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Technical Review of Human Performance Models and Taxonomies of Human Error in ATM (HERA)

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Abstract

This report is the first of a series of three which, within Phase 1 of the Human Error in ATM (HERA) Project, deals with how human errors in Air Traffic Management (ATM) can be analysed to improve safety and efficiency in European ATM operations. The purpose of this work is to increase the effectiveness of error recording, analysis and prevention. This first report reviews the theoretical and practical techniques from other industries, from general psychology, and from the few ATM-oriented approaches that have been developed so far. This review culminates in a conceptual framework, which will be the basis for a detailed methodology for analysing and learning from error-related incidents in ATM. A shorter management summary of this report is also available (EATMP, 2002a).

Keywords

Human error Classification system Incident analysis Model
Taxonomy

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CONTENTS

EXECUTIVE SUMMARY

This report is the first of a series of three which, within Phase 1 of the Human Error in ATM (HERA) Project, deals with how human errors in Air Traffic Management (ATM) can be analysed to improve safety and efficiency in European ATM operations. The purpose of this work is to increase the effectiveness of error recording, analysis and prevention. This work has arisen as a result of the increasing importance of human error, error recovery and error reduction in ATM. In particular, the analysis in ATM is becoming more important as traffic levels increase, as European airspace becomes more harmonised and as ATM operational centres make more use of computerised support and automation. Human error is a potential weak link in the ATM system and, therefore, measures must be taken to minimise errors and their impact, and to maximise other human qualities such as error detection and recovery.

Theories of human error and practical approaches for analysing and managing error have largely been developed in other industries such as the chemical and nuclear power process industries. In these industries the effects of human error have already resulted in numerous incidents and catastrophic accidents. These have resulted in a large body of knowledge on issues such as what errors occur, how and why they occur, and how they can be prevented or guarded against. ATM can borrow from this knowledge to develop an ATM-specific approach.

This first report reviews the theoretical and practical techniques from other industries, from general psychology and from the few ATM-oriented approaches that have been developed so far. This review culminates in a conceptual framework which will be the basis for a detailed methodology for analysing and learning from error-related incidents in ATM. This methodology will be the subject of the second technical report in this series (see EATMP, 2002b). The third technical report (EATMP, 2002c) will summarise the results of a thorough validation of the methodology, demonstrating its application in Pan-European ATM incident analysis.

A companion ‘management summary’ (EATMP, 2002a) of this first technical report is also available. This was produced to be more accessible to the general reader, whereas this current technical report will be of more interest to the practitioner who wishes to understand the technical details of the work.

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1. INTRODUCTION

1.1 Human Error in Air Traffic Management

Human error is a major contributor to ATM incidents, with some reviewers suggesting that the human error contribution is in the order of 90% or more (e.g. Kinney, et al, 1977; FAA, 1990). Most industries have similar human error contributions (e.g. nuclear power - 70-90%). Controllers often handle high numbers of aircraft movements every day without major incident and so the ATM system is in fact very reliable. However, the fact remains that almost all incidents do involve human error. Hence, if such errors could be reduced, or the system made tolerable to them, there would be large increases in safety, with the additional potential for significant ATM capacity gains.

The aim of this study is therefore to increase knowledge and understanding of human performance mechanisms and the human errors with which they are associated. While investigation of incidents in this environment often conclude human error as the main causal factors, investigation of the human performance factors aims to go beyond this category alone, analysing the different facets of the situation and trying to understand the mechanisms and context which led to the error. The idea of personal responsibility is rooted in western culture and the occurrence of a human-made accident leads inevitably to a search for the human to blame. Given the ease with which the contributing human failures can subsequently be identified, such people are not hard to find. But it must be realised that most of those involved in serious errors are neither reckless nor stupid, although they may have been oblivious to the consequences of their actions. This is also true for an organisation, as Wagenaar and Groeneweg (1987) state: 'Accidents appear to be the result of highly complex coincidences which could rarely be foreseen by those involved … accidents do not occur because people gamble and lose, they occur because people do not believe that the accident that is about to occur, is at all possible.'

One of the obvious consequences of assessing human error in this environment is that, in understanding how and why it happened we may be able to prevent similar events. This process is not concerned, therefore, with the attribution of blame, but rather the analysis of the error and its underlying factors which will help our understanding of human performance and therefore give us the opportunity to recover and manage these occurrences in future.

One potential engineering solution is that of automation. However, paradoxically, automation can often increase the importance and impact of human error (e.g. Bainbridge, 1983 & Reason, 1998). This problem has been seen in aviation via the so-called ‘glass cockpit’ generation of aircraft (Wiener, 1988 & Billings, 1997). This is because automation merely shifts the location of human error from the ‘operator’ to the designer, the maintenance personnel, and the supervisor who must deal with automation problems and failures.

Furthermore, in ATM, full automation is not foreseen as a feasible option for some decades to come, because human traits such as flexibility and adaptability, problem-solving and decision-making capabilities are needed to optimise dynamic ATM situations. Therefore, automation, or rather computerised support, could help ATM to cope with human error even if alone it will not prevent human error occurrences.

Air Traffic Management (ATM) is currently under pressure as traffic levels increase. Airspace in many parts of Europe is already complex and congested and there is also pressure from the airlines, who are under strong competitive commercial constraints, to optimise routes and timings. These issues lead to complexity and time pressure on ATM operations that can subsequently lead to errors. Additionally, many ATM systems are currently being upgraded and developed into ‘next generation’ systems, which include computerised displays with new functionality and computerised tools. There is also the prospect in the near future of the introduction of datalink technology, which will significantly impact the method of operation in ATM.

These major shifts in work practices will affect both controller and pilot performance, and new opportunities for error could arise, particularly in the ‘transition period’ during which new systems and practices are introduced. These developments suggest that the ATM system is at the beginning of a long period of significant change and evolution, a period that will possibly see increased error rates and potentially new errors. This indicates a need for the development of an approach to better understand errors and monitor error trends.

Air Traffic Management (ATM) is therefore ready for the development of a methodology that allows a better understanding of human error and the opportunity to learn from these situations. Furthermore, since errors and those incidents arising from them are relatively rare, the best way to learn from such errors is to maximise the size of an error ‘database’. Since European ATM is becoming more harmonised, working collaboratively with its neighbours, much more will be learned about errors if all States use the same approach. If a methodology can be developed that can be applied to any European ATM situation, the European ATM organisation as a whole and each individual Member State can maximise learning from all human error events and incidents. This should make the ATM system safer and more effective.

1.2 Overall Work Plan and Focus of this Report

The overall work plan for this project is summarised in Figure 1. This work plan covers Phase 1 of the Human Error in ATM (HERA) Project (HERA 1), namely the development of a methodology for analysing human errors in incidents in ATM. Phase 2 is not yet fully defined but will seek to encourage the implementation of the methodology in Europe.

Phase 1 has three distinct Work Packages (WP):

(i) WP1: Development of a conceptual framework and model of human error in ATM (see this report and EATMP, 2002a).

(ii) WP2: Development of a methodology (a taxonomy and an associated method of use) based on WP1 for analysing errors and their causes in ATM incidents and preparation of user guidance material (see EATMP, 2002b).

(iii) WP3: Validation of the methodology/taxonomy developed in WP2 (see EATMP, 2002c).

This first WP therefore defines the model of human error in ATM, noting the human behaviours and functions in ATM and how they can fail. The second WP takes this basis and from it derives a detailed methodology including all error forms and their causal/contributory/compounding factors. The second WP then develops structured methods for classifying events into these forms and factors. The third WP attempts to validate the methodology. Practitioners from various (European Civil Aviation Conference (ECAC) States will use a set of incident descriptions to test the consistency of usage of the methodology and to assess its perceived usefulness.

The focus of this report is therefore the development of the conceptual framework and model of human error in ATM. This will be achieved by integrating different aspects from existing models and approaches, and from a knowledge of the ATM task such as required controller behaviours and functions. The review therefore covers a number of sources of information:

(i) Human error taxonomies - classifications of human error types.

(ii) General psychological models of human performance and error.

(iii) Approaches from other industries.

(iv) Models of ATM controller performance.

(v) Consideration of current and future controller task and behaviour requirements.

The first three sources are reviewed to see what **should** be present in a model and framework of human performance or error, and the last two sources help to determine what is **needed** by an ATM-specific framework and model.

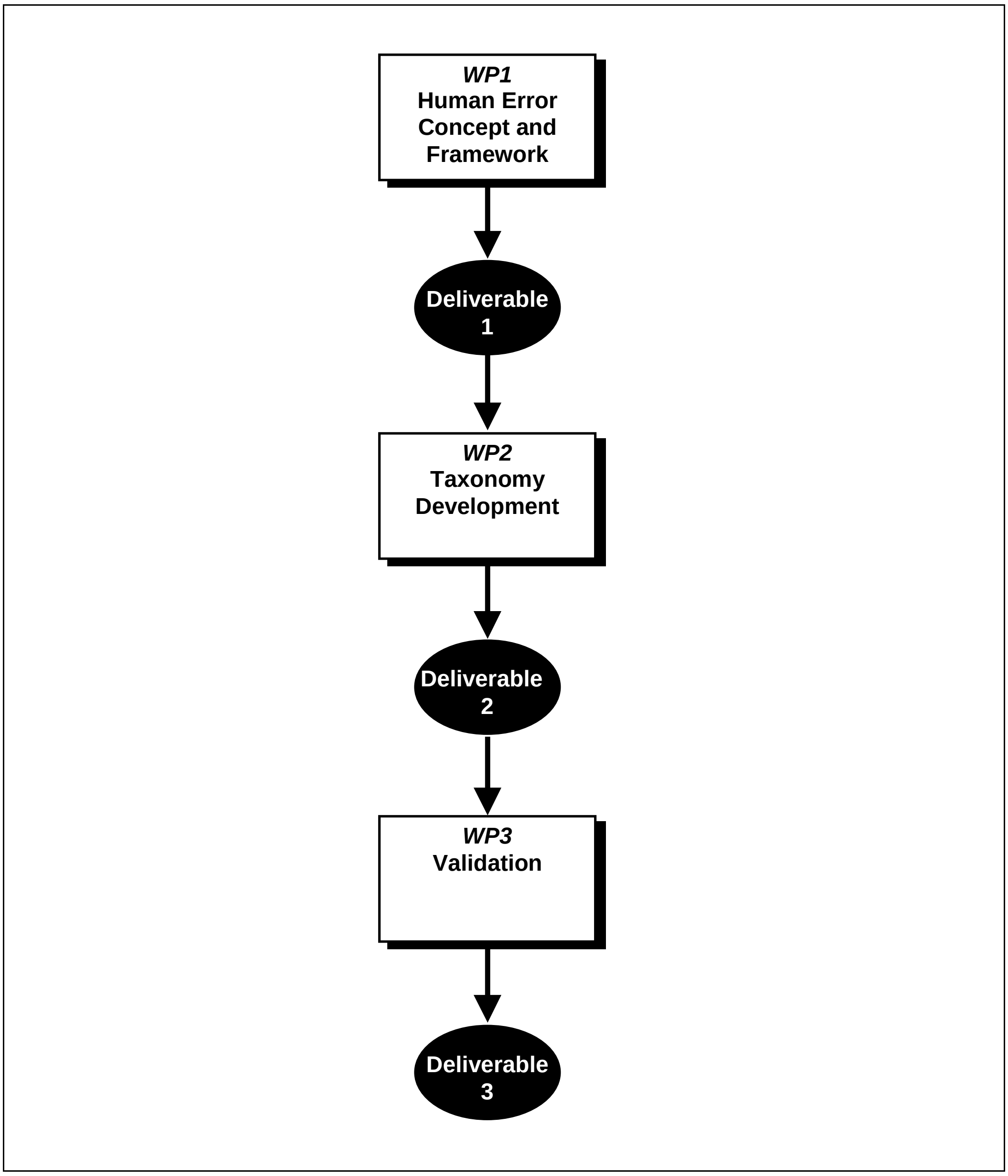

Figure 1: Overall work plan for Phase 1 of the Human Error in ATM (HERA) project

1.3 The State-of-the-Art in Human Error Theory and Practice

Given the desirability of a methodology for analysing human errors, it is useful to research what methodologies already exist. Currently, there are no ‘off-the-shelf’ ATM-oriented Human Error Analysis (HEA) methodologies. This is partly because ATM has been a relatively high-reliability organisation - human reliability and system reliability is higher than many other industries. There has therefore been little demand for such approaches. This could mean that ATM is somewhat ‘naive’ in methodological terms in this area, compared to other ‘high-risk’ industries (e.g. nuclear power, chemical process and offshore petro-chemical industries). These other industries have developed approaches following large-scale catastrophes and accidents such as the Three-Mile Island (TMI, 1979) and Chernobyl nuclear accidents, the Bhopal poisonous gas release, the Challenger explosion, and the Piper Alpha oil platform fire. However, since human error is mainly a function of the human rather than the operational working context, this ‘naïveté’ may not matter. ATM can borrow from other industry knowledge and experience, and from general psychological understanding that has evolved over the past three decades of industrially-related research in this area.

Human error has always been part of psychology, but in the industrial setting its beginnings are usually traced to the late fifties and early sixties, when formal methods for identifying and classifying human errors in missile development systems were developed along with hardware reliability approaches. Human error classification systems, and even human error databases, were developed in the sixties and seventies, although their main application was in the military domain and in some early nuclear power plant developments.

The nuclear power accident at TMI raised the importance of human error in many industries. Within a few years of TMI the emerging approach of Human Reliability Assessment (HRA) became mandatory in all nuclear power risk assessments worldwide. HRA aims to identify and predict human errors in complex systems. During the eighties in particular there was further development of HRA techniques. Furthermore, a deeper understanding of human errors arose, including their causes, manifestation and consequences. The nineties has seen a maturing of some of these HRA techniques and a broadening of models of human error to account for organisational influences on error and, more recently, maintenance error and errors associated with automation.

Certain industries such as nuclear power have sought to set up ways of systematically recording errors, such as databases, so that lessons can be learned from them. One such database, called 'Computerised Operator Reliability and Error Database (CORE-DATA)' (discussed in detail later), is a state-of-the-art system for classifying errors in a range of industries, based on a thorough review of human error models and predictive techniques. Systems such as CORE-DATA are being reviewed by international bodies such as the International Atomic Energy Agency (IAEA), to determine if they are suitable as an international approach to classifying human error in the nuclear power domain. Such industrial initiatives reflect and reinforce this current project for ATM.

The detail of state-of-the-art human error theory and practice will be reviewed in depth in Chapter 3. However, it appears that there is sufficient knowledge from other domains and from Psychology and Human Factors to attempt to develop an ATM approach.

1.4 The Need for a Scientific ‘Model-based’ Approach

At this stage it is necessary to explain exactly what is needed in terms of an error analysis because, to some extent, every ECAC State will already have some means of recording, classifying and learning from human errors in ATM. The development of a new European system for analysing incidents may be seen as an implicit criticism of existing approaches. The question that should be addressed is why current approaches may not suffice and, therefore, why a new approach is necessary.

First, it is hoped that the new system developed in this project will be seen as adding value to existing approaches. As noted above, concern over human error has not been the most important concern in ATM (although it has always been a major concern) and so many approaches will have evolved over time, adding new categories of error to existing systems as each new error arises. What this project will attempt to do is define all error types that can occur or could occur, whether with existing or future systems. The project will do this by using more general human error frameworks and approaches based on tens of thousands of errors in many industries.

Second, the work presented in the second report will examine error analysis systems from several countries, to ensure comprehensiveness and compatibility with such approaches. In the third report, where the results of the validation will be presented, comments from incident investigators and analysts who have participated in the validation will be noted. A workshop may also be held with various ECAC Member States who would be able to view and comment on the developing methodology. The development phase will therefore take note of existing approaches. Finally, following this current development phase (model development, methodology development, and validation), there will be an implementation phase which will consider in detail, with various Member States, how the approach developed in Phase 1 can be implemented and introduced into existing operational systems. This project as a whole will therefore take due account of existing ATM knowledge and approaches, and aim to develop a system which is compatible with, and can enhance, existing systems.

Third, the approach being developed in this project will attempt to carry out a ‘deeper’ analysis, in the psychological sense, than previous and existing error analysis systems. Other industries have realised the need to take this approach, for two fundamental reasons. The first is that such depth of analysis prevents ambiguities and aggregation of errors which are fundamentally different. The second reason is that error prevention and reduction measures are never easy to achieve. The more precise the understanding of the causes, the more successful error prevention and reduction measures are likely to be.

The model-based approach itself has some intrinsically desirable properties. Most importantly, a model allows causes and the interrelations between causes to be better understood. An error model provides an ‘organising principle’ to guide learning from errors. Trends and patterns tend to make more sense when seen against the background of a model, and more ‘strategic’ approaches to error reduction may arise, rather than short-term error reduction initiatives following each single error event. This will be particularly important as new tools and functions or procedures are introduced across Europe.

Models also need precise definition so that practitioners can agree a common set of terms and meanings. This is particularly important to learn lessons across Europe. This precision also has the advantage that different users will tend to classify the same events in the same way, thus ensuring a consistent and accurate picture of where problems originate. The consistency of the methodology (i.e. the taxonomy and its associated method of use) which is being developed for this project will be tested in the validation stage, WP3.

Therefore, a model-based approach has certain advantages in terms of understanding the errors and being able to learn from them and in terms of increasing the effectiveness of error analysis. The development of a model-based approach that also incorporates the vast experience that has been accumulated by existing operationally-based systems would represent a valuable tool that can significantly protect ATM from human error.

1.5 Structure of the Report

The remainder of this report is concerned with developing the conceptual framework and model of human error in the ATM system. Chapter 2 starts with an outline of the approach taken, and some definitions of terms, which are necessary to navigate through the detail of the review and development process. Additionally, some basic criteria for a conceptual framework and model are given. Such criteria are necessary to ensure a coherent approach. The criteria are based on the context in which the model will be used, namely incident analysis and error reduction.

Chapter 3 contains the majority of this report. It details the reviews of major modelling approaches and error classification systems. It addresses the available models of human performance and error, and also the types of behaviours that a model must be able to address. This leads on to Chapter 4 where a conceptual framework and model is proposed and defined. Chapter 5 defines the more detailed and stringent criteria that must be applied to the development of a methodology, to provide a basis for the next Work Package (WP). Finally, Chapter 6 presents a number of conclusions derived from WP1.

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2. APPROACH

The approach taken in this WP is to review extensively the important factors for creating a human error taxonomy and conceptual framework. First, relevant models of human performance, human error theories and taxonomies, and conceptual frameworks have been reviewed. These areas and domains include early taxonomies of error modes, communication models, information processing, symbolic processing and cognitive simulations. The review also describes an ATM-specific error analysis technique called the Technique for the Retrospective Analysis of Cognitive Errors in ATM (TRACEr).

