effects of automation. Contrary to other reports, they found that automation showed no negative effects on performance. Instead their subjects showed enhanced prospective memory and planning, possibly due to the reduced working memory load in the automation condition. This result again highlights the possibility of using automation devices as cognitive tools (Leroux, 1994).

6. CONCLUDING REMARKS

The present report illustrates that a simple structural model of the cognitive aspects of ATC allows the integration of complex information processing activity, planning and decision-making. The basic idea of the process model is a primarily top-down guided activity of controllers based on their mental model and the mental picture. A controller's activity is proactive under normal conditions. Either planned action or situationally triggered scripts characterise ATC. This activity can be described Anticipation-Action-Comparison Unit.

Basic aspects of the model could be validated in our final interviews. It is not possible to state that the model describes the activities of ATCOs in all situations but many situations and actions, as well as errors and risks, can be described by the model well.

6.1 Results from the Validation Interviews

The validation interviews were designed to scan different aspects of the tasks of an ATCO with respect to the cognitive activity involved. Based on a task analysis conducted by Cox (1994) questions were formulated to represent the cognitive aspects of the following activities:

(1) Take-over of a position.
(2) Acceptance of a new aircraft in the sector/control space.
(3) Monitoring and controlling air traffic.
(4) Planning.
(5) Handling of unforeseen events.
(6) Handling of conflicts.
(7) Hand-over of an aircraft to the next sector.
(8) General questions.

The interviews demonstrated that top-down activity can really be taken as the core process of ATC. The mental picture can be viewed as an actual situational adjusted mental model of the sector/traffic situation. The picture serves as a basis for planning processes.

Several functions of the process control systems were investigated by the interview: allocation of attention, especially in non-routine situations, active clustering to reduce working memory load, I/O problems, problems of information integration.

Finally, the interview addressed unplanned situations, detection of deviation from plans, detection of conflicts, mental error picture and forgetting of previous events (clearing of working memory).

The interviews were conducted at the Frankfurt ATC centre (DFS) with six controllers on two occasions each. The interviews were repeated in modified forms so that the controllers were allowed to reconsider some of the highly automated processes they were questioned about in the first interview.

Two interviewers (one male, one female) recorded the answers of the semi-structured interview on audio and videotape. Each interview took about 90 minutes.

Basic results of the interviews are as follows:

All the controllers describe their jobs as pro-active. Having to do the job in a reactive way is classified as a precursor of losing track of things and finally losing the picture.

The question of whether all activities were conducted as planned actions was answered differentially. Depending on the actual task, a continuum from highly event-triggered to more plan-/concept-driven activity was outlined.

Even in situations which could be characterised as situationally determined, controllers tended to draw back on preformatted action patterns and conduct control in a proactive, future-oriented way. Pure reactions to the informational input were either described as a situation preceding the loss of the traffic picture or preceding a “repair“ phase. This kind of repair situation is a rare event in ATC. It is actively avoided and systematically counteracted by the team.

The mental picture is formed very quickly in many instances. The time required depends on the traffic density, the position and the quantity of information that has to be integrated.

Finally, it has to be stressed that controllers are quite aware of their own process control unit. Learning to handle one’s own limits is explicitly taught to trainees, and their own personal state is well monitored as long as they are on duty.

6.2 Implications of the Cognitive Model of ATC

One of the basic messages of the cognitive model of ATC emphasises that ATC should be viewed as a process which is primarily governed in a top-down mode. ATC should therefore not be described as a continuous reaction to changing ATC events. Instead controllers are acting proactively according to preformatted plans, rules, and the mental picture of the situation. The mental picture of the air traffic situation is based on the controller’s mental model and the actual situational input. To act proactively, anticipations of future system states are of crucial importance. Accordingly, an Anticipation-Action-Comparison Unit was selected as the basic functional unit of the cognitive model of ATC. The current model does not neglect bottom-up processes in ATC.

Under normal conditions these bottom-up processes are dominated by the planned activity of the controller. One important hint of our validation interviews on this assumption is that the dominance of top-down processes in ATC varies from controller to controller. At least the self-descriptions of the controllers and probably their attentional processes governing their own activity place different weights on situational input and the planning processes. A detailed cognitive task analysis may help to understand the different aspects and modes of ATC which are possibly hidden behind these different views. All in all, the interviews confirm that ATC can be viewed as a primarily top-down governed proactive cognitive activity. To evaluate the relative importance of cognitive top-down processes, bottom-up processes and the behavioural aspects of ATC, cognitive task analysis has to be supplemented by methods of classic behavioural and action-oriented task analysis. Therefore, an approach which has been termed Integrated Task Analysis should be selected to account for the cognitive processes in ATC. The cognitive model of ATC can be used to derive practical guidelines for selection, training, licensing and HMS development in future Air Traffic Management (ATM). Some of the implications will be outlined in the final paragraphs below.

6.3 Implications for Training

The cognitive model of ATC stresses the importance of the controller's mental model and the mental picture. Therefore, anticipation, prediction, judgement, as well as adequate process control, are important elements of ATC which should be actively included in ATC training. Given the importance of mental processes in ATC, the controller should be aware of the weak points of human information processing, e.g. confirmation bias and overconfidence. In addition, mental models seem to differ drastically depending on different levels of expertise. One important feature pointed out by Isaac (1994) is imagery. This corresponds closely to the notion of Norman (1988) who points out that visibility of a system is one of the key features for fostering understanding.

These notions stress the importance of simulation systems for the training process.

In addition, the acquisition of mental skills should be emphasized in the training process. Some general guidelines can be drawn from the studies of Roth and Woods (1988; cf. Wickens, 1992). They showed that novice and expert operators control complex dynamic systems quite differently.

Expert operators:

- are better able to anticipate future system states;
- possess a superior mental model of the process, including time constants and interrelations;
- have a conscious setting of the speed-accuracy trade-off to go slow (which shows that they are more aware of the risks of fast as a well as sluggish actions);
- possess a broader spotlight of attention to guard against cognitive tunnelling;
- have better skills in communication and co-ordination with other operators. This implies that they are better able to act according to shared mental models in a team of controllers.

These facts lead to the conclusion that one of the main goals of training should be the provision of a valid mental model.

Given the importance of cognitive processes in ATC, skills from cognitive psychology to cope with the limitations of the human information processing system should be included in the training process. These include memo-techniques as well as the avoidance of typical judgement errors and the enhancement of the performance of the process control systems by explicit planning activity.

The explicit training of a mental model will enhance performance especially for non-routine situations.

The importance of mental factors makes it feasible to include techniques from cognitive psychology in order to optimise knowledge acquisition, storage and retrieval.

6.4 Implications for Selection

One possible reason of the low predictive validity of most selection batteries for *ab initio* trainee controllers might be the low specificity of tests employed. Tests of cognitive performance do not address specific cognitive activities of ATC, nor do they represent the core processes of ATC.

From the current model and the subsequent cognitive task analysis one can derive basic processes which are necessary for a good expert controller.

Up to now functions of the process control systems and the cognitive skill of designing a mental picture from a mental model and of managing a mental picture and have not explicitly been included in the selection process. The process of maintaining situational awareness has to be broken down into basic cognitive skills to derive and select tests which address the necessary aptitudes of *ab initio* trainees.

The different cognitive loads posed on controllers for different jobs (ACC, TWR, APP) can be derived from differential cognitive and integrated task analysis. Selection batteries based on the cognitive model of ATC will account for the abilities which are necessary for the monitoring and controlling of complex systems, decision-making in complex situations and the multitasking of the ATCO.

6.5 Implications for Licensing

For the purposes of this overview report Licensing is used as a generic term to cover the initial and periodic certification of competence in an ATC function at various levels. It is essentially a set of procedures to ensure safety. The cognitive model of ATC accounts for the fact that the mental model of the controller has to be updated after several weeks off duty. This update needs a considerable amount of time. Up to now, licensing procedures do not explicitly take account of an optimal mental model of the situation or possibilities of easy transfers between different activities. The problem of shared mental models also has to be integrated into the licensing procedures. Another important aspect is that licensing has to make sure that the process control systems is not weakened by individual or situational factors. To adjust licensing procedures to the implications of the cognitive model, thorough cognitive and integrating task analyses have to be conducted. They will serve as a basis for the derivation of practical guidelines for the modification and optimisation of current licensing procedures which show wide variation throughout the European Civil Aviation Conference (ECAC) area taken as a whole.

6.6 Implications for Human-Machine Systems (HMS)

In this context HMS is a broad term taken to encompass a range of artefacts used by an ATCO in carrying out his/her job. The cognitive model of ATC stresses the importance of viewing the technical systems in ATC as a kind of tool which should serve the purpose of supporting the cognitive functions of the human controller. With growing technical possibilities a change in the general point of view seems possible. The controller should no longer serve as the operator of a complex technological system, which leaves to the controller those tasks which the machine is unable to manage but which are error-prone because of the limitations of the human information processing system or the human motivational system. Instead, the technical devices should serve as cognitive tools which support the weak parts of the human information processing system.