Each classification system, taxonomy, technique and model of human performance is reviewed briefly with explanatory illustrations. Furthermore, ‘Lessons Learned’ are summarised for each taxonomy, model, theory or group of similar approaches. These ‘lessons’ will be taken forward to guide and inform the development of the developing error taxonomy and conceptual framework for ATM.

Secondly, a selection of other domain approaches have been explored. A number of comparable projects exist from other industrial domains, and these provide guidance and ‘benchmarks’ for this ATM project.

Thirdly, the ATM context was examined, both in the present and possible future developments, to provide an insight into what is required to ensure that the developing methodology is useful and applicable to ATM incident investigators and analysts.

In reviewing these diverse sources of information the relevant aspects of human performance in ATM were captured. These feed into a conceptual framework for error analysis in ATM. Also, a set of detailed requirements have been recorded for an ATM error analysis methodology.

The resulting conceptual framework (and in WP2, the taxonomy) will be called:

HERA - **H**uman **E**rror in **A**TM taxonomy.

Before reading the rest of this report a number of common terms must be defined as they will be used frequently during the review and development chapters of this report.

Human Action, Behaviour, Functions and Performance – 'Action' is anything the human does that can impact on the ATM system. This is usually understood as a set of human 'behaviours' or 'functions' such as touching, deciding, talking, monitoring, problem-solving, etc. The degree to which these behaviours and functions are supportive of the system goals represents the performance of the human ‘component’ in the system.

Human Error - Action (or inaction) that potentially or actually results in negative system effects. ‘Opposite side of the coin’ of human performance. The important point to understand is that error and performance are both merely the outcomes of behaviours and actions - these behaviours and actions are intrinsically the same, whether they result in a good or a negative outcome. In fact, if the system performance criteria were not known it would be difficult to observe human behaviour and say whether it was good or ‘in error’. A true model of error must therefore be able to account for performance and vice versa.

Framework - Aggregation of functions or behaviours that, taken together, can account for more complex behaviours or human-system interactions. For example, a simple framework could comprise a listening function, a monitoring function, some rules for pattern recognition of separation between aircraft and an output communication function. Such a framework would account for certain ATM functions, albeit at a basic level. Integrative in nature, its purpose is explanative in nature and usually only at a high level.

Conceptual Framework - Specialised form of framework which aims to capture the essence of what is being represented, i.e. at a more generic or abstract level. Its intent is to be more generalisable to variations in context, e.g. applicable to many ATM situations in different states. This abstraction makes the framework more useful but also enables more reasoning about the nature of errors, their causes and their interactions to take place.

Model - Representation of a system, in this case the human system in an ATM context. Is explanative but should ideally also have more interpretative and predictive power. For instance, should be able to interpret and derive the causes of errors (i.e. knowing what to look for), and ideally be able to predict the occurrence of certain errors, given certain conditions. Arises from a conceptual framework. However, in order for it to be more useful for the practitioner, should be more concrete and precise in its specification of the inputs and outputs and how the various intervening functions interact.

Methodology - In this context, is a complete approach for analysis based on a model, which can analyse situations and determine the errors and their causes. Should be applicable to a specified range of situations and variations in context, and its results should be consistent across different users. Must offer insight into the problems being analysed.

External Error Mode (EEM) - External manifestation of the error, i.e. what action or inaction occurred (e.g. contacted wrong aircraft; said ‘XX123’ instead of ‘XX223’; etc.). Does not denote how or why it happened.

Error Mechanism - Way in which the behaviour or function failed. A simple example is ‘memory failure’ or ‘forgetting’. Does not denote the outcome or the causes but is useful to know for error reduction purposes.

Error Cause - Reason why the error occurred - without the error cause, or causes, the error would not have occurred. Is sometimes called ‘Performance Shaping Factor’ (PSF), operates on the human, and via an error mechanism.

Contributory Cause - On its own would not have led to the error - another cause or causes must also have occurred for the error to happen. Is important because often there is no single cause and it is therefore counter-productive to name a single cause, because error reduction based on such an analysis will prove ineffective. Sometimes there is a single main cause which is sufficient to cause the error. However, the contributory cause could have increased its likelihood or strength of effect or system impact.

Taxonomy - Systematic set of principles for the classification and arrangement of human error concepts.

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3. REVIEW OF ERROR THEORY, MODELS AND PRACTICE

3.1 Why Classify Human Errors in Air Traffic Management

There are four primary purposes for classifying human error in ATM in the context of incidents that have occurred during operations:

(i) Incident investigation - To identify and classify what types of error have occurred when investigating specific ATM incidents (by interviewing people, analysing logs and voice recordings, etc.).

(ii) Retrospective incident analysis - To classify what types of error have occurred within present ATM systems on the basis of incident reports; this will typically involve the collection of human error data to detect trends over time and differences in recorded error types between different systems and areas.

(iii) Predictive error identification - To identify errors that may affect present and future systems. This is termed Human Error Identification (HEI). Many of the classification systems in this review are derived from HEI tools.

(iv) Human error quantification - to use existing data and identified human errors for predictive quantification, i.e. determining how likely certain errors will be. Human error quantification can be used for risk assessment purposes.

Within these applications, retrospective incident analysis (see (ii) above) is the main focus of HERA, although the resulting taxonomies should also be usable for other purposes.

Human error classification can, and frequently does, play a vital part in ATM incident analysis. First, it allows monitoring of error occurrence over time to detect trends in serious errors. Incident recording systems allow incident investigators and analysts to organise, structure and retrieve information on errors. Second, human error classification helps to generate research into errors, their causes and manifestations. Third, and most importantly, human error classification aids the development strategies to eliminate or reduce errors, or reduce their unwanted effects in systems. Despite this, error classification has been an under-developed part of the incident investigation process.

3.2 Models of Human Performance and Error

Despite the dominance of human error in ATM-related incidents there are few specialised human error classification systems to analyse and classify ATM errors. Many error classification systems already exist but most of these are either generic in nature or were developed for the nuclear and process industries. These systems range from simple lists of error types to classification systems based around a model of operator performance. Unfortunately, many of the existing systems do not adequately identify the errors that can occur in ATM, such as errors of judgement, hearback errors and visual misidentifications. Furthermore, some systems are based on models of performance that do not represent ATM tasks.

Stager and Hameluck (1990) claimed that the application of a human error **model** would provide advantages in addressing the issue of error classification in ATM. Furthermore, Rouse and Rouse (1983, p. 540) stated that the 'internal consistency of a classification scheme is likely to be enhanced if the scheme is based on a model of the process within which errors occur'. Such a model, they argue, can help both to identify categories within the classification scheme and illustrate the relationships among categories.

The absence of a useful human error taxonomy also creates difficulties in learning from incidents. A ‘tailored’ classification system for ATM would have practical value in gaining deeper insights into the causes of incidents and in suggesting measures for error prevention, protection, and mitigation.

For the following reasons there are currently no widely accepted models of human performance and human error in ATM:

- ATM is associated with several ‘covert’ cognitive skills or activities such as pattern recognition, situation assessment and awareness, judgement, projection, and prospective memory. These can be difficult to represent in an ATM model.

- ATM differs between different functional areas and different countries, so specific ATM models may have low applicability.

Air Traffic Management (ATM) changes over time, with new technology and new ways of working. Therefore, ATM models could become obsolete. Fortunately, several generic models and theories of human performance and error exist, which have been widely accepted. These provide a general framework for classifying and understanding specific errors based on human characteristics such as behaviour, psychological processes and task characteristics.

Most models of human performance elaborate on the basic ‘input-organism-response’ model of human performance, which is analogous to models used for the physical component. Rasmussen (1981) gives the example in Figure 2.

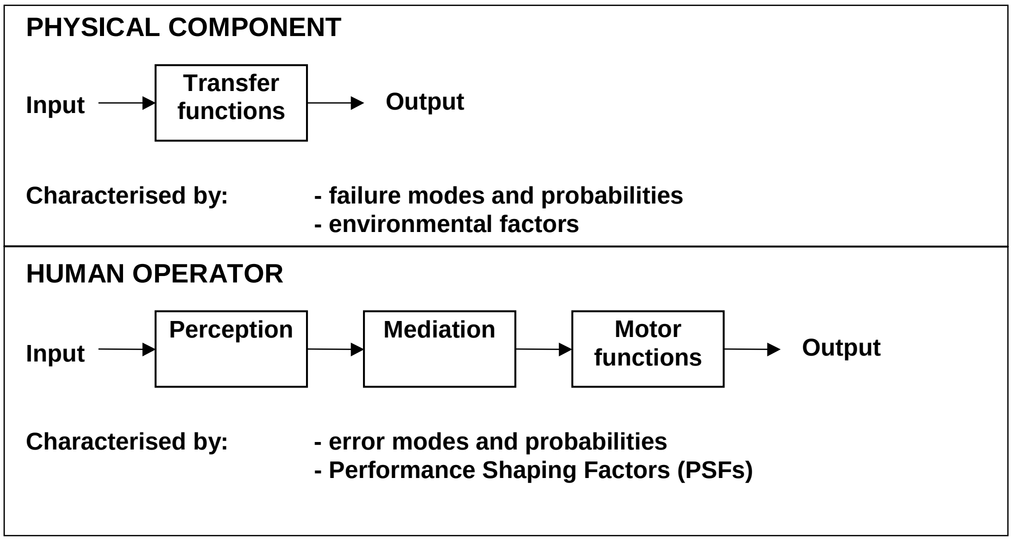

Figure 2: Rasmussen's (1981) schematic diagrams for failure analysis of physical components and human operator

Rasmussen notes that there is no one-to-one relationship between external task performance and internal human functions - intentions, expectations, goals and values guide action and information seeking. Error mechanisms and failure modes depend on mental functions and knowledge which are activated by both external events and subjective factors. Mental functions and subjective factors cannot be observed but must be inferred from characteristics of the task and the work situation together with the external manifestation of the error. Rasmussen claims that for this to be possible, a model of human information processing must be available. This model must relate elements of human decision-making and action to internal processes for which general psychological mechanisms and limitations can be identified.

A number of theoretical traditions have developed in the evolution of models and taxonomies of human performance and error. These are shown in Figure 3, also showing the overall structure of this report.

Woods and Roth (1986) note that the various human performance modelling traditions are all concerned with some aspect of 'information', and how a person acquires and uses this information to guide observation and action. The issue which varies across models is how the particular information is gathered and how it is represented internally. These theoretical approaches will be the main focus of the remaining part of this report.

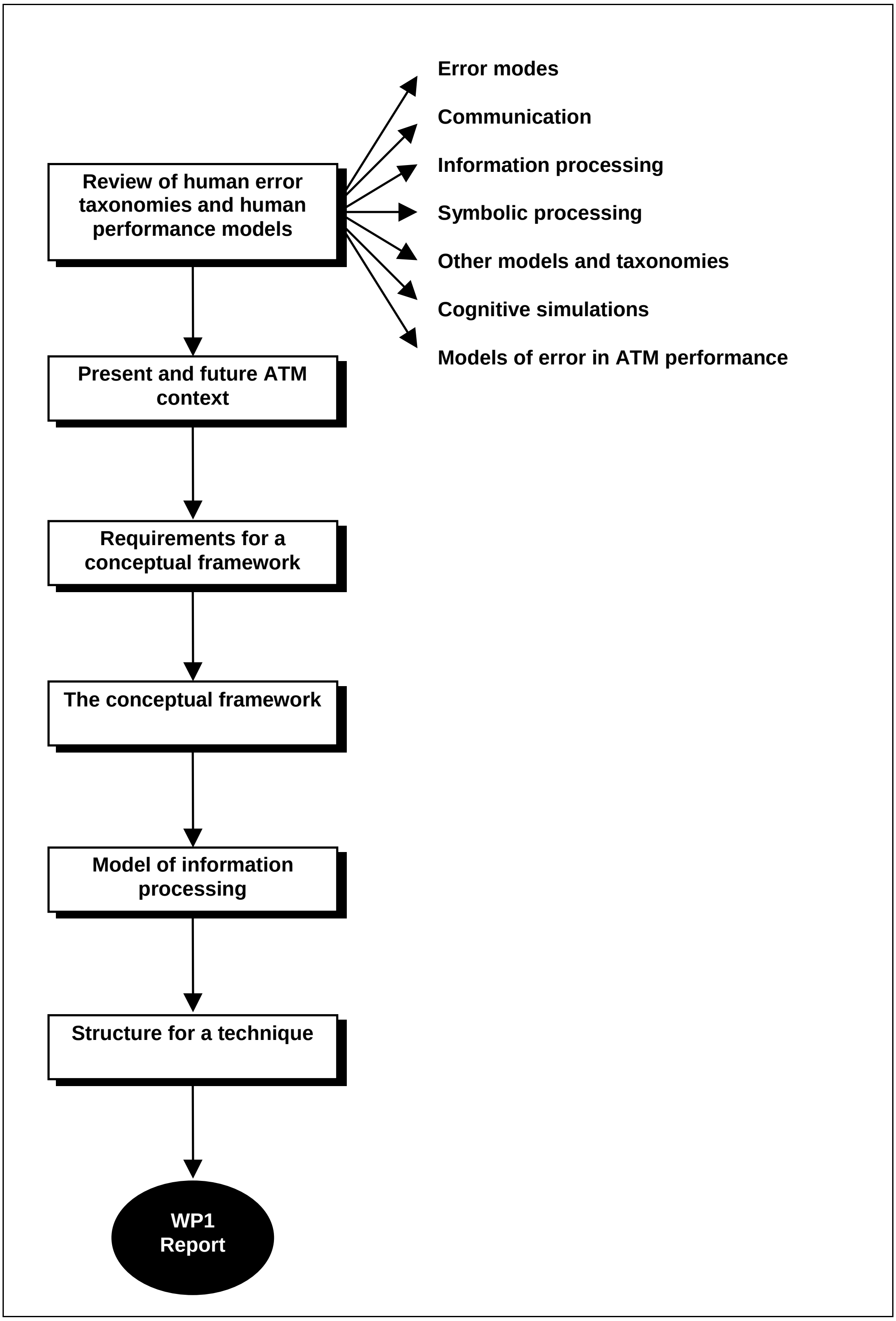

Figure 3: Overall structure of this report

3.3 Task-based Taxonomies

3.3.1 Error Modes

Early taxonomies of human error were developed in the sixties for use in Human Reliability Assessment (HRA). Most of these taxonomies are simple lists of ‘External Error Modes’ (EEMs) which refer to the structure and elements of the external human task and classify the overt characteristics of the error. A famous taxonomy was proposed by Swain (1982) and Swain & Guttman (1983), who distinguished between three main categories of errors:

(i) **Errors of omission - Required action not carried out**

- a) Entire task omitted.
- b) Step in task omitted.

(ii) **Errors of commission - Required action performed incorrectly**

- a) Selection error - Wrong object selected, object mispositioned or wrong command or information issued.
- b) Sequence error - Acts carried out in wrong sequence.
- c) Timing error - Acts carried out too early or too late.
- d) Qualitative error - Acts carried out to too great or too little extent, or in the wrong direction.

(iii) **Extraneous acts – Wrong or unnecessary acts are performed**

This terminology is still in widespread use today and, in a general manner, encompasses almost all possible types of errors. However, these classifications are fairly non-specific and give little or no insight into the causes of errors and the associated mental limitations. This analytical approach is therefore based on a model of the **task** rather than a model of the **human** performing the task.

Rasmussen (1987) argues that such simple taxonomies are inadequate and that human errors must be classified in terms of human characteristics. Furthermore, Rasmussen argues that taxonomies must encompass the analysis not only of manual task elements, but also of internal cognitive task components and the psychological mechanisms associated with both. Nonetheless, EEMs offer a useful method of classifying errors as part of a wider classification framework.

Lessons for HERA

1. EEMs must be represented within HERA to show the manifestation of the error, i.e. ‘what happened’.
2. EEMs should be represented within a hierarchical structure.
3. EEMs alone are not sufficient for ATM error analysis.

3.3.2 System-oriented Taxonomy (Spurgin et al, 1987)

Spurgin et al (1987) proposed a system-oriented taxonomy as shown below.

1. Maintenance testing errors affecting system availability.
2. Operating errors initiating the event/incident.
3. Recovery actions by which operators can terminate the event/incident.
4. Errors which can prolong or aggravate the situation.
5. Actions by which operators can restore initially unavailable equipment and systems.

This taxonomy usefully classifies human actions in terms of the propagation and effects of errors over the course of an event (e.g. an incident), but the taxonomy does not describe how the particular action was erroneous. Again, the taxonomy offers no insight into underlying mechanisms and causes of the error.

Lessons for HERA

1. Contextual factors should be considered within HERA to describe the task that the controller was performing when the error occurred.
2. HERA should be capable of describing errors initiating the event, recovery actions and compounding/aggravating errors.

3.4 Communication System Models and Taxonomies

Several models of communication have been developed since the forties. Most of these are models of **mass** communication, and are not primarily models of cognition, and so they are not applicable to ATM. However, some models have had a large influence on subsequent models from other traditions, e.g. information processing. Since ATM is heavily dependent on communication, this chapter considers a selection of communication models.

3.4.1 The Lasswell Formula (Laswell, 1948)

'A convenient way to describe an act of communication is to answer the following questions: Who? Says what? In which channel? To whom? With what effect?' (Lasswell ,1948).

Whilst not a model as such, these questions have been used in communication research to examine aspects of communication. Braddock (1958) included two further aspects of communication: the circumstances under which a message is sent and the purpose of the message (see Figure 4).

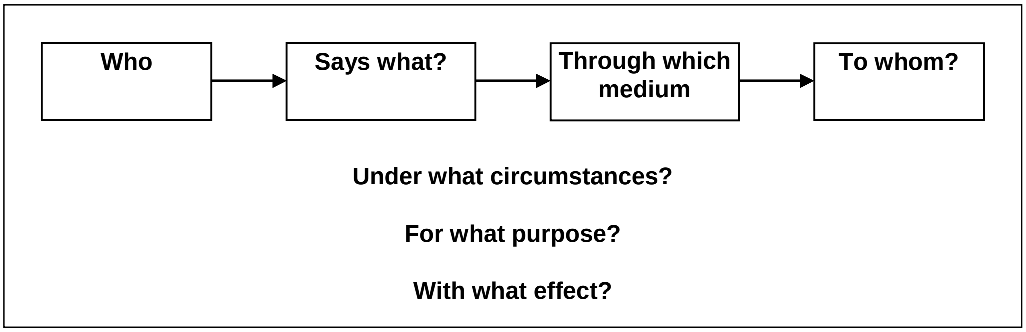

Figure 4: Braddock's extension (1958) of the Lasswell formula (1948)

This introduces a number of concepts into error research, for instance:

- 'Through which medium', e.g. how does the type of display affect the type of errors?
- 'Under what circumstances?', e.g. how can the context of a R/T transmission affect interpretation and understanding?
- 'For what purpose?', e.g. what is the controller's goal in a coordination, and how is the goal perceived by the other controller?
- 'With what effect', e.g. how does a pilot interpret a controller's message?