With growing technological possibilities there is an increased risk that the activity of the ATCO is more and more reduced to a monitoring task. The activity of monitoring cannot be considered as a strength of human information processing.

In addition, it bears the risk that, in the case of equipment failure, the ATCO is unable to take over in a manual or semi-automated way. A major reason is that, while carrying out exclusively monitoring tasks over a prolonged period of time, the situational awareness and the traffic picture of the ATCO cannot be fully maintained. From a cognitive-oriented job and task analysis one could deduce a more appropriate distribution of tasks between ATCOs and technology. The aim should be to transfer tasks to the ATCO that take advantage of the strengths of human information processing and compensate for weaknesses of the technological system (Brainbridge, 1987). As a result, the technical equipment of an ATCO's workplace will serve as cognitive tools for the top-down activity of the ATCO (Leroux, 1994).

6.7 Outlook

Based on a simple structural information processing model, one basic functional principle Anticipation-Action-Comparison Unit, and four basic processes (monitoring, controlling, checking and diagnosing), a cognitive model of ATC is proposed. This model explains and integrates current concepts such as situational awareness or resource management.

At the same time, many aspects of the model correspond with current developments in automation, training, selection and licensing procedures. The model is in accordance with the controllers' view of their task and their traffic pictures. The model explains emotional responses as well as cognitive errors.

The validation interview of the model can easily be transferred into a cognitive interview to conduct cognitive task analysis. Thus, this model could serve as a platform to develop cognitive task analysis methods and cognitive tools for the controller, and to point out advantages and disadvantages of the HF in ATC.

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DEFINITIONS

For the purposes of this document the following definitions shall apply:

Action: An intentional, goal-directed behaviour.

Anticipation-action-comparison unit: A set of nervous components allowing us to predict changes in the environmental input as a consequence of our own changes in position and posture.

Bottom-up process: An activity controlled by external cues and commands. This term is also used to describe behaviour which is primarily driven by incoming information.

Checking: Is one of the basic functions of ATC consisting in selecting information from a new situation in order to update the actual mental picture.

Cognition: Human thought processes and their components such as perception, memory and decision-making.

Cognitive psychology: A general approach to psychology which emphasizes the internal mental processes including thinking and perception.

Controlling: One of the basic functions of ATC. It is a process of intervention which includes the selection of a strategy, the allocation of time, and a decision to terminate. The ATCO directs single aircraft or groups of aircraft to obtain a desired traffic situation according to the principles of ATC.

Decision-making: One of the basic functions of ATC. It is an active cognitive process which selects one out of a set of possible courses of action. It includes a weighing of the pros and cons of different alternatives.

Diagnosing: One of the basic functions of ATC. It is an active cognitive process taking place in order to assimilate new unexpected situational conditions into the actual mental picture of the traffic situation or to change the mental picture to account for the new evidence.

Epistemic knowledge: Knowledge about things, events and rules.

Heuristic knowledge: Knowledge that enables us to solve problems and adapt to new situations.

Input/Output (I/O)-system: One of the four components of the structural model of the cognitive processes of ATC. It is responsible for the selection of information and the selection of responses.

Interruption thresholds: Thresholds to switch from one task to another or to attend to environmental stimuli.

Long-term memory: One of the four components of the structural model of the cognitive processes of ATC. It stores the mental model, information, information processing routines and programmes.

Memory: A psychological construct representing the repository of knowledge in the brain. The human memory is divided into a short-term sensory store, a long-term memory and a working memory (cf. Atkinson & Shiffrin, 1968).

Mental model(s): The cognitive process(es)/representation(s) whereby humans are able to generate descriptions of system purpose and form, explanations of system functioning and observed system states and predictions about future system states (according to Rouse & Morris, 1986).

Mental picture: The actual mental picture of a situation represents a moment-to-moment snapshot of the actual situation based on the mental model and the actually perceived external cues. A series of mental pictures represents the actual mental model including the actual parametrisation.

Monitoring: One of the basic functions in ATC. It is a process of continuous or discrete comparison between the actual state of the system and the expected state of the traffic situation. Monitoring is a top-down process governed by the expected state of the system.

Process control system: One of the four components of the structural model of the cognitive processes of ATC. It is a kind of internal evaluation system which makes sure that action takes place as planned by the controller.

Retroactive/Proactive Interference: If you learn two series of information (e.g. two series of words) one after the other, the second series might inhibit the memorization of the first one (retroactive interference). Also, the first series might have an inhibitory influence on the memorization of the second series (proactive interference).

Receptor: A sensory nerve ending that changes specific stimuli into nerve impulses.

Schema: A cognitive representation that contains the typical features of a certain class of things, for example the schema of a “bird“ for most people contains the features “has wings“, “has feathers“, “is able to fly“. Schemata are stored in the long-term memory. They facilitate the processes of perception and cognition.

Script: A cognitive representation that describes the regular sequence of events in specific situations or contexts (e.g. Script of “visiting a restaurant“: go inside, wait to be seated, sit down, read the menu, order, etc.). A script may include roles and ramifications for special subscripts. Scripts are stored in the long-term memory. The knowledge that is stored in a script is used for the orientation in situations which occur often.

Short-term sensory store: Is related to the perception of information in the different receptor systems.

Situational awareness: The perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future (Endsley, 1988). This also means the continuous extraction of environmental information and the integration of this information with previous knowledge to form a coherent mental picture and the use of that picture in directing further perception and anticipating future events.

Stress: High stress in terms of H. Selye (1982) is characterized by central and vegetative arousal, which is prolonged during a longer time-period. The individual departs from his normal homeostatic equilibrium. Stress will also change information processing.

System: A group or combination of interrelated, interdependent or interacting elements forming a collective entity. The fundamental characteristic feature of a system is the interdependence of its parts or variables.

Top-down process: The ‘top-down“ behaviour is a behaviour governed by plans, mental models, intentions and rules.

Tunnel vision: Extreme focusing of attention on a short range of cues.

Working memory: One of the four components of the structural model of the cognitive processes of ATC. According to Baddeley & Hitch (1974), it is a short-term buffer with limited capacity and consists of three parts: the central executive, the visuo-spatial sketch pad and the phonological loop. Furthermore, it can only handle a set of about four to seven elements or combined elements (chunks) at the same time.

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ABBREVIATIONS AND ACRONYMS

For the purposes of this document the following abbreviations and acronyms shall apply:

ACC	Area Control Centre
APP	Approach Control
ATC	Air Traffic Control
ATCO	Air Traffic Control Officer / Air Traffic Controller *(UK/US)*
ATM	Air Traffic Management
DED	Directorate EATCHIP Development
DFS	Deutsche Flugsicherung
EATCHIP	European Air Traffic Control Harmonisation and Integration Programme
ECAC	European Civil Aviation Conference
EWP	EATCHIP Work Programme
HF	Human Factors
HMS	Human-Machine System(s)
HRT	Human Resources Team
HUM	Human Resources
ICAO	International Civil Aviation Organization
I/O	Input/Output *(system, unit, device, loop, etc.)*
IFB	Institut für Begleitforschung
PC	Personal Computer
R/T	Radio Telephony
TWR	Aerodrome Control Tower

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COGNITIVE INTERVIEW GUIDE

First Interview: ***Executive Controller in Area Control***

Please imagine your last shift as an executive controller in the area control, e.g.:

- the working position you were working at,
- the co-ordinator you were working with.

Taking over the Working Position

1. Imagine that you are taking over the position of the executive controller in the area control. Please describe exactly what you have to do before you can start working.

1.a What kind of information sources do you use to get a general idea of the traffic situation? Can you rank these sources, starting with the most important information source?

1.b Is this all the information you need or are there any other sources you use that have not been mentioned yet?

1.c How do you build up your "picture"? When do you usually start planning? Or do you wait and see what happens and then put your "picture" together, like a puzzle? What kind of information is particularly important?

2. Are there situations where taking over the working position is particularly easy?

2.a On what does it depend that taking over the position is easy to handle?

2.b How long does it take you to get into your work and fully adapt to the actual traffic situation when you take over the position in an easy situation?

3. Are there situations where taking over the working position is particularly difficult?

3.a On what does it depend that taking over the position is difficult to handle?

3.b How long does it take you to get into your work and fully adapt to the actual traffic situation when you take over the position in a difficult situation?

4. For what reasons do you change the arrangement of the flight progress strips (fps)? Are there any situations that require a complete rearrangement of the flight progress strips?

Important:➢ Here, we are talking about "restructuring", not only integrating new flight progress strips.

Taking over Control Responsibility for an Aircraft

5. When there is an aircraft for which you are soon going to assume responsibility, do you pay as much attention to that aircraft on the radar display as to all the others on the display?