3.4.2 Linear Model of Communication (Shannon & Weaver, 1949)

The communication system modelling tradition is largely derived from Shannon and Weaver's (1949) Communication Theory. The model emphasises the role of uncertainty in human performance - behaviour is a function not just of what happened but also of what could have happened. The model was constructed as part of a mathematical theory of communication which could be applied to a wide variety of information transfer situations, involving humans, machines, or other systems. The basic linear graphical model is illustrated in Figure 5.

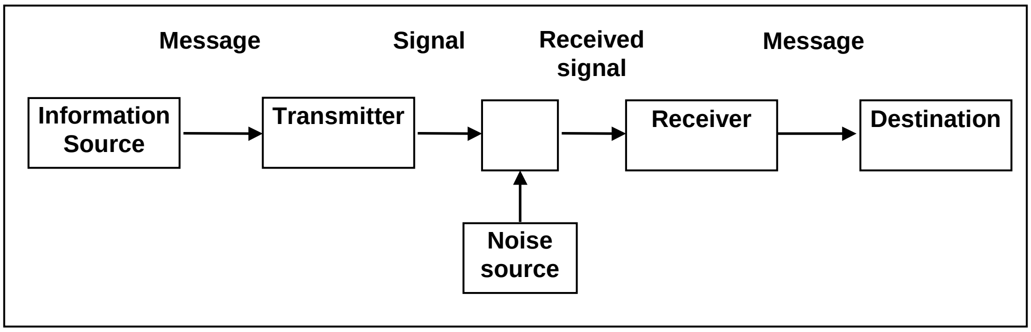

Figure 5: Shannon and Weaver's (1949) Model of communication

Shannon and Weaver identified the three following levels of problem in the analysis of communication:

- Level A - technical;
- Level B - semantic;
- Level C - effectiveness of reception or understanding on the part of the receiver.

The model examines the role of noise on the signal. For example, noise in the control room could be heard by a pilot and consequently interfere with a controller's transmission. Errors can also occur when the communicators fail to realise that the sent and received messages were not identical. The concept of noise in Shannon and Weaver's Model refers to 'physical' noise, but noise could also be 'psychological', such as unclear communication.

3.4.3 Circular Model of Communication (Osgood & Schramm, 1954)

Osgood and Schramm (1954) further developed Shannon and Weaver's (1949) Model to account for the role of feedback, to create a circular model as shown in Figure 6.

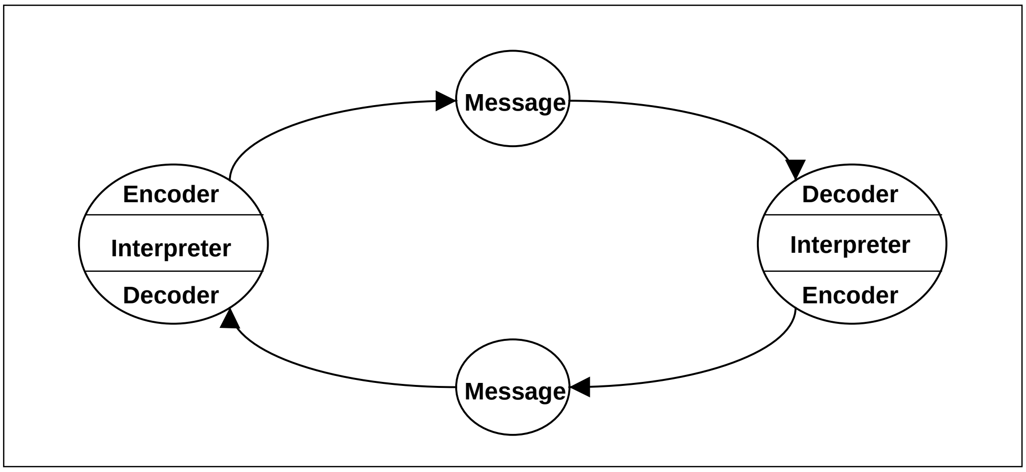

Figure 6: Osgood and Schramm's (1954) Circular Model

At a basic level, this model represents communication between pilot and controller. Whilst the model is still very simplistic, it can be seen that errors could occur in the encoding, interpretation and decoding of a message.

3.4.4 Helical Model of Communication (Dance, 1967)

Dance's (1967) Helical Model is actually a metaphor, which combines aspects of the early linear models of communication and the later circular models of communication to form a helix. Linear models omit the role of feedback in communication and circular models are flawed in that they suggest communication comes full circle to the same point from which it started. The helix implies that while communication is moving forward, it is also coming back upon itself and being affected by its past behaviour. For instance, what is communicated now will influence the structure and content of communication later on. The helix suggests that different aspects of the communication process change over time. The shape of the helix can differ according to the situation - with prior knowledge of a topic the helix widens quickly. With little or no prior knowledge, such as in new situations, the helix widens more slowly. This notion of existing knowledge and how it affects communication is something that should be considered in a human error classification system.

3.4.5 Source, Message, Channel, Receiver Model of Communication (Berlo, 1960)

Berlo's (1960) Source, Message, Channel, Receiver (SMRC) Model adds a sociological slant to Shannon and Weaver's (1949) Model of Communication. It suggests that successful communication depends upon a match between the skill and attitudes of the source and receiver. This knowledge must be acknowledged and the significance of culture and social systems are emphasised. Berlo's SMCR Model of Communication is shown in Figure 7.

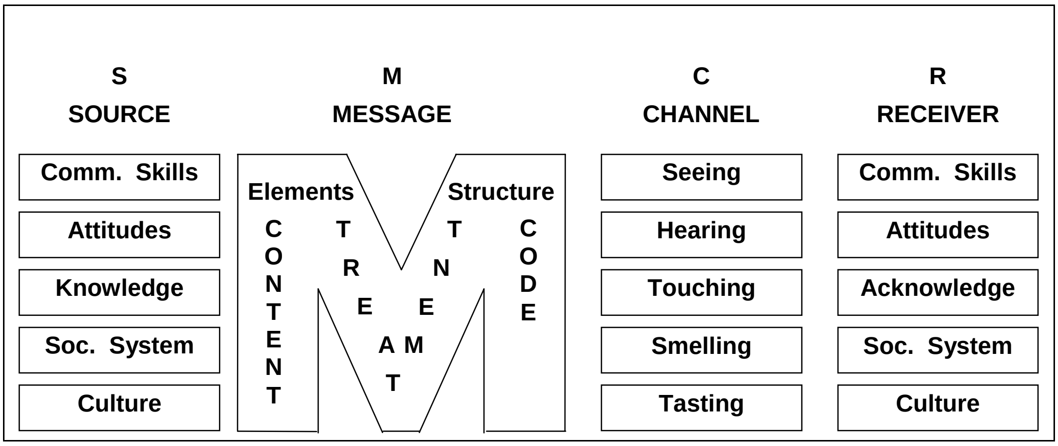

Figure 7: Berlo's (1960) SMCR Model of Communication

It suggests that errors may arise if, for instance, there are differences in communication skills or if a message is not acknowledged. Differences in social systems and culture may also affect communication in European ATM.

3.4.6 Andersch, Staats and Bostrom's Model of Communication (Andersh, Staats & Bostrom, 1969)

Andersch et al's (1969) Model emphasises environmental or contextual factors. It also stresses the transactional nature of the communication process in which messages and their meanings are structured and evaluated by the sender, and subjected to reconstruction and evaluation on the part of the receiver while interacting with factors in the environment. Andersch et al's Model is shown in Figure 8.

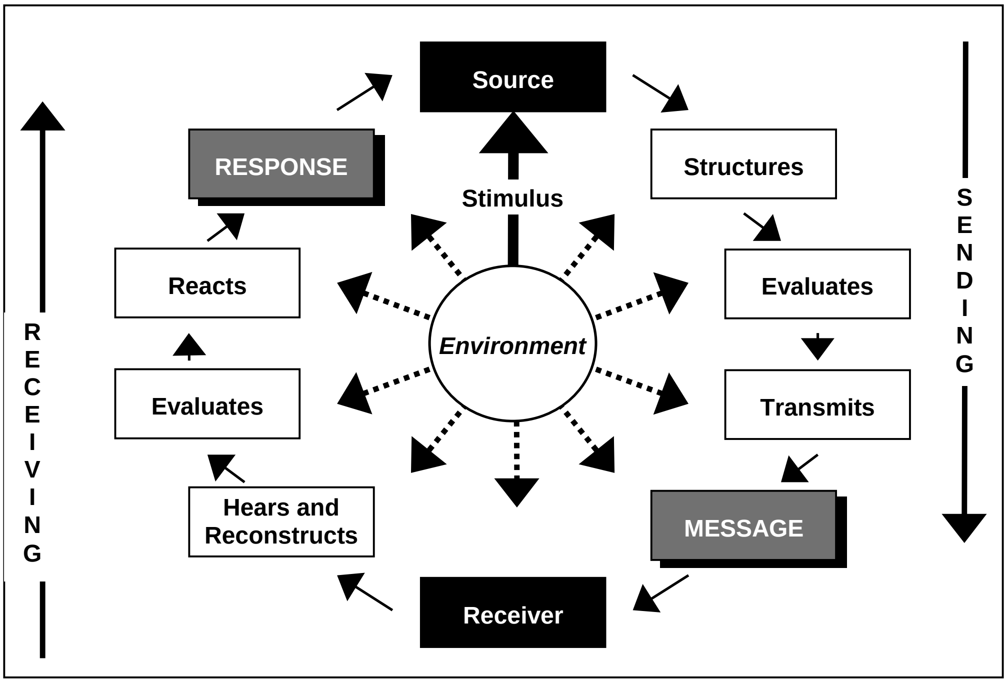

Figure 8: Andersch et al's (1969) Model of Communication (adapted)

It details the process of communication more explicitly than many previous communication models and could be developed further to classify errors in the various stages of communication.

3.4.7 Pilot - Air Traffic Control Communication Loop – Cultural, Linguistic and Technical Factors

Based on a review of communication process there are few models or taxonomies that can be directly applied to HERA. However, this review suggests that there might be variables which could be used to develop a dedicated communication model. Such a model should contain the following elements:

1. A depiction of a message-medium-receiver relationship (similar to Shannon and Weaver's (1949) Model of Communication);
2. An account of the role of feedback, i.e. a Circular Model (similar to Osgood and Schramm's (1954) Model of Communication);
3. An account of linguistic factors known to have contributed to incidents and accidents,
4. The context of communication must be considered, including social and cultural aspects (similar to SMCR Model of Communication (Berlo, 1960)).

An attempt to fulfil these requirements is made in the model shown in Figure 9:

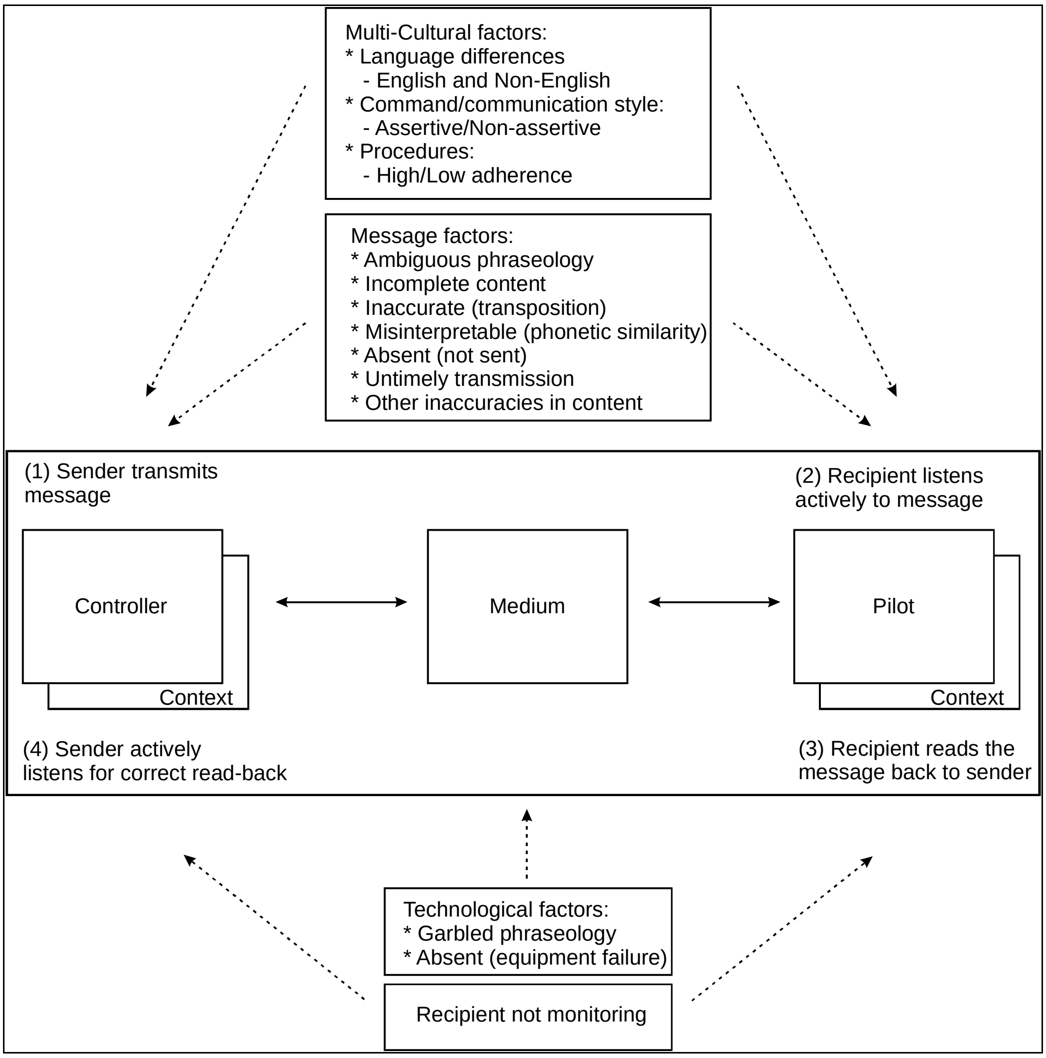

Figure 9: Pilot-ATC Communication Loop - adapted from Cushing, (1994 & 1995), Grayson & Billings (1981); Helmreich & Merritt, A.C. (1998).

This model depicts the pilot-ATC communication loop and contains cultural, linguistic and technical factors that may result in communication breakdowns in the present aviation system. It may be noted that, in principle, the pilot could also be the sender, and the controller the receiver. Furthermore, the model could be used to describe the communication between two controllers.

3.4.8 Communication within the Organisation

Although a broader approach regarding communication, Westrum (1995) has proposed a categorisation of communication types within organisational practices. This approach captures the problems of a sociological nature which have an important influence on the safety health of aviation organisations.

Three types of communication styles which produce different organisational climates are described by Westrum as Pathological, Bureaucratic and Generative. These varying organisational climates handle safety information quite differently and are summarised in Table 1.

Table 1: Types of organisational practice adapted from Westrum (1995)

Generative Culture	Bureaucratic Culture	Pathological Culture
actively seek information	information may not be found	information is not wanted
the messengers are trained	the messengers are listened to if they arrive	the messengers are 'shot'
the responsibility is divided	the responsibility is shared	the responsibility is avoided
the organisation inquires and implements reforms	failures lead to local repairs	failure is punished
new ideas are welcomed	new ideas often present problems	new ideas are actively discouraged

The generative culture is obviously the type of approach which should be the goal in a safety critical organisation. In these groups, hidden failures are actively sought and if possible removed. However, this can only be successful if the management not only encourages all levels to communicate but also promotes all personnel to critically evaluate all levels of operation. These organisations also develop effective ways of reporting problems, and deal positively with errors; the system learns through its mistakes and rather than punishing those that are involved in the error chain, they use these events to improve the safety health of the group. This can have a very influential affect on the beliefs and operating practices of staff who will increase their risk taking behaviours in environments which follow extreme bureaucratic or pathological cultures.

3.4.9 Communication across Cultures

Communication failures and errors across **cultures** have a natural place in this survey of error modelling. They do so, first, because they are pervasive and potentially dangerous - and, indeed, are known to have played some role in a number of well-known aviation accidents (Cushing, 1994) - and, second, because the nature of cultural differences in aviation and similar professional domains has been the subject of a range of illuminating studies.

Helmreich and his collaborators at the NASA/FAA sponsored Aerospace Crew Research Programme have conducted an extensive series of studies regarding the differences of national culture within the same professions, mainly civil airline pilots, but also flight attendants, doctors and nurses and, more recently, ship's officers (Helmreich & Merritt, 1998).

One of the research instruments developed by Helmreich and his associates is the **Flight Management Attitudes Questionnaire (FMAQ)** and its derivatives (**Operating Room MAQ**, **Ship MAQ**, **Train MAQ***)* based in part on Hofstede's seminal studies of national culture differences. The FMAQ seeks to elicit from respondents their perception and awareness of a range of safety related factors (check lists, the importance of adhering to procedures, effects of fatigue) and work values. It is almost impossible to establish accurate empirical data which demonstrate a correlation between the number of incidents or accidents and their attitudes as revealed by the FMAQ type questions. The reason is that accidents are fortunately too rare to support any claim of correlation and incidents are nearly always reported in very selective ways. (A recent example of a demonstrated empirical relation between attitudes - work pride and motivation - and the independently gathered rate of incidents was found when this type of questionnaire was applied to Japanese Bullet train track maintenance crews (Itoh & Andersen, 1999).

There are, in general, two types of failures arising in communication across cultures in the ATM domain: one concerns the fact that non-English speakers have to communicate in English; but even when speaker and hearer understand each other phrase by phrase, they may still not be able to convey what they would have been able to, had they been speaking in their own native tongue.

The very same instruments and methods that can be used to study differences among national cultures can also be used to elicit differences in employees' perceptions between different organisations or between different groups within the same organisation. Furthermore, for the ATM error classification, the results from studies considering cultural and organisational differences, suggest that local differences within the 'organisational climate' can make a great difference in operational performance and safety.

Lessons for HERA (Summary)

1. Errors in the process of communication must be represented in HERA.
2. The way in which the medium (e.g. Human-Machine Interface - HMI) affects error should be represented, including 'noise' that might affect communication.
3. The individual's intention and prior knowledge should be considered.
4. The context of error must be considered, including social, cultural and organisational aspects.