5.a On what do you focus your attention particularly?

6. When do you start including an aircraft for which you are going to take control responsibility in your plans?

6.a Is this different for different aircraft?

6.b On what does it depend?

If this question is hard to understand; let’s put it another way:

6.c Under what circumstances is taking over control responsibility a routine action, and under what circumstances does it need special effort?

7. How do you mentally organize the integration of an aircraft for which you are going to take control responsibility into the traffic flows in your sector?

If this question is hard to understand:

➢ *What do you do with the flight progress strips?*

7.a What information do you have to take into consideration for this process?

7.b What information is of special importance?

7.c Do you categorise aircraft in a certain way? (e. g. type, speed, route). If yes: how do you do this?

Traffic Monitoring

8. At what intervals do you usually check the entire traffic situation (backup rate)?

9. Under what circumstances do you check more frequently?

10. What does the attention you pay to a certain aircraft in your sector depend on? Is your attention distributed equally to all aircraft? When does this distribution of attention change?

10.a What is the reason for paying more attention to one particular aircraft?

10.b Are there any aircraft that need very little attention?

11. Do you consider any aircraft as belonging together, as a cluster? (e. g. planes that fly in a certain formation).

11.a Which aircraft do you consider as a "group", as a cluster?

11.b Can a so-called "parcel" be considered a cluster of aircraft?

11.c What are your criteria for clustering aircraft?

11.d Under what circumstances do you usually cluster aircraft?

12. When you are talking to a pilot, are there sometimes problems in communication?

12.a Do you sometimes have non-technical difficulties in communication? If yes, what kind of problems?

Prioritisation

14. Please assume a situation in which the sequence of contacting the aircraft is not fixed by explicit rules. What are your criteria for determining the sequence of contacting the aircraft?

14.a Do you pay special attention to some aircraft, based on experience?

(e. g. you know that some pilots have difficulties in understanding the English language and therefore you instruct these pilots earlier). What kind of experience do you base this on?

14.b Do you have additional criteria to safety? (e.g. saving fuel and protecting the environment).

14.c Do you have any personal criteria?

Unplanned situations

15. What makes you notice that something is going wrong?

15.a What makes you notice that a pilot is doing something unexpected?

15.b What kind of information makes you notice this?

15.c Is it something like repeatedly occurring errors? (e. g. technical faults).

Error picture: One knows exactly what needs to be checked in a certain error situation.

16. How long does it take until you notice that an aircraft is doing something different from what it should be doing?

17. How much time do you take before reacting to such a deviation?

Conflict Situations

18. How quickly do you usually recognise a conflict situation?

18.a From what kind of information do you recognise a conflict situation?

19. How do you keep the other aircraft in mind that are not involved in the conflict?

19.a In a conflict situation, do you check the aircraft that are not involved more or less frequently than usual?

19.b Can you expect the remaining planes to fly their planned flight path?

Handing over Responsibility for an Aircraft

20. When do you need additional co-ordination with other ATC units?

21. What do you do with an aircraft after handing it over?

21.a After you have handed over responsibility for an aircraft, how do you erase this aircraft from your mind?

21.b After you have handed over responsibility for an aircraft, do you sometimes think about it again later?

21.c If yes, what prerequisites make a aircraft remain in your memory?

General Questions

1. When was the last time you were absent from your work place for more than ten days? (e. g. holiday).

1.a How did you adapt to your job after coming back?

1.b How long did it take you before you reached your 100% work efficiency at all positions?

2. All controllers have days when they are not satisfied with their performance. On such a day, do you already notice this during your work hours or when you sum up at the end of your work shift?

3. Do you notice when your concentration decreases during your working time?

3.a How do you notice it?

3.b What do you do in such as situation?

4. Do you think that your state of mind or your physical and emotional state is influencing your performance?

5. Does it happen that in certain situations your work is easier and more fun, and time is passing by faster than usual?

5.a What are the characteristics of such a situation?

5.b Could you please describe the last situation which was like this?

5.c What makes a situation as described above different from situations where working is more laborious?

5.d Does this also depend on your mood?

6. After having the traffic situation under max. control, are you able to:

   a. Recognise and name key elements like aircraft, clusters of aircraft, or dangerous areas?

   b. Perceive the traffic situation as a "whole" (as a Gestalt), and handle it with regard to safety, economy and the flow of the traffic?

   c. Predict how the future traffic situation will look after a certain period of time?

6.a. What are you able to predict?

6.b. How many minutes are predictable?

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