3.5 Information Processing Models and Taxonomies

The information processing tradition examines human performance by attempting to trace the information flow through several processing stages from information input to response output.

This approach is largely based on the work of Broadbent (1958), who regarded much of cognition as consisting of a sequential series of processing stages. Early information processing models state that a stimulus is processed first by basic perceptual processes followed by attentional processes that transfer some of the products of the initial perceptual processing into a short-term memory store. Rehearsal then serves to maintain information in the short-term memory store and then some of that information is transferred to a long-term memory store. However, these early models omitted processes of thinking and problem-solving, and there is new evidence that the serial processing assumption was incorrect. Furthermore, the model saw the individual as inactive and therefore did not account for the role of past experience or expectations.

This early model highlights the need for a distinction between 'top-down' and 'bottom-up' processing. Bottom-up processing refers to processing directly affected by stimulus input and top-down processing refers to processing affected by aspects of context and an individual's past experience. Most cognitive activity involves both types of processing.

Later theories argued that cognitive activity consists of interactive bottom-up and top-down processes occurring at the same time. For instance, perception is affected by a person's expectations about a stimuli.

The recent information processing framework shares a number of basic characteristics. For instance, people are seen as autonomous, intentional beings who interact with the external world. Second, the mind is viewed as a limited capacity processor having both structural and resource limitations. Third, cognitive processes occur in time, so that predictions about reaction times can be made if one assumes that certain processes occur in sequence and/or have some specifiable complexity. The information processing framework also draws on the metaphor of the human as a computer. The human is seen as a serial information processor who takes data input, recodes it, stores it, makes decisions and produces output.

An important outcome from this tradition is the notion of the speed-accuracy trade-off, which describes the relationship between the time available to respond and the probability of making an error. Both qualitative and quantitative methods are available for information processing modelling.

A second important contribution from this approach is the performance-resource function that relates the quality of performance to the resources (e.g. attention) available to be invested in a task (Norman & Bobrow, 1975). Quality of performance can be 'data-limited' in that poor input restricts a person's ability to perform a task (i.e. degraded signals such as R/T interference). Performance can also be 'resource-limited' where there are inadequate resources available to devote to one task because of other demands (e.g. when attention must be divided among multiple tasks, such as reading and speaking). This concept is important for modelling human performance in complex environments because it provides analytical tools for dealing with multiple task and time-sharing issues. The concept of resource limitation leads to the role of mental workload in human performance.

3.5.1 Early Information Processing Taxonomies

Payne and Altman (1962) produced an early information processing taxonomy which classified errors at three basic levels within the information processing system:

(i) Input errors that are attributable to sensory and perceptual processes (e.g. vision, hearing).

(ii) Mediation errors associated with the mental or cognitive processes between perception and action.

(iii) Output errors due to the selection and execution of physical responses.

Berliner, et al. (1964) proposed a taxonomy that is based on information processing characteristics, and distinguished the following processes and activities:

(i) ***Perceptual***

Searching for and receiving information, e.g. detect, observe, scan.

Identifying objects, actions, and events, e.g. identify, locate, categorise.

(ii) **Mediational**

Information processing, problem-solving and decision-making, e.g. calculate, code, interpolate.

Problem-solving and decision-making, e.g. compare, plan, choose.

(iii) **Communication**, e.g. advise, instruct, request

(iv) **Motor**

Simple, discrete tasks, e.g. press, set, adjust

Complex, continuous tasks, e.g. regulate, synchronise, track

Whilst this classification is not an error taxonomy as such, it usefully categorises the specific **behaviours** associated with the information processing activities. With some modification, the taxonomy could be adapted to classify errors at various levels, such as:

- ‘perceptual failure’ (gross level);
- ‘search failure’ (intermediate level);
- ‘detection failure’ (detailed level).

Such information processing classifications attempt to locate human error at parts of the information processing system. Although they involve more assumptions than do the surface categories, they are likely to be of far greater use in error reduction.

3.5.2 Wickens’ Model of Information Processing (Wickens, 1992)

The most widely known model of information processing is perhaps that proposed by Wickens (1992) who draws on previous models to provide a composite qualitative model of human information processing. This model elaborates on the ‘organism’ part of the basic Stimulus-Organism-Response (SOR) models or the ‘mediational’ aspects of previous information processing models to describe the critical stages of information processing (see Figure 10).

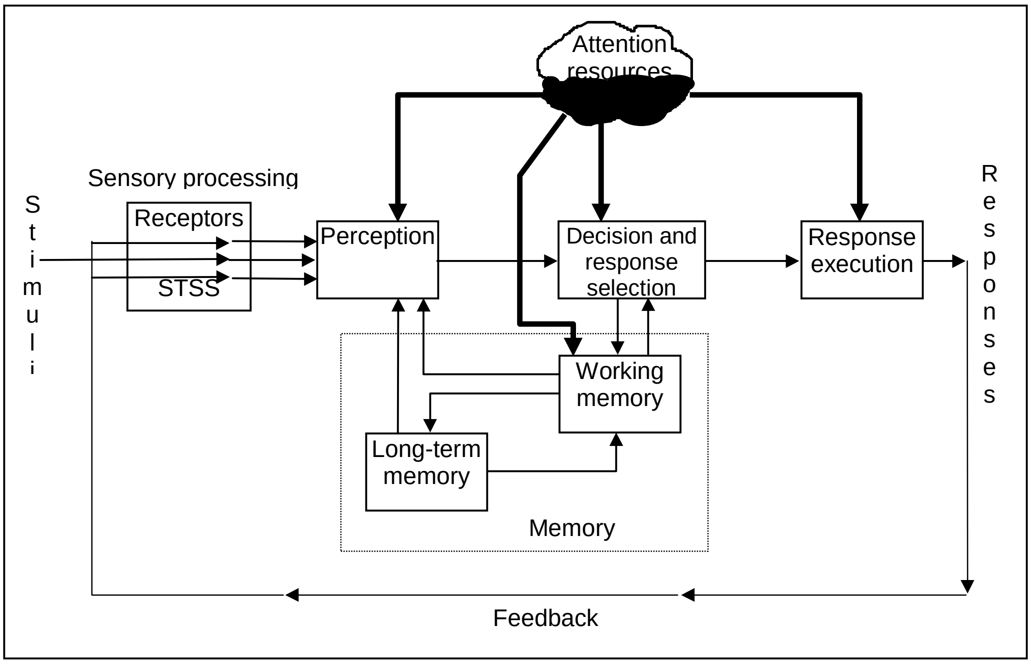

Figure 10: Wickens’ Model of Human Information Processing

The model assumes that each stage of processing performs some transformation of the data and demands some time for its operation. **Sensory processing** refers primarily to the processing characteristics of the visual, auditory, and kinaesthetic senses. Sensory limitations can affect the quality and quantity of information. Alternatively, the stimulus can be of poor quality.

The Short-Term Sensory Store (STSS) prolongs a representation of the physical stimulus for a short period after it has terminated. The STSS demands no conscious attention, preserves most of the physical details of the stimulus and decays rapidly, from less than a second for the short-term visual store **(iconic memory**), up to eight seconds for short-term auditory memory **(echoic memory**) and short-term memory of movement and bodily position **(kinaesthetic memory)**.

The stimulus is further processed and is *perceived* or recognised, and a perceptual decision is made regarding the perceptual category of the stimulus. The perceptual process is a ‘many-to-one’ mapping, so many different physical stimuli may be assigned to one perceptual category (e.g. different aircraft may be assigned to a ‘fast jets’ category), although the individual is able to differentiate between different stimuli. Tasks demand different levels of perceptual processing, from ‘detection’, through ‘identification’, to ‘recognition’ (Sanders and McCormick, 1993). Furthermore, the task may demand that the individual makes one ‘absolute judgement’, concerning a dimension of one stimulus (e.g. speed), or it may demand ‘pattern recognition’ of a combination of at least two dimensions. Alternatively, ‘relative judgements’ may be required, concerning the relative differences between two or more stimuli (e.g. climb performance). Finally, perception may require ‘analogue judgements’ of differences on a continuous scale.

The individual then decides what to do with the information (a stimulus becomes information once it has been assigned meaning, but the terms are used synonymously). The **decision** may be rapid or thoughtful, and the individual may choose a **response**. Alternatively, information may be stored in memory for a short period (seconds - minutes) in **working memory** by rehearsal (Baddeley & Hitch, 1974). According to Baddeley and Hitch, working memory consists of three stores:

(i) a modality-free central executive - this has limited capacity and is used when dealing with cognitively demanding tasks.

(ii) an articulatory loop (a ‘slave system’) - this holds information in a speech-based form.

(iii) a visuo-spatial scratch pad or sketch pad (a ‘slave system’) - this is specialised for spatial and/or visual memory.

Information can be transferred for a longer period (hours - years) in **long-term memory** by learning.

If a response is selected, then the appropriate muscle commands are called upon to act (including speech). Finally, the consequences of actions are monitored as feedback, using the sensory modalities, forming the closed loop feedback structure.

An important part of the model is the limited pool of **attentional resources**. Wickens (1992) distinguishes four types of attention:

(i) Selective (scanning selected channels).
(ii) Focused (on one channel with a particular signal).
(iii) Divided (over different, simultaneous tasks).
(iv) Sustained (over long periods, i.e. monitoring and vigilance).

With a shift from passive reception to active collection, attention becomes more focused. A limited pool of attention is shared between perception, working memory, decision and response selection, and response execution. Hence, if one function demands a large supply of attention, then performance of other functions deteriorates.

Wickens (1992) claims that the model aids the investigation of the components of human performance and so provides a useful ‘technique’ for examining performance limitations. However, the sequential representation has been criticised. Reason (1990) calls such models ‘pipeline models’, where data flows from the sensory input to motor output, and states that these do not adequately represent human behaviour and therefore advocates more parallel processing models. However, Wickens adds a caveat in his explanation of the model that information flow need not start with the stimulus (decisions may be triggered by thoughts in working memory), and that the flow need not be from left to right, but does not explicitly map any further links.

Hollnagel (1993) asserts that, whilst any behaviour looks sequential once it has occurred, this is not sufficient to assume that there is an underlying causal mechanism or normative organising principle. Hollnagel states that 'the procedural prototype model of decision-making… ill fits the observed variety, and the principle of sequential ordering may therefore be considered an artefact of the method of description' (p. 157). Another criticism can be aimed at the fuzziness of the decision and response selection stage of Wickens’ model. It may therefore be useful, for error analysis, to analyse this stage of processing.

Despite these criticisms, Wickens’ model is relatively enduring and some of the concepts are used by writers to shape discussions concerning human error (Nagel, 1988 & Hawkins, 1993).

Lessons for HERA

1. Information processing allows the ‘tracking’ of an error through stages and levels of human performance.
2. Information processing should be considered as a useful classification system for organising error types within stages of information processing.
3. Wickens’ model provides a good ‘platform’ on which to base an error taxonomy.
4. Wickens’ model allows the classification of errors of sensing and perception, working memory, long-term memory, decision and response selection, and response execution.
5. Other sub-models for each of Wickens’ information processing ‘stages’ could be considered to derive error types (e.g. models of perception, working memory and decision-making).
6. The role of attentional resources, and their effects on error, can be represented using Wickens’ model.

3.5.3 McCoy and Funk Model of Human Information Processing (McCoy & Funk, 1991)

McCoy and Funk (1991) proposed a modified version of Wickens’ (1984) Model of Information Processing aimed at understanding the nature and frequency of human errors to aviation accidents implicating the ATM system. The model is shown in Figure 11.

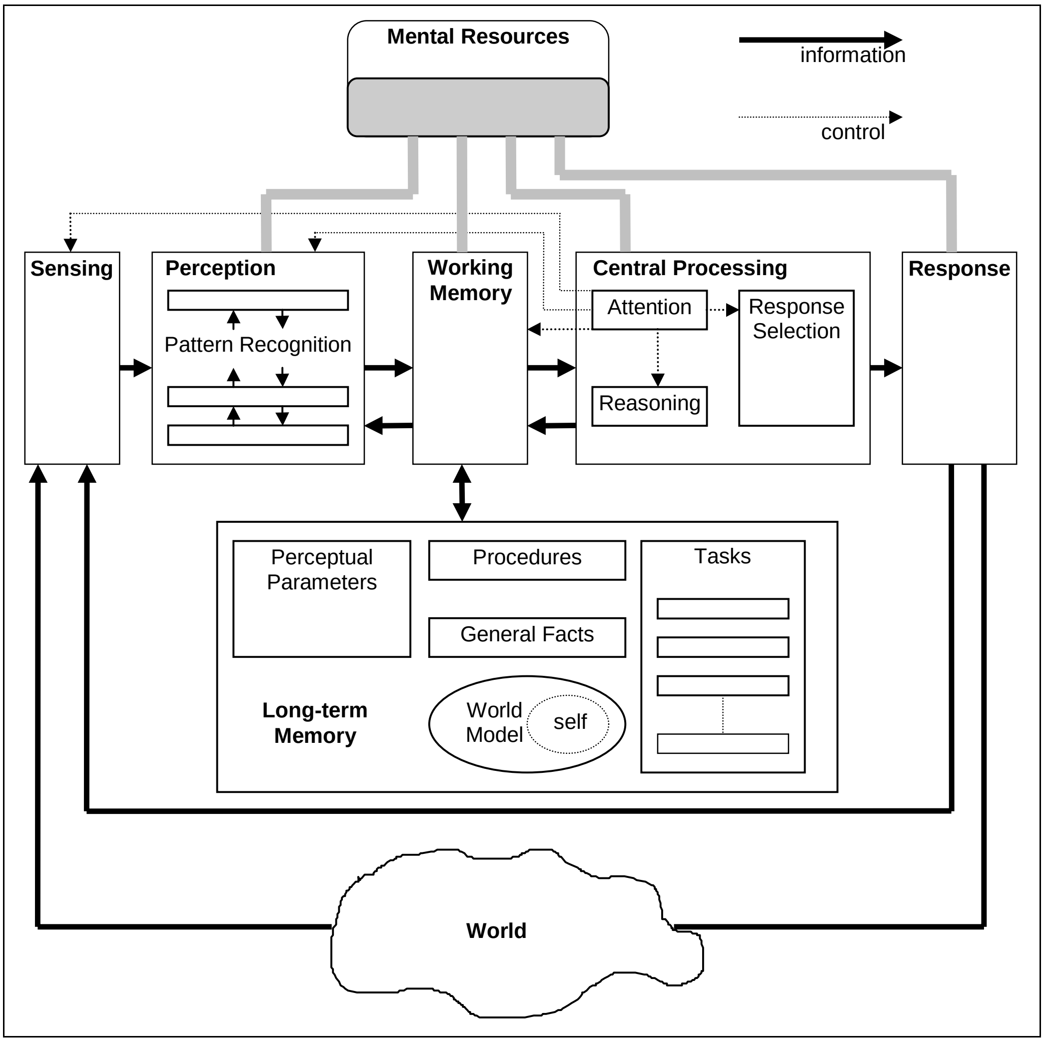

Figure 11: McCoy and Funk’s Model of Human Information Processing

The main features of the model are broadly those of Wickens’ Model. The sensing function samples raw stimuli from the environment and passes sensory information to perception. The role of perception is to assign sensory information to perceptual categories and comprises such sub-functions as signal detection and pattern recognition. Relevant performance issues of sensing and perception include sensory detection thresholds, limits to sensory discrimination, the loss of vigilance and limits to perceptual attention.

Working memory is the centre of conscious behaviour. It has a limited capacity and duration, which causes a major bottleneck in the information processing system. In McCoy and Funk’s Model, working memory follows directly from perception. This appears to better reflect human information processing, since information must necessarily be held in working memory before subsequent mental activity, such as reasoning and response selection, can be conducted.

Long-term memory stores factual knowledge, retains perceptual parameters, and plays a major role in maintaining an internal model of the world, including that of the person themselves. It also maintains representations of tasks to be accomplished to achieve current goals. Storage is apparently not limited but retrieval is limited by many factors.

Central processing includes decision-making and response selection, and limitations to the sub-functions include confirmation bias and speed-accuracy limitations. An executive mechanism allocates mental resources to functions required to perform various competing, concurrent tasks. There are limitations in the human's ability to allocate resources, especially when multiple tasks compete for the same resources. The response function transforms selected responses into motor movements and speech.

The main contribution of the model is the unpacking of long-term memory, and the introduction of the concept of 'self' in information processing models. The model also differs from Wickens' Model in the linkages between functions. For instance, the model appears to assume that the controlling effects of long-term memory on perception are mediated through working memory rather than having a direct influence. Also, 'executive mechanism' or attention is a sub-function of 'central processing', while the equivalent 'central executive' is a component of Baddeley and Hitch's (1974) Model of Working Memory, and also within the working memory function of Wickens' Model.

McCoy and Funk's Model was used to classify ATM errors that contributed to aviation accidents in the abstracts of National Transport Safety Board (NTSB) Aircraft Accident Reports. Of twenty-one controller errors which were causal or contributing factors in eighteen accidents, fourteen were attributed to response selection, including issuing clearances and coordination. The remaining seven controller errors were classified as perception, memory or attention.

Information processing models were developed by analysing tasks into elemental information processing units. One example of such a technique is the Keystroke Level Model (Card, Moran & Newell, 1983). This model predicts performance across numerous tasks involving human interaction with video keyboards (e.g. text editing) by taking into account such factors as the time to locate an item on the display, remembering its meaning, and to depress an appropriate key. This detailed analysis permits predictions of the effect of different text-editor designs and different users on performance time; thus it fulfils one of the primary criteria for a successful model by predicting the effect of changes in interface systems. Another example is the Human Operator Simulator Model (Lane et al., 1980). This breaks a complex task down into elemental information processing tasks such as information absorption, information recall, mental computation and decision-making.

Lesson for HERA

Distinctions within long-term memory, such as the concept of ‘world model’, ‘self’, and memory of tasks, facts, procedures and perceptual parameters should be considered in HERA.

3.5.4 Other Studies Using Information Processing Concepts

Kinney, Spahn and Amato (1977) (cited in Stager & Hameluck, 1990) found that 90% of the documented ATM system errors were due to humans. These were directly due to controllers and first-line supervisors, and were attributed directly to **attention**, **judgement** and **communication.** According to Kinney, et al., inappropriate control techniques and work habits are the main factors causing system errors (defined as a loss of separation minima). It is claimed that these factors are the result of incomplete technical supervision, poor awareness of the usefulness of good work habits, and lack of detailed description in standard operating procedures. Factors such as traffic load, traffic peaks and complexities, and average controller experience were not implicated.

Stager and Hameluck (1990) reviewed the reports of 301 investigations by the Fact Finding Boards of the Air Traffic Services Branch of Transport Canada. As with Kinney, et al. (1977), Stager and Hameluck found that **attention, judgement**, and **communication** errors were the most frequently cited causes of system errors. Within these broad categories, non-recognition of conflict, inattention, deviation from required operating procedures, failure to coordinate and poor judgement were the most frequently cited errors. Attention and judgement errors accounted for over 60% of the cases. These were both cited with approximately twice the frequency of communications, except where incidents involved two or more controllers. Stager and Hameluck (1990) claim that the application of a human error model would provide further insight into the problem of causal factors.

3.6 Symbolic Processing Models and Taxonomies

The symbolic processing tradition regards humans and computers as general-purpose symbol manipulating systems, and is therefore closely related to the information processing tradition. This approach forms the basis of work in artificial intelligence and cognitive science (Newell & Simon, 1972). Symbolic processing models view knowledge structures and ‘mental models’ as the critical determinant of human performance, including both the form or representation of knowledge and the content of the representation. These models attempt to articulate the form and content of internal knowledge representations based on analyses of task requirements and on analyses of the details of human performance at these tasks.

Many of the models that have developed from this tradition emerged from the cognitive science tradition. They incorporate a multi-level view of cognition where higher order executive processes guide and monitor deployment of lower order behavioural routines. The representation, activation and utilisation of different types of knowledge play a central role in these models.

Theoretical work on the sources of errors such as the work of Norman (1981; Norman & Shallice, 1980) and Reason (Reason & Mycielska, 1982; Reason, 1990) model errors in performance in terms of the activation of inappropriate knowledge structures or ‘schemas’ and related empirical work on human error (e.g. McRuer et al., 1980; Langan Fox & Empson, 1985) are also related to this tradition.

Symbolic processing became the dominant theoretical position in cognitive psychology, and also became popular in the modelling of behaviour in complex dynamic environments such as Nuclear Power Plants (e.g. Pew & Baron, 1983).

Work within this tradition has emerged from cognitive psychology and cognitive science, which has developed theories to explain intelligent human behaviour, and computer science that attempts to develop machines that display intelligent behaviour (e.g. expert systems), with little regard for whether the underlying processes resemble internal human processes.

3.6.1 Skill-, Rule- and Knowledge-based Behaviour (Rasmussen, 1981)

Rasmussen (1981) describes human errors as instances when human variability is outside acceptable task performance and as 'unsuccessful experiments in an unfriendly environment' (Rasmussen, 1988, p. 16). Rasmussen (1983) also discussed some basic distinctions that are useful in human performance modelling. Rasmussen and Jensen’s (1974) verbal protocol study of technicians engaged in electronic ‘trouble-shooting’ led to the proposal of a tripartite distinction of human performance: **skill-**, **rule-**, and **knowledge-based behaviour**. The three stages are associated with decreasing levels of familiarity (or expertise) with the task.

1. **Skill-based Behaviour**. This level represents sensori-motor performance without conscious control, as smooth, automated, and highly integrated patterns of behaviour. Performance is based predominantly on feed-forward control, to maintain rapid coordinated movements. Skilled performance proceeds without conscious attention or control, as the person composes sets of automated subroutines suited for specific purposes. Hence, parallel task performance is possible. Sensory input is used to align a dynamic internal map of the environment. Sensory input is not selected, but the senses are directed towards those aspects of the environment needed subconsciously to update and orient the map. Errors at the skill-based level can be traced to ‘motor programs’, and are based on variability of force, space, or time coordination.

2. **Rule-based Behaviour**. While skill-based performance is largely ‘automatic’, rule-based behaviour is schematic and generally based on explicit ‘know-how’. As with skill-based behaviour, parallel processing is

possible, even if rule-based behaviour requires medium attentional control. Stored rules or procedures control the behavioural sub-routines in familiar environments which are acquired from previous problem-solving and planning behaviour, or are learned from other people. Behaviour is goal-oriented, but structured by 'feed-forward control' through stored rule. Often the goal is found implicitly in the situation releasing the stored rules. Errors at this level could be said to involve long-term memory and are often associated with mis-classification of situations leading to the application of the wrong rule or with the incorrect recall of procedures (Reason, 1990).

3. **Knowledge-based Behaviour**. Knowledge-based behaviour is event-specific and is driven by explicitly formulated goals. Plans are developed and tested against a goal, physically by trial and error or conceptually against a mental model of the system. This behaviour is characterised by high attentional control and limited to sequential processing. Knowledge-based behaviour usually requires problem-solving, goal-selection and planning, and is generally put to use in novel situations. Errors at this level can be seen as errors in mental representation, at the levels of reasoning/problem-solving, goal selection and planning.

Rasmussen's (1983) Skill, Rule, Knowledge (SRK) framework compares to Fitts and Posner's (1967) three phases of skill learning: the early cognitive phase, the intermediate associative phase and the final autonomous phase.

Step-ladder Model (Rasmussen, 1986)

Rasmussen's (1986) 'step-ladder model' is a well-known procedural model of decision-making and an important contribution to Human Error Analysis (HEA). This model identifies eight stages of decision-making: activation, observation, identification, interpretation, evaluation, defining the task, formulation of procedures and execution (see Figure 12).

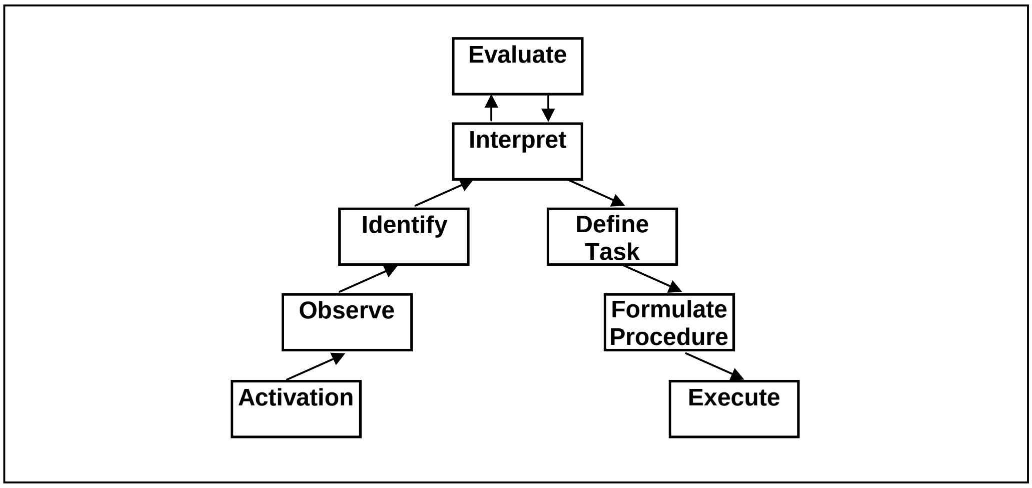

Figure 12: The 'Stepladder Model' of human performance (simplified from Rasmussen, 1986)

Figure 12 shows only the ‘data processing activities’ in the model whereas Rasmussen’s elaborated version shows intervening ‘states of knowledge resulting from data processing’. Rasmussen (1986) considers that rational, causal reasoning connects the states of knowledge in the basic sequence. However, perhaps the most useful part of the elaborated model are the stereotyped rule-based shortcuts in decision-making, between data processing activities and states of knowledge. Changes in the environment are inputs to decision-making, but do not affect the prototypical sequence apart from the skipping of one or more steps.

Despite the success of the SRK paradigm, it has also been criticised. Dougherty (1992) criticises the ambiguity in the interpretation of the three levels, and the difficulty in defining transitions between levels. However, Rasmussen (1983) has stated that there can be overlap between the terms, and that more than one mode can operate at any one time. Dougherty also questions the ‘brain validity’ of rule- and knowledge-based behaviour. For instance, he cites that there is much evidence - from evolutionary and AI perspectives - to suggest that the brain does not store ‘rules’ (although many would strongly disagree, see Swain, 1990b). Dougherty (1990) further claims that Rasmussen’s SRK ‘albatross’ has led to many 'silly adaptations' within human reliability analysis models.

Hollnagel (1993) believes that Rasmussen’s stepladder model is also inadequate, because it describes decision-making as if an individual attempts to make ‘one-way’ rational progress through the various stages, which rarely happens. Furthermore, he argues that the introduction of many 'by-passes' introduces a problem of control - what causes a 'by-pass' to be made? Despite these objections, Rasmussen’s framework has been highly influential, particularly with industrial installations. When judged on utilitarian criteria, the framework is quite robust, but its success may be largely due to its high face validity and ease of understanding.

3.6.2 Rasmussen’s Multifaceted Taxonomy (Rasmussen, 1982)

Rasmussen (1982) described a multifaceted taxonomy which includes seven subsystems:

(i) Causes of human malfunction.
(ii) Factors affecting performance.
(iii) Situation factors.
(iv) Personnel task.
(v) Mechanisms of human malfunction.
(vi) Internal human malfunction.
(vii) External mode of malfunction.

The sub-systems of most interest to this project are ‘mechanisms of human malfunction’ and ‘internal human malfunction’. Rasmussen (1981) stated that these are basically different categories and should therefore be treated separately. Internal human malfunctions are mental functions of decision-making which are not performed as required by the task. Rasmussen's internal human malfunctions are listed as follows:

1. Detection missing
2. Identification not correct
3. Goal not acceptable
4. Target state inappropriate
5. Task inappropriate
6. Procedure is incorrect
7. Execution is erroneous

Mechanisms of human malfunction are those internal mechanisms that produce the internal human malfunction. Rasmussen's categories were derived from a preliminary analysis of 200 United States Licensee Event Reports (Rasmussen, 1980). However, the mechanisms are not a definitive set and were derived from the nuclear industry and so different mechanisms may apply to ATM.

Error mechanisms can be divided according to Rasmussen's SRK framework, as follows:

1. Skill-based - Manual variability, topographic variability.
2. Rule-based - Stereotype fixation, familiar pattern not recognised, stereotype takeover, forgets isolated act, mistakes alternative, other slip of memory.
3. Knowledge-based - Familiar association shortcut, information not seen or sought, information assumed not observed, information misinterpreted, side effects or conditions not adequately considered.

Rasmussen represents internal human malfunctions, mechanisms of human malfunction and causes of human malfunction are represented within decision flow diagrams. These guide the analyst in selecting the appropriate classification, and increase analyst agreement.

Rasmussen emphasised that the structure of the taxonomy is more important than the elements used within the categories.

Lessons for HERA

1. HERA must capture all skill-based, rule-based and knowledge-based error mechanisms.
2. HERA should consider all of Rasmussen's subsystems.
3. Decision flow diagrams should be considered to help structure the technique.

3.6.3 Murphy Diagrams (Pew et al., 1982)

Murphy Diagrams (Pew et al., 1982) are diagrammatic representations of error modes and illustrate the underlying causes associated with cognitive decision-making tasks. Each ‘activity’ within the decision-making process is shown as a separate diagram. These stages, which are based on Rasmussen’s (1986) Stepladder Model, are shown below:

1. Activation/detection of system state signal.
2. Observation and data collection.
3. Identification of system state.
4. Interpretation of situation.
5. Definition of objectives.
6. Evaluation of alternative strategies.
7. Procedure selection.
8. Procedure execution.

Each activity is associated with two ‘outcomes’: correct or incorrect performance. The negative outcomes are associated with ‘proximal sources’, which are high level error causes. Finally, proximal sources are linked to ‘distal sources’, which generally equate to Performance Shaping Factors (PSFs). An example of a Murphy Diagram is shown in Figure 13.

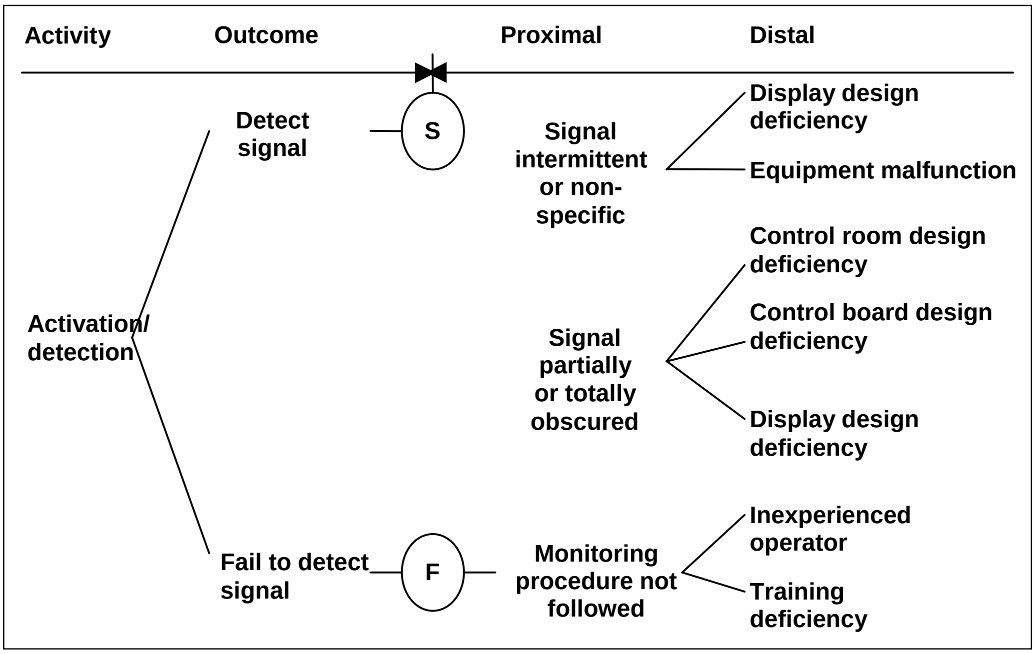

Figure 13: An example of a Murphy Diagram (adapted from Pew et al., 1981)

Kirwan (1992b) stated that Murphy Diagrams are potentially useful for incident analysis, although there are some deficiencies in scope and comprehensiveness.

3.6.4 Operations in Control Systems (Rouse & Rouse, 1983)

Several systems have been proposed which trace the information processing assumed to occur when a human operates in a control system. Rouse and Rouse (1983) proposed such a methodology, which did not presuppose a particular theory or mechanism of human error, but draws from Rasmussen's conceptual model of the process plant operator. The following outlines the general categories, representing tasks, and the specific categories, representing error types. (Note that Rouse and Rouse represent the system as a flowchart.)

1. Observation of system state excessive, misinterpreted, incorrect, incomplete, inappropriate, lacking.
2. Choice of hypothesis inconsistent with observations, consistent but very unlikely, consistent but costly, functionally irrelevant.
3. Testing of hypothesis incomplete, false acceptance of wrong hypothesis, false rejection of correct hypothesis, lacking.
4. Choice of goal incomplete, incorrect, unnecessary, lacking.
5. Choice of procedure incomplete, incorrect, unnecessary, lacking.
6. Execution of procedure step omitted, step repeated, step added, steps out of sequence, inappropriate timing, incorrect discrete position, incorrect continuous range, incomplete, unrelated inappropriate action.

During normal operations the human cycles through observing the system state (1), and choosing and executing procedures (5, 6). However, when one or more state variables have 'abnormal' values or when alarms have been activated, the operator resorts to problem-solving. If the abnormality is familiar to the operator they may directly choose a procedure (i.e. rule-based behaviour). Unfamiliar problems will require the choice and testing of a hypothesis and the choice of a goal. Rouse and Rouse comment that there may be several (conflicting) goals.

Lessons for HERA

1. Stages of task performance such as 'choice of hypothesis' and 'testing of hypothesis' cannot be clearly specified for ATM due to the changing nature of ATM and differences between ECAC States.
2. The concept of hypothesis testing does not apply very well within ATM.
3. EEM-type error classification within different aspects of task performance should be considered for HERA.
4. The series of activities could be restated in terms of information processing to make the classification more suitable for ATM.
5. It is difficult to consider the level at which a 'goal' exists in ATM, and this could cause some confusion in error classification.
6. The term 'procedure' in ATM refers to written procedures, rather than a sequence of actions.

3.6.5 Systematic Human Error Reduction and Prediction Approach (Embrey, 1986)

Embrey (1986) developed the Systematic Human Error Reduction and Prediction Approach (SHERPA), based on both the Skill, Rule, Knowledge (SRK) Model (Rasmussen, 1982) and the Generic Error-Modelling System (GEMS) (Reason, 1987). The technique comprises a list of seventeen SRK External Error Modes (EEMs) (errors of omission, commission and extraneous acts) and twelve psychological error mechanisms:

1. Failure to consider special circumstances.
2. Shortcut invoked.
3. Stereotype takeover.
4. Need for information not prompted.
5. Misinterpretation.
6. Assumption.
7. Forget isolated act.
8. Mistake among alternatives.
9. Place losing error.
10. Other slip of memory.
11. Motor variability.
12. Topographic or spatial orientation inadequate.

The Systematic Human Error Reduction and Prediction Approach SHERPA was developed as a predictive Human Error Identification (HEI) technique rather than an incident analysis technique, and is generally used with a Hierarchical Task Analysis (HTA). A computerised version is available where EEMs and Psychological Error Mechanisms (PEMs) can be identified via a set of flowcharts. Kirwan (1992c) considers SHERPA to be potentially highly comprehensive (but not for knowledge-based behaviour), with a high resolution of EEMs, and with the ability to usefully identify the underlying psychological error mechanisms. However, despite its title, it is not clear that SHERPA is systematic, since inter-analyst reliability may be low. Also, the technique is fairly 'jargon-based' and analysts may find it difficult to use.

Lessons for HERA

1. HERA should represent differences between aspects of the task (i.e. EEMs).
2. HERA should represent different psychological states and mechanisms that could lead to errors (i.e. PEMs).
3. Decision flow diagrams (flowcharts) should be considered to help structure the technique.

~~4.~~ Avoid the use of jargon.

3.6.6 Slips, Lapses, Mistakes and Violations (Reason, 1990)

Reason (1990) offered a comprehensive treatise on the nature of human error in his book ‘Human Error’. Reason defines human error as:

> *‘a generic term to encompass all those occasions in which a planned sequence of mental or physical activities fails to achieve its intended outcome, and when these failures cannot be attributed to the intervention of some chance agency’*.

Reason’s ideas rest upon the notion of intentionality, comprising two elements: an expression of the end-state to be attained and an indication of the means by which to attain it. It is claimed that, for most everyday actions, prior intentions or plans consist of little more than a series of verbal tags and mental images. Reason noted the distinction between prior intention and intention in action. Actions without prior intention fall into two categories: **intentional** and **non-intentional** actions. Intentional actions without prior intention can be further divided into **spontaneous** and **subsidiary** *actions*. Spontaneous actions have no prior intention, but seem to ‘emerge’. Subsidiary actions are the ‘small print’ of components of well-practised action sequences. For such ‘automatic’ subsidiary actions, there is intention, but no prior intention. Non-intended or involuntary actions have no prior intention to act, and no intention in action.

Moments of absent-mindedness may result in actions straying from their intended path, where there is prior intention to act, but actions do not proceed as planned. According to Reason (1990), this tends to occur during the performance of largely automatic tasks in familiar surroundings, with attentional capture by something other than the task in hand. Reason distinguishes between **slips** and **lapses**, which are 'errors resulting from some failure in the execution and/or storage stage of an action sequence, regardless of whether or not the plan which guided them was adequate to achieve its objective'. Slips are potentially observable as 'actions-not-as-planned'. Lapses (failures of memory) may be concealed unless one realises that something has not been done.

Intended actions may proceed as planned, but fail to achieve their intended outcome. Such errors are termed **mistakes**. Reason (1990) defines mistakes as, 'deficiencies in the judgmental and/or inferential processes involved in the selection of an objective or in the specification of the means to achieve it, irrespective of whether or not the actions directed by this decision-scheme run according to plan'. Reason notes that mistakes are likely to be more subtle, more complex, and more dangerous than slips. They are difficult to detect, as there is no departure of action from intention. Thus, detection may rely on external intervention before implementation, or the emergence of unwanted consequences after implementation. Even then, the quality of a plan is open to debate. Reason (1990) claims that mistakes can be subdivided into:

a) **Failures of expertise**, where some pre-established plan or problem solution is applied inappropriately;

b) **lack of expertise**, where the individual, not having an appropriate 'off the shelf' routine, is forced to work out a plan of action from first principles, utilising existing knowledge.

It may be that mistakes can only be defined with reference to the known past and present system state. Reason also describes **violations**, which can only be described in terms of the motivational framework and social context in which behaviour is governed. Violations are deviations of actions from safe operating procedures. Whilst the actions may be intended, the consequences are usually not. Violations are perhaps the most disturbing 'errors' as they take individuals into areas of greater risk that are both ill-understood and unforgiving (Reason, 1995).

Lesson for HERA

HERA should be capable of classifying slips, lapses, mistakes and violations.

3.6.7 'Actions not as Planned' (Reason, 1979)

Reason (1979) conducted a diary study of unintended or absent-minded actions, and derived a classification system and a theory of 'actions not as planned'. The insightful, yet frequently overlooked classification system, is structured as follows:

(i) Discrimination failures - occur where stimulus objects are mis-classified.

i.e. perceptual confusions, functional confusions, spatial confusions, temporal confusions.

(ii) Program assembly failures - occur where program elements are transposed, either within the same program, between active programs, or between an ongoing and stored program.

i.e. behavioural spoonerisms, confusions between currently active programs, confusions between ongoing and stored programs.

(iii) Test failures - stem from a failure to verify the progress of an action sequence at key ‘checkpoints’.

i.e. stop-rule overshoots, stop-rule undershoots, branching errors, multiple side-tracking.

(iv) Sub-routine failures - errors occur at the level of component actions in the sub-routine.

i.e. insertions, omissions, disordering.

(v) Storage failures - characterised by the forgetting or misrecalling of plans and actions.

i.e. forgetting previous actions, forgetting discrete actions in the plan, reverting to an earlier plan, forgetting the substance of a plan.

Reason (1979) stated that motor learning is accompanied by a gradual shift from ‘closed-loop’ control (feedback monitored and conscious) to ‘open-loop’ control (feed-forward and automatic). In the former, control resides in the limited capacity central processor and relies upon feedback from the environment. In the latter mode, motor output is governed by ‘motor programs’ or pre-arranged instruction sequences, that run independently of feedback information. Hence, the central processor can deal with future aspects of the task. Reason posited that plans have critical decision points, at which closed-loop control is necessary. Furthermore, motor programs have variable habit strengths. Frequently used programs have a stronger habit strength, and are more likely to be disruptive if closed-loop control is not used.

Langan-Fox and Empson (1985) observed eight military radar director and approach controllers under three conditions of workload for a total of 40 hours. 131 errors were observed. 94% could be categorised using Reason’s classification system. The breakdown of the errors into Reason’s categories was as follows: 24% discrimination failures, 31% program assembly failures, 12% test failures, 15% subroutine failures and 12% storage failures.

Langan-Fox and Empson stated that most errors were self-corrected, either during performance of the error, on noticing shortly afterwards, or on being informed of the error by a pilot or another controller. The effects of the errors were to take up time, extend interaction unnecessarily, produce momentary confusion and interfere with effective control. Some errors, where controllers did more than was intended (e.g. removing memory aids), resulted in controllers completely forgetting about aircraft under control. Overall, the authors considered that 23% of the recorded errors were potentially serious.

However, the production of these potentially serious errors was not particularly distinct from the remaining errors and there was no bias toward any type of error. Langan-Fox and Empson suggest a number of implications for equipment design, including landline (telephone line) keys, memory aids and digital confusion.

Reason's classification system is limited to 'actions not as planned' and so does not classify errors of judgement, planning and decision-making. Nonetheless, the error types could be used in a classification system that includes errors of perception, memory, and action execution, as part of a more comprehensive classification system.

Lessons for HERA

1. Slips of action and lapses of memory occur in air traffic control and should be addressed within HERA.
2. Reason's error types should be considered for inclusion within HERA.

3.6.8 Generic Error-modelling System (Reason, 1990)

Reason (1987d & 1990) proposed another conceptual framework within which to locate the origins of basic human error types - the Generic Error-Modelling System (GEMS). The method borrows Rasmussen's (1982) SRK framework to yield **three basic error types: skill-based slips and lapses, rule-based mistakes and knowledge-based mistakes**. The dynamics of GEMS are shown in Figure 14.

Reason's (1990) GEMS contains a number of 'failure modes' at the levels of skill-based slips and lapses, rule-based mistakes and knowledge-based mistake. At the skill-based level these **include omissions following interruptions**, **reduced intentionally**, **repetitions,** and **reversals**, among others. At the rule-based level, failure modes include **informational overload**, **rule strengths**, **wrong rules, inelegant rules** and **inadvisable rules**. At the knowledge-based level, Reason represents several failure modes, including Tversky and Kahneman's (1974) representativeness and availability heuristics, overconfidence, thematic vagabonding (cognitively 'flitting') and encystment (cognitively 'lingering').

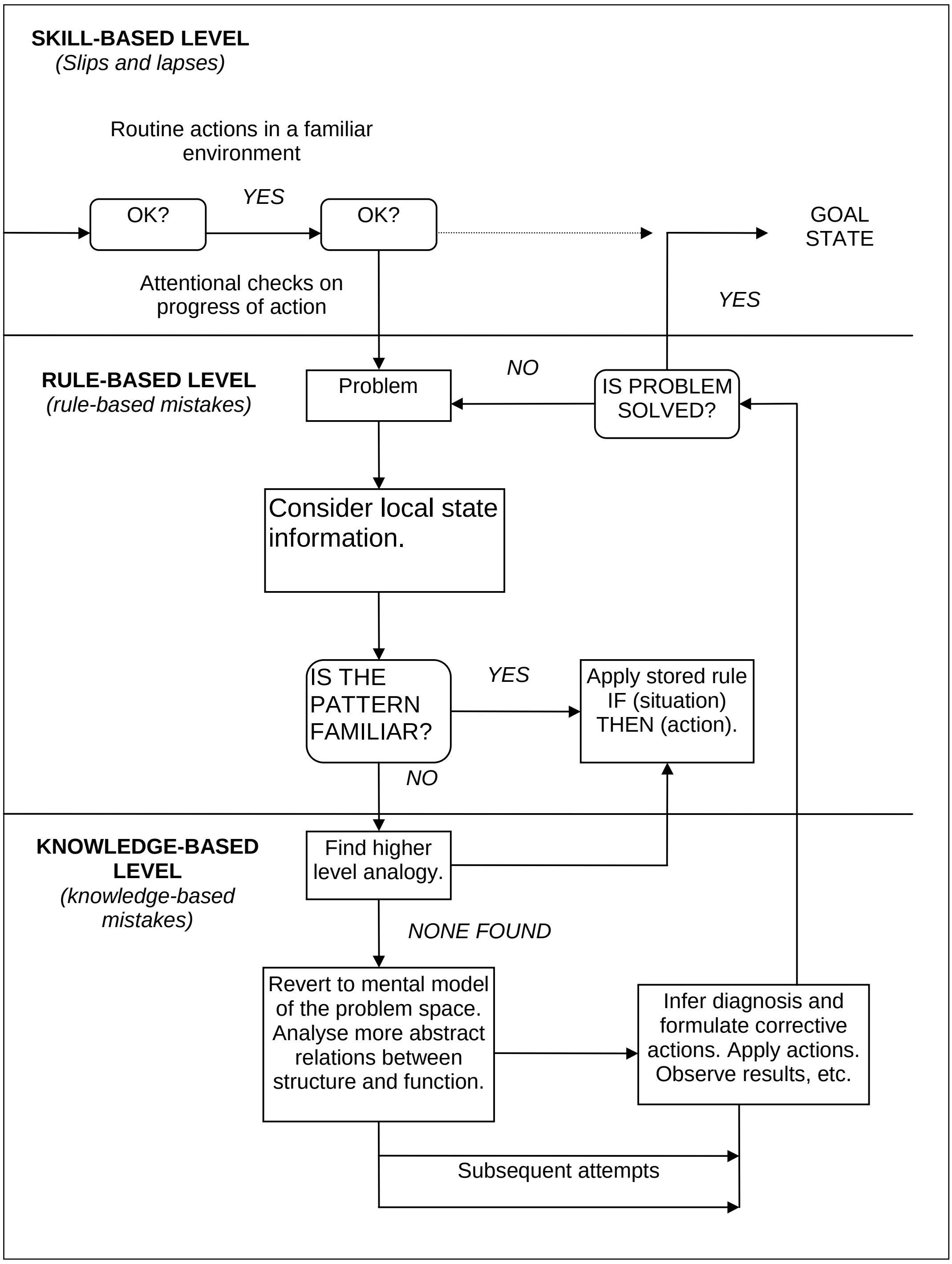

Figure 14: The Generic Error-Modelling System (GEMS)

The Generic Error-Modelling System (GEMS) goes beyond the slips/mistakes dichotomy. Skill-based errors are attributed to monitoring failures: either **inattention** or **over-attention**. Rule-based mistakes are related to a ‘symptomatic search’ strategy, identified by Rasmussen and Jensen (1974). However, a problem is identified from a match between local system cues and some stored representation of the pattern of indications of that failure state (i.e. automatic pattern-matching). If a match is found, a stored 'if-then' rule is applied. According to Reason (1990), rule-based mistakes arise either from **misapplication of good rules** or the **application of bad rules**. Knowledge-based mistakes (i.e. the lack of expertise) are related to a 'topographic search', where the diagnosis emerges from a series of good/bad judgements relating to the location and sphere of influence of each of the system components. This mode of search is dependent upon a mental model of the system. Knowledge-based mistakes originate from **bounded rationality** (a limited conscious workspace to display the problem space) and **incorrect/incomplete knowledge.**

According to Reason (1990), the defining condition for both rule-based and knowledge-based mistakes is an awareness that a problem exists. The necessary condition for a slip, however, is the presence of attentional capture, associated with distraction or preoccupation. Reason further expands the basic error types with a number of **failure modes**. Some of these will be introduced in the subsequent coverage of error classification systems.

Reason (1988 & 1990) further argues for the existence of two 'computational primitives' in the cognitive system - mechanisms for knowledge retrieval that represent both a strength and a weakness of human cognition. The first primitive is **similarity**, or matching like-to-like on the basis of the correspondence between states of the world and the attributes of stored knowledge (the **similarity-matching heuristic**). The second primitive is *frequency*, or resolving conflicts between partially matched structures in favour of those employed frequently in the past within that particular context (the **frequency-gambling heuristic**).

Reason (1988) extends this to posit that six error-shaping 'primaries' form most, if not all, the varieties of systematic error. These have their origins in the fundamental characteristics of human cognition, and give recognisable forms to all skill-, rule- and knowledge-based errors. These 'primaries' are:

- **Similarity bias**. Errors corresponding to salient aspects of the current stimulus, to the intended actions or both.

- **Frequency bias**. When cognitive operations are under-specified, they tend to default to contextually appropriate and high-frequency responses.

- **Bounded rationality**. People have a limited conscious workspace to display problems.

- **Imperfect rationality**. Problem-solvers tend to violate normative decision theories (e.g. logic, subjective expected utility).

- **Reluctant rationality**. The need to minimise cognitive strain results in automatic parallel processing when serial processing is required.

- **Incomplete/incorrect knowledge**. People tend to form an incomplete model of external reality.

One criticism aimed at GEMS concerns its lack of structure. Kirwan (1994) states that it is very much left up to the analyst's insight and imagination to classify and reduce errors. Also, Reason has frequently been criticised for using terms which are difficult to understand.

Reason's theory contains a number of complex concepts that render the theory less economical than other theories. This complexity lends itself to criticism from a practical standpoint. From a theoretical position, the ideas are based on sound experimental evidence from a large number of sources, but several ideas do not appear to sit comfortably together. This may be because they are expressed somewhat clumsily, with no concise synthesis of the ideas. Consequently, although GEMS is well-known, and comprehensive, it has not been used frequently. Finally, as GEMS is tied to the SRK framework, the user is left an underlying model of human performance that might be inappropriate for classifying human errors in ATM.

Lesson for HERA

HERA should capture the relevant error types within the Generic Error-modelling System (GEMS).

3.6.9 Categorisation of Action Slips (Norman, 1981)

Norman (1981) formed a classification of actions slips, which is similar to that of Reason (1979), based on a schema theory of human error. The categories, in bold, are as follows:

(i) Slips during the formation of an intention.

Mode errors, description errors. (Also errors that are not classified as slips.)

(ii) Slips that result from faulty activation of schemas.

a) Unintentional activation - schemas not part of a current action sequence become activated for extraneous reasons, then become triggered and lead to slips.

Capture slips, external activation, associative activation

b) Loss of activation - schemas that have been activated, lose activation, thereby losing effectiveness in controlling behaviour.

Forgetting an intention, disordering the components of an action sequence, skipping steps in an action sequence, repeating steps in an action sequence.

(iii) Slips that result from faulty triggering of active schemas.

a) False triggering - a properly activated schema is triggered at an inappropriate time.

Spoonerisms, blends, thoughts leading to actions, premature triggering.

b) Failure to trigger - when an active schema never gets invoked.

Action pre-empted by competing schemas, insufficient activation and failure of trigger condition to match.

Langan-Fox and Empson (1985) attempted to classify observed ATM errors but found that observed errors were difficult to classify within Norman's system. Langan-Fox and Empson found that errors could be classified across several categories and sub-categories. Reason's classification system of 'actions not as planned' was more successful in classifying ATM errors, which suggests that Reason's system may be more suitable for ATM tasks and possibly that schema theory does not lend itself to error classification.

Lessons for HERA

1. Slips of action should be considered within HERA.
2. Schema theory does not appear to lend itself to error classification in ATM.

3.6.10 Seven-stage Model of Human Action (Norman, 1986)

Norman (1986) proposed seven stages of mental activity that occur in the control of action at an interface. First, a goal is formed, then three further stages generate an action: forming an intention to act, specifying the action sequence, and executing the action. The effect of the action is assessed through another three stages: perceiving the system state, interpreting the system state, and evaluating the interpretation in relation to the system goal. The circular series of stages is shown in Figure 15. Whilst not a taxonomy of errors, this framework could potentially assist in identifying which stage of human action 'went wrong'.

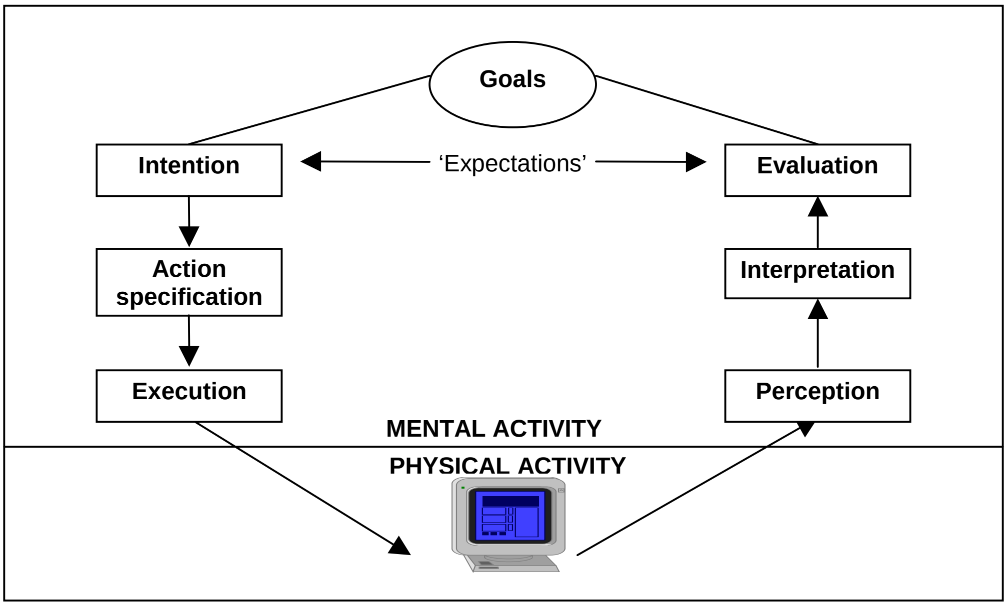

Figure 15: The Seven-stage Model of Human Action

3.6.11 The Cognitive Reliability Error Analysis Method (Hollnagel, 1993)

The Cognitive Reliability Error Analysis Method (CREAM) (Hollnagel, 1993 & 1998) has been developed recently as both a means of retrospectively analysing accidents and incidents and as a predictive human error analysis methodology. The approach is intended to bridge the gap between the practical human error analysis methods which have little under-pinning theory (i.e. they are not essentially model-based), and approaches that have evolved from cognitive psychology.

The model in CREAM is a simplified version of performance that is reminiscent of Rasmussen et al's SRK step-ladder' model. This simplification arguably avoids some of the difficulties that the original step-ladder model has faced and the under-pinning CREAM model, called the Simple Model of Cognition (SMoC) is certainly easy to grasp (see Figure 16).

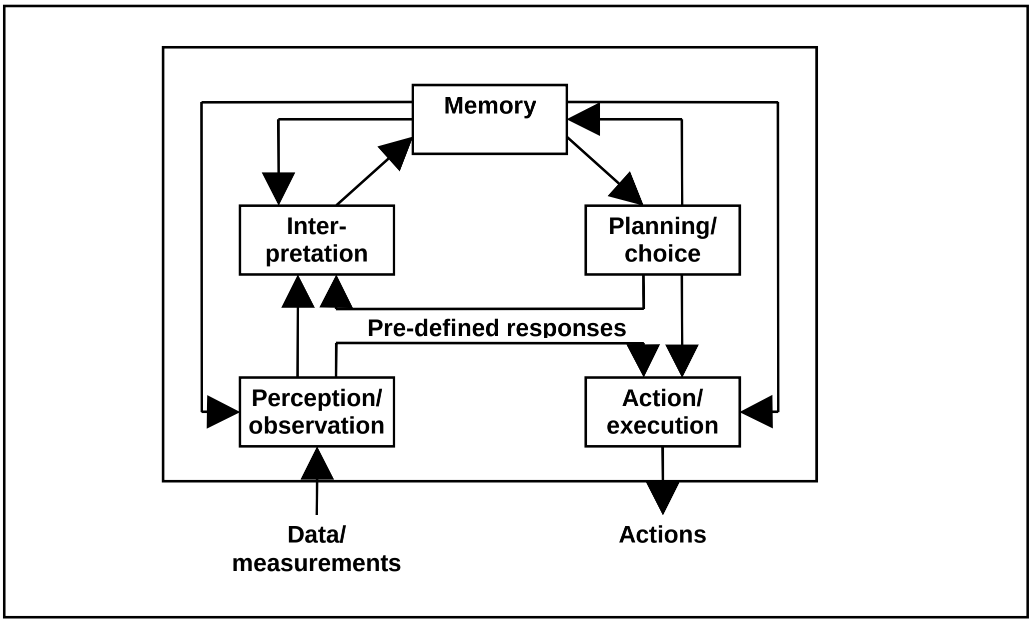

Figure 16: CREAM's Simple Model of Cognition (SMoC) (adapted from Hollnagel, 1993)

The CREAM philosophy is essentially one of multi-causality, in line with others' conclusions after two decades of incident analysis, that there is usually no single cause and, hence, no single treatment to avoid the error in the future. CREAM goes further than simply stating this, however, and attempts to investigate the interactions and likely connections between different Performance Shaping Factors (PSFs), called Common Performance Conditions (CPCs). The main CPCs in CREAM are:

- availability of procedures,
- crew coordination quality,
- adequacy of organisation,
- number of goals,
- time of day,
- adequacy of HMI,
- available time,
- working conditions,
- adequacy of training.

The CPCs represent a reasonable set of PSFs. Whether or not the proposed links between the PSF are correct, the philosophy and principle that such links need to be considered appear sound and have been attempted by other developers in the field (e.g. Whalley, 1988 'Potential Human Error Cause Analysis (PHECA)'; Phillips et al., 1985 'Influence Diagrams'; Kirwan, 1989 & 1998b 'HRMS'.

The Cognitive Reliability Error Analysis Method (CREAM) also has error modes associated with it, and various procedures for establishing the causes of the incident. Although the approach aims to be simple and practicable the two main texts on CREAM are relatively complex. This is probably partly a function of the recency of the text and also the subject matter itself - trying to develop a robust cognitive framework for analysing errors, their causes, and the inter-relationships between their causes, is difficult when there is so little data from which to determine such inter-relationships. Nevertheless, CREAM represents a significant development in error models and taxonomies, and challenges other approaches to address two basic tenets about accidents: that they are multi-causal in nature, and that different factors and causes can and do interact in complex ways.

Lessons for HERA

1. PSFs must play a significant part in accident analysis.
2. Interactions between PSFs should ideally be established in the approach.
3. The CREAM PSFs and interrelations could be considered as a potential starting point in the development of HERA.

3.6.12 The Contextual Control Model (Hollnagel, 1993)

The Contextual Control Model (COCOM: Hollnagel, 1993 & 1998) is linked to, or even considered part of, CREAM. It is effectively a less ‘simple’ model of cognitive activity than the Simple Model of Cognition shown above. Although COCOM does not seem to play a dominant role in the most recent version of CREAM (Hollnagel, 1998), it is worthy of note because it is unusual and potentially has some direct relevance to ATM. The main part of COCOM relevant to this current work is shown in Figure 17. This shows four different modes of processing:

- scrambled,
- opportunistic,
- tactical,
- strategic.

These modes of processing essentially relate to how much time the controller may have to deal with the tasks at hand and the degree of control the controller has over the task and situation. These four ‘modes’ do appear intuitively relevant to ATM, in that ideally the controller works at the strategic level (especially the ‘planner’ role), but frequently the tactical level. When traffic becomes busy, the controller will be less proactive and more reactive, and becomes opportunistic (i.e. flexibly deploying his or her resources) in dealing with an increasing number of competing tasks.

Finally, and this is obviously undesirable for ATM performance and safety, the controller can become purely reactive and driven by the latest event on the radar screen or strips, and is in danger of ‘losing the picture’ (the ‘scrambled’ mode).

Therefore, although COCOM is not formally used in CREAM, these four performance modes do represent different degrees of control by the controller, and HERA should be able in some way to account for these shifts in behavioural styles, and the errors that may arise in them.

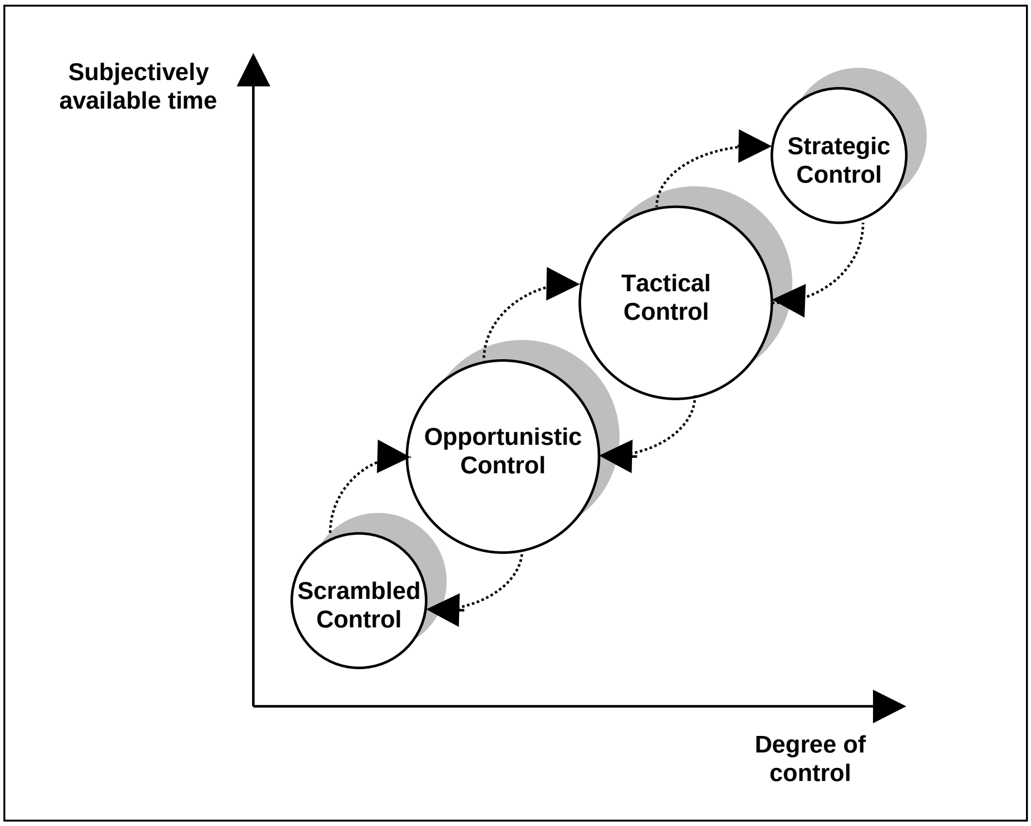

Figure 17: The correspondence between control modes, subjectively available time, and degree of control (adapted from Hollnagel, 1993)

3.7 Other Models and Taxonomies

3.7.1 Situation Awareness Error Taxonomy (Jones & Endsley, 1996)

Endsley (1988) defined Situation Awareness (SA) as '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'. This concept is broken down into three levels of SA:

- Level 1 SA encompasses awareness of key elements in the situation;
- Level 2 SA involves the comprehension and integration of that information as a whole in light of operational goal;
- Level 3 SA entails the projection of future states of the system.

Endsley (1995) developed a taxonomy for classifying and describing errors in SA which presents factors affecting SA at each level. This taxonomy is shown below:

Level 1: Fail to perceive information or misperception of information
Data not available
Hard to discriminate or detect data
Failure to monitor or observe data
Misperception of data
Memory loss

Level 2: Improper integration or comprehension of information
Lack of or incomplete mental model
Use of incorrect mental model
Over-reliance on default values (i.e. expectations)
Other

Level 3: Incorrect projection of future actions on the system
Lack of or incomplete mental model
Over-prediction of current trends
Other

Jones and Endsley (1996) used reports from the Aviation Safety Reporting System (ASRS) database to investigate the types of SA errors that occur in aviation. The ASRS is a US confidential incident reporting system for personnel within the aviation industry (mostly pilots and controllers). Jones and Endsley analysed 143 controller- or pilot-reported incidents that involved SA problems. The errors were classified at the lowest level in the taxonomy. That is, a lack of awareness of altitude would be rated as a Level 1 error, even if it led to a lack of understanding of flight safety (Level 2) and prediction of time (Level 3). Of the 143 incidents 111 involved SA errors on the part of the flight crew and 32 involved SA errors on the part of Air Traffic Controllers (ATCOs). The majority of reports had either one or two identifiable errors as causal factors. The results of the study are shown next:

Level 1: Fail to perceive information or misperception of information (76.3% total: 77.4% pilots, 72.4% controllers).

Data not available (13%).

- Task was previously omitted that would have provided needed information (5%); Other factors (8%).

Hard to discriminate or detect data (11.1%).

- Visual (7.3%); Noise (1.9%); Crew communication (1.1%); Miscellaneous (0.8%).

Failure to monitor or observe data (35.1%).

- Task distraction/workload (22.9%); Other distraction (non-task) (3.8%);

Vigilance (2.7%); Over-reliance on automation (2.7%); Stressors (1.1%); Miscellaneous (1.9%).

Misperception of data (8.7%).

- Negative interference problems (e.g. call sign confusion) (3.8%); Misunderstanding information due to task distraction (2.3%); Miscellaneous (2.6%).

Memory loss (8.4%).

- Due to workload or task distraction (5.0%); Interruption of normal routine (1.5%); Non-task distractions (0.8%); Miscellaneous (1.1%).

Level 2: Improper integration or comprehension of information (20.3% total: 21.1% pilot, 17.2% controller).

Lack of or incomplete mental model (6.9%).

- Problems in understanding how automation worked (3.1%); Incomplete mental models not related to automation (3.8%).

Use of incorrect mental model (6.5%).

- Mismatching information to one’s mental model due to expectations (3.4%); Using wrong mental model for situation (3.1%).

Over-reliance on default values (4.6%).

- Due to memory lapses; Basing expectations of others (or the system) on how they would normally perform.

Other (2.3%).

Level 3: Incorrect projection of future actions on the system (3.4% total: 1.5% pilot, 10.4% controller).

Lack of or incomplete mental model (0.4%).

Over-prediction of current trends (1.1%).

Other (1.9%).

The results suggest that Level 1 SA accounts for three quarters of all errors by both pilots and controllers. Failure to monitor or observe data account for over one third of the errors. The categories of ‘data not available’, ‘hard to discriminate or detect data’, ‘misperception of data’ and ‘memory loss’, also account for over one third of the data. This data shows the involvement of perception, vigilance and working memory in error production, and emphasises the need for these factors to be captured within an error classification technique.

However, the SA taxonomy appears to be difficult to use. Making distinctions between ‘incomplete’ and ‘incorrect’ mental models is very difficult, particularly without structured or clear guidelines. Also, the category of ‘Lack of or incomplete mental model’ is repeated in both Levels 2 and 3 SA errors.

Finally, as a taxonomy of SA errors, errors of action selection and action execution (including speech) are not represented.

Lessons for HERA

1. Errors of Perception and Vigilance and Working Memory must be clearly represented in HERA.
2. A structured technique is required to make classification more straightforward.
3. HERA must capture Situation Awareness (SA) concepts.

3.7.2 Control System Models

The control system modelling tradition uses concepts from modern control theory to understand human-machine systems. The human is seen in these models as a control or decision element in a closed-loop system, which includes monitoring, communication, supervisory situations, and manual control. As a cybernetic system, feedback plays a central role in guiding behaviour. This tradition assumes that the expert possesses an internal representation of the controlled process which enables open-loop behaviour such as anticipation and prediction as well as closed-loop behaviour such as stimulus-response behaviour. The expert human is assumed to exhibit many of the characteristics of a good or optimal inanimate system performing the same functions.

One set of models in this tradition applied **Optimal Control Theory** to understand human performance modelling (e.g. Baron & Levison, 1980; Pew & Baron, 1983). This approach has more recently considered communications and decision-making in multiple goal situations, but such modelling needs to incorporate other models such as Artificial Intelligence (AI).

Optimal Control Model (Baron & Levinson, 1980)

The Optimal Control Model (OCM) (Baron & Levinson, 1980) is the predominant model in the control systems modelling tradition and gives a closed-loop view of human functions in control tasks. Its main operator-related functions are monitoring, assessment, decision-making and action. The OCM assumes serial rather than parallel processing.

Kirwan (1992a) notes that this type of model fails to address the ‘jump’ from information assimilation to decision-making.

Procedure-oriented Crew Model (Baron, 1984)

Procedure-Oriented Crew Model (PROCRU) uses optimal control theory as a framework to integrate diverse models of cognitive activities. Pew and Baron (1983) note that while PROCRU owes many important concepts to the control-theoretic modelling tradition, there are limitations that surface when it is applied to more complex supervisory systems.

The Perceptually-centred Model of Human Control Behaviour (McRuer et al., 1980)

McRuer et al's (1980) Model combines concepts about types of control that represent different stages of skilled behaviour (compensatory, pursuit and pre-cognitive), executive supervision of these skilled routines and a model of human error mechanisms. McRuer's Model combines a control theory view of levels of skill, a model of executive control that is related to schema-based symbolic processing ideas and a model of error mechanisms.

In order to deal with more complex tasks, the control system perspective has drawn from different traditions including the statistical decision tradition, the communication system tradition, the symbolic processing tradition and AI. The result is a set of narrow-scope sub-models within a broad conceptual framework. This suggests that the control system perspective cannot adequately deal with complex tasks such as ATM and as a result few pure control system approaches are now used for performance modelling. Rasmussen's SRK (1982) framework was conceived from a control theoretic background, but the ideas overlap considerably with the schema concept in the symbolic processing tradition.

Stassen, et al (1985) reviewed the history and progress of control system human performance modelling and concluded that the tools and concepts are insufficient by themselves to model performance at supervisory control tasks. Furthermore, Rouse (and his colleagues) have shifted from systems engineering modelling tools (e.g. Rouse, 1980) to symbolic processing tools, to model human performance in larger scope, more complex real-world tasks (Hunt & Rouse, 1984). As predominantly closed-loop structures, control system models are unable to describe, explain, or predict the open-loop behaviour that characterises ATM.

3.7.3 Signal Detection Theory

Signal detection theory can be applied to situations where an observer must detect signals among noise (such as a critical event in ATM, see Bisseret, 1981). The combination of Response (Yes/No) x State (Signal/Noise) gives a 2 x 2 matrix providing four outcomes of signal detection (see Figure 18).

		STATE	
		Signal	**Noise**
RESPONSE	**Yes**	**Hit**	**False alarm**
	No	**Miss**	**Correct rejection**

Figure 18: Outcomes in Signal Detection Theory

Data can be gained on the numbers of each different outcome. This can be used to derive probabilities of error or correct responses.

Signal Detection Theory assumes two stages of information processing in detection:

1. The senses gather evidence regarding the presence or absence of a signal, according to increased sensory and neural activity.
2. A decision is made about whether the evidence constitutes an external signal.

In ATM a lack of a signal can also be a ‘trigger’. For instance, if a pilot failed to call a controller before entering a sector, this would normally act as a ‘trigger’ to the controller. This is related to the notion of ‘expectancy’.

3.7.4 Errors of Commission Approaches

An Error Of Commission (EOC) is an action that is incorrect and also not required. An example is where a controller gives a pilot a heading change which is not necessary, causing further problems. Such errors can arise due to carrying out actions on the wrong objects, or can be due to a misconception, or to a risk recognition failure. These EOCs have become of increasing concern recently for the three following reasons:

- First, they do appear to happen, even if rarely;
- Second, they can have a large impact on system risk;
- Third, they are very difficult to identify (therefore anticipate and defend against). This means that they may be underestimated in terms of their contribution to risk and not even be represented in a risk assessment such as a Probabilistic Safety Assessment (PSA).

The method INTENT [not an acronym] (Gertman, 1991) examines decision-based errors, i.e. errors involving mistaken intentions, including cognitive errors and rule violations, as well as EOCs. In this method the following four categories of error of intention were identified:

- action consequence (e.g. tolerating an out-of-range situation with potentially major consequences);
- crew response set (e.g. incorrect interpretation of symptoms);
- attitudes leading to circumvention (e.g. violate procedure and reconfigure equipment);
- resource dependencies (e.g. inadequate communication resulting in improper actions).

A set of twenty errors of intention (and associated PSFs) were derived and quantified using seven experts.

Potential Human Error Cause Analysis (Whalley, 1988)

Potential Human Error Cause Analysis (PHECA) was developed by Whalley (1988) for predictive Human Error Identification (HEI) and contains five mains parts:

(i) task type (seven categories of mental involvement),
(ii) response type (seven categories of action type),
(iii) error types,
(iv) error causes,
(v) PSFs.

PHECA also contains a set of ten error types:

1. Not Done
2. Less Than
3. More Than
4. As Well As
5. Other Than
6. Repeated
7. Sooner Than
8. Later Than
9. Mis-ordered
10. Part Of

Error causes (see Figure 19) are mapped onto each error type, each task type and each response type. Only those causes related to all three are considered relevant. A printout is produced showing the error causes in order of importance. The error causes are then linked to a list of PSFs (e.g. noise) and a list of relevant PSFs is produced.

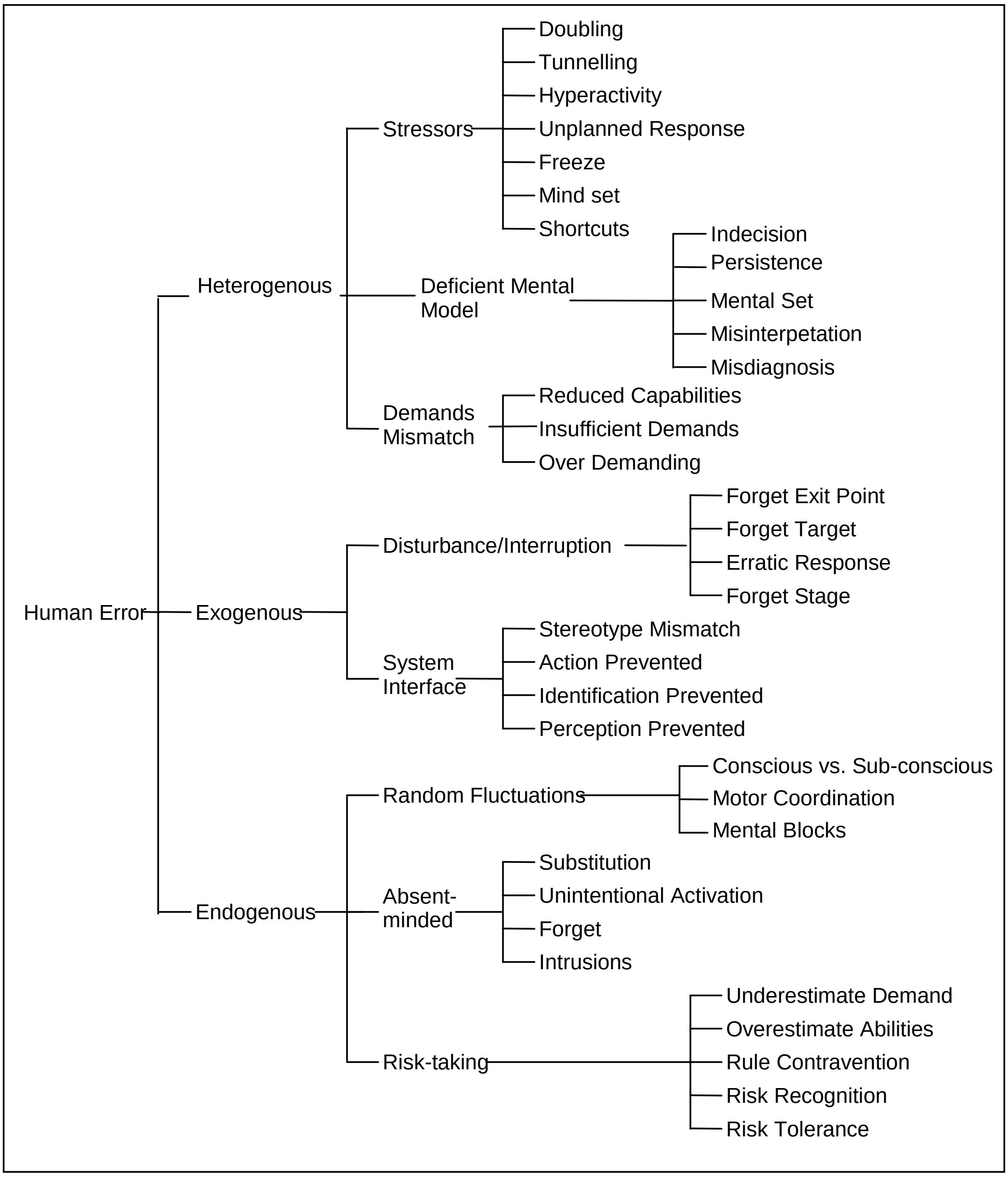

Figure 19: PHECA error causes (adapted from Whalley, 1988).

Procedure to Review and Evaluate Dependency in Complex Technologies (Williams & Munley, 1992)

The Procedure to Review and Evaluate Dependency In Complex Technologies (PREDICT) method has been proposed by Williams and Munley (1992), but to the authors' knowledge has not been formally applied. It is targeted at the relatively unpredictable event sequences which characterise real accident events from such accidents as Three-Mile Island (TMI) and the

Herald of Free Enterprise. The method utilises a group of individuals to identify errors, and uses Kletz's (1974) and Whalley's (1988) keyword systems (e.g. 'no action'; 'action repeated'; etc.), followed by three categories of assumption-testing keywords (low, medium and high-severity challenge: e.g. 'confirmed by'; 'not recalled because'; and 'defeated by'). The technique essentially allows the analyst to test the assumptions underpinning design and safety cases. The paper also mentions a facility to insert a keyword randomly to enable the analyst to consider more 'lateral' possible causal connections. Exactly how effective or resource-intensive this method would be in practice is difficult to say. It is also not clear how easy it is to isolate all the key assumptions underpinning design/safety cases. The approach is however unusual, and takes an open-ended and open-minded philosophy to a more extreme position. This approach currently occupies a unique potential niche in identifying errors of commission, idiosyncratic errors and rule violations.

Error of Commission Analysis (kirwan, 1994; Kirwan, Scannali & Robinson, 1995; 1996)

Error of Commission Analysis (EOCA) also uses experienced operators and a set of keywords to consider procedures in detail, and what actions could occur other than those desired (Kirwan, 1994; Kirwan, Scannali & Robinson, 1995; 1996). Particular task formats, error mode keywords and PSFs are utilised to structure the assessment process and to prompt the assessors. Identified significant errors are then utilised in risk assessments. This approach has only been used once, albeit successfully, in a real and large-scale risk assessment.

A Technique for Human Error Analysis (Cooper et al., 1996)

A Technique for Human Error Analysis (ATHEANA) (Cooper et al., 1996) has been developed relatively recently to analyse operational experience and to understand the contextual causes of errors, and then to identify significant errors not typically included in risk assessments (PSAs) for nuclear power plants. These errors may well be errors of commission, and their identification relies heavily on an understanding of the context surrounding the performance of tasks. These contextual factors amount to plant events and anomalies (e.g. incorrect readings from indications etc.) and PSFs. The ATHEANA process in brief requires that key human failure events and associated procedures etc. are identified from the PSA (e.g. operator fails to start pumps in an emergency), and unsafe acts (e.g. running equipment is turned off) are then identified as those things that could affect or cause these events. Associated error-forcing conditions (e.g. badly structured procedures; misleading indications) are then identified to explain why such unsafe acts could occur. The important point is that these forcing conditions are based on the system being assessed, i.e. the real context that is the focus of the assessment.

3.7.5 Violations (Mason, 1997)

Mason (1997) described violations as 'deliberate deviations from the rules, procedures, instructions or regulations introduced for safe or efficient operation and maintenance of equipment' (p. 288). Mason reported that in certain industries, violations of rules and procedures were a significant contributor to approximately 70% of their total accidents. Mason described two major factors that promote violations at work: 'direct motivators', which directly motivate operating and maintenance personnel to break the rules, and 'behaviour modifiers', which could increase or reduce the probability of any individual deciding to commit a violation. A list of direct motivators and behaviour modifiers is provided next.

Direct Motivators	Behaviour Modifiers
• Making life easier	• Poor perception of the safety risks
• Financial gain	• Enhanced perception of the benefits
• Saving time	• Low perceptions of resulting injury or damage to plant
• Impractical safety procedures	• Inadequate management and supervisory attitudes
• Unrealistic operating instructions or maintenance schedules	• Low chance of detection due to inadequate supervision
• Demonstrating skill and enhancing elf-esteem	• Poor management or supervisory style
There could also be:	• Complacency caused by accident environments
• real and perceived pressure from the 'boss' to cut corners;	• Ineffective disciplinary procedures
• real and perceived pressure from the workforce: (a) to break rules, (b) to work safely.	• Inadequate positive rewards for adopting approved work practices

Mason noted that ideally it should be possible to identify those direct motivators and behaviour modifiers that have contributed to major incidents. This is, however, difficult as most inquiries fail to elicit causal factors that lie behind the decision to break rules and procedures. In many cases the underlying causes can only be speculated. An additional classification is based on the mechanism behind the motive rather than the motive itself. Four classes of violations are described. **Routine violations** are behaviours in opposition to the rule, procedure or instruction that has become the normal or automatic way of behaving within the person's peer or workgroup.

Situational violations occur as a result of factors dictated by the employees immediate workspace or environment. These include the design and condition of the work area, time pressure, the number of staff, supervision, equipment availability, design, and factors outside the organisation’s control, such as weather and time of day.

Exceptional violations are those which are rare and occur only in exceptional circumstances, such as an emergency. Mason notes that exceptional violations often occur at the ‘knowledge-based level’, when an individual is attempting to solve a problem in an unusual situation where existing rules and procedures are considered inapplicable to the specific circumstances and over-prescriptive. The individual adapts existing knowledge to deal with the new problem and, in doing so, violates a rule. Such violations are often associated with high risk, because the potential consequences of the action are not fully understood or because the violation is known to be dangerous.

Finally, **optimising violations** are created by a motive to optimise a work situation. These violations are usually caused through inquisitiveness, boredom or a need for excitement. This classification of violations is potentially applicable to HERA, and could be used or adapted in the HERA taxonomy.

Mason (1997) reports on a methodology for addressing procedural violations which combines the classifications of direct motivators, behaviour modifiers and violation types. This approach identifies organisational factors that increase the potential for violations. Such organisational factors include training, management and supervision, job design and equipment design.

The violation approach was developed by the Human Factors in Reliability Group (HFRG) in the UK, and published jointly with the UK Health and Safety Executive (HSE, 1995). The approach is designed to identify the main organisational factors which might promote violations, and management strategies that could help to eliminate or reduce these factors by addressing the motives behind them. The approach can be applied by the non-specialist and is applicable to a wide range of industries.

The methodology involves interviews and questionnaires applied to generic or specific sets of rules within an organisation which are considered to have the greatest potential impact on safety if they are not followed. Each set of rules or procedures is assessed using a checklist. Examples from the checklist include:

- 'supervision recognises that deviations from the rules are unavoidable’;
- 'the rules are not written in a simple language’;
- 'rules commonly refer to other rules’;
- 'I have found better ways of doing my job than those given in the rules';
- 'I often encounter situations where no prescribed actions are available’.

A selection of the workforce is asked to rate the ‘degree of agreement’ with forty-eight statements with a score between zero (disagree) and six (strongly agree). Scores are then linked to approximately five out of thirteen possible ‘solution avenues’ as either ‘priority’ and ‘secondary’ such as:

• rules and procedures - application	PRIORITY
• training - hazards and risks	PRIORITY
• supervision - monitoring and detection	PRIORITY
• supervision - style	secondary
• job design	secondary

3.8 Cognitive Simulations (Cacciabue & Hollnagel, 1995)

When discussing models of the human, the disciplines of psychology and Human Factors meet within the domain of cognitive science, and the output is known as cognitive simulation. Cacciabue and Hollnagel (1995) define a cognitive simulation as follows:

> *'The simulation of cognition can be defined as the replication, by means of computer programs, of the performance of a person (or a group of persons) in a selected set of situations. The simulation must stipulate, in a pre-defined mode of representation, the way in which the person (or persons) will respond to given events. The minimum requirement to the simulation is that it produces the response the person would give. In addition the simulation may also produce a trace of the changing mental state of the person (p.58)'*

Therefore, if a model is taken to its logical conclusion, it becomes sufficiently specified that it can be computerised. If the complete definition above is adhered to, then such a model not only will characterise the external error mode, but also the internal mechanism of failure, and the psychological error mechanism. In other words, it would be clear in psychologically meaningful terms exactly what failed and how it failed.

A cognitive simulation generally requires three components (see Figure 20).

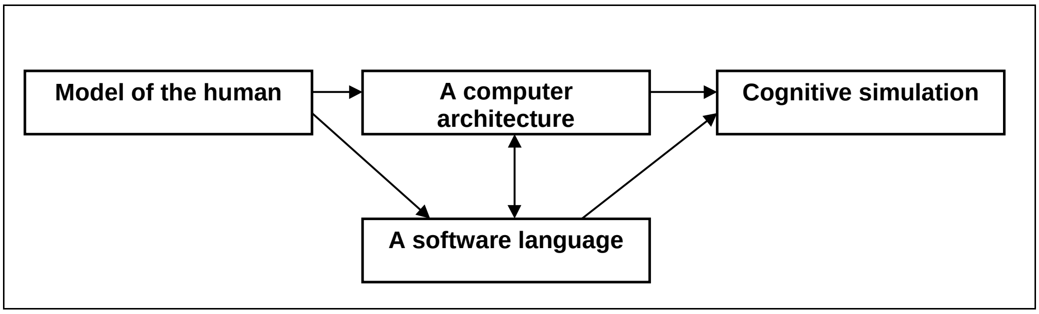

Figure 20: Key components of a cognitive simulation

The model of the human must be very detailed, not merely in terms of the cognitive functions (e.g. working memory; long-term memory; speech output; etc.) but also in terms of the contents of those functions (e.g. the strategies stored in the memory; information search strategies and priorities; etc.) and in the detailed interactions between the different functions (e.g. information sensed is then passed to the working memory, which then calls up particular models from the long-term memory, then goes back to the working memory, etc.). If the simulation is to simulate behaviour in real time, then temporal aspects of these interactions must also be modelled. Clearly, this is an ambitious modelling area.

Cognitive simulations were generally preceded by expert systems, which were programmed using a specialised language such as LISP (List Processing) and PROLOG which could emulate human knowledge storage and retrieval. Later cognitive simulations could be expressed using more conventional contemporary software languages such as C++. The focus now tends however to be less on the language and more on the architecture within which the language fits. The software architecture is the way the computer will represent the mental model in practice. As an example, blackboard architecture (Hayes-Roth, 1985) usefully represents working memory, in that incoming knowledge is ‘posted’ onto a mental ‘blackboard’. This allows for ‘flexible decision-making’ - depending on what happens, and when it happens, the human can call up information appropriately from the blackboard. The controller may have a number of potential plans, and then choose to ‘call up’ a particular plan at the appropriate time. This blackboard is ‘scanned’ frequently for information, using a strategic focus (Woods et al., 1987), which can only ‘see’ part of the blackboard at any given time (representing our cognitive processing limitations).

From an error perspective such an architecture also allows the occurrence of forgetting (parts of the blackboard are not scanned properly or frequently enough), or even of tunnel vision caused by stress (which causes the strategic focus to ‘shrink’ and become fixated: Cacciabue, 1998). Such an architecture has a certain appeal for ATM, since it potentially represents the ‘picture’ of the controller and Situation Awareness (SA) and flexible decision-making, which occurs during ATM controller behaviour.

Another architecture worthy of mention is that of neural nets, which simulate learning via experience. Such architectures have significant potential training applications, as they can be used to explore how learning is achieved and how to optimise training strategies. Many psychologists also believe that this particular architecture most likely reflects how thinking actually happens, i.e. neuropsychologically in the brain (i.e. it is how the brain works, and how the pure biology of the brain can manifest thought), but there is still much debate on such issues.

It is important to realise that cognitive science and cognitive psychology, although clearly related, do not always have the same goals. Cognitive psychologists (especially those looking for a neuropsychological [or brain] ‘metaphor’) want software architectures that truly represent human cognition or thinking. However, much of cognitive science is aimed at emulating human behaviour, including human error, irrespective of whether the architecture is neuropsychologically correct or not. From this perspective such a modelling tradition remains of potential interest and utility to those involved in the investigation and prediction of human error in complex systems.

There are a number of cognitive simulations that deal with general human performance and error, and a couple that deal with ATM performance, and these are reviewed below in that order.

There have been several recent reviews of cognitive simulations from the human error perspective, albeit mainly in the process industries such as nuclear power applications (Kirwan & Hollnagel, 1996; Cacciabue, 1998, Kirwan, 1998).

Some examples of key developments include the following:

• CES	Cognitive Environment Simulation (Woods et al., 1990).
• COSIMO	Cognitive Simulation Model (Cacciabue et al., 1992).
• CREWSIM	Crew Simulation (Dang et al., 1993).
• CAMEO/TAT	Cognitive Action-Modelling of Erring Operator Task Analysis Tool (Fujita et al., 1994).
• SYBORG	System for the Behaviour of the Operating Group (Takano, Sasou & Yoshimura, 1996).

3.8.1 Cognitive Environment Simulation (Woods et al., 1990)

Cognitive Environment Simulation (CES) system is a blackboard architecture system in the nuclear power environment, modelling a single operator, and in trials the simulation was found to be able to outperform a real nuclear power plant operator in a range of scenarios.

3.8.2 Cognitive Simulation Model (Cacciabue et al., 1992)

The Cognitive Simulation Model (COSIMO) also used a blackboard architecture and simulated the effects of stress on error causation such as tunnel vision, and also utilises Reason’s error mechanisms of ‘similarity-matching’ and frequency-gambling’, both of which are relevant to ATM errors. It also represents confidence in decisions and judgements.

3.8.3 Crew Simulation (Dang et al., 1993)

Crew Simulation (CREWSIM) is interesting in that it models human interactions, i.e. it simulates an interacting team trying to solve a nuclear power plant accident scenario. Furthermore, it can begin to identify the Crew Resource Management (CRM)-type errors such as a lack of confidence resulting in failure of the team to solve the problem.

3.8.4 Cognitive Action-modelling of Erring Operator Task Analysis Tool (Fujita et al., 1994)

Cognitive Action-Modelling of Erring Operator Task Analysis Tool (CAMEO-TAT) is a simulation approach acting as a task analysis tool, primarily for evaluating task design (e.g. ease of use of procedures). It allows designers to ensure that operators can carry out tasks. PSFs used in the approach include task load, complexity, time pressure, opportunistic change of task order, multiple task environments, negative feedback from previously made decisions or actions, operator's policies and traits, etc. The CAMEO-TAT system is primarily an information processing approach based on Information Processing theory, containing psychological (simulated) 'modules' such as working memory, long-term memory, etc. Errors are modelled mainly as a function of insufficient resources and designers then manipulate the design of the system until no more erroneous tendencies occur. The system is a single operator simulation and the total amount of resources may vary as a function of stress. Furthermore, task-switching mechanisms exist to determine the next task to carry out, and these mechanisms can be opportunistic, random, or linked to likely preconceptions and dispositions of the operator. In this way, pattern matching strategies (and associated errors such as similarity matching) can be modelled. One interesting feature of the model is the ability to vary individual differences, so that, for example, the simulation could model one operator who would switch more often than another, etc. (possibly reacting too fast leading to premature decisions based on insufficient evidence).

3.8.5 System for the Behaviour of the Operating Group (Takano, Sasou & Yoshimura, 1996)

The System for the Behaviour of the Operating Group (SYBORG) is a recent cognitive simulation approach, the first to try to deal with emotional aspects of performance. It aims to predict what emotions personnel will experience when dealing with difficult nuclear power plant events, and aims to determine how these emotions will affect attention, thought, action and communication. The basic emotions considered include fear, anxiety, tension, surprise, etc. There is ongoing work to determine how emotions interact with each other and with error forms, and some of these interactions are fairly sophisticated, e.g. their research suggests that 'indecision' is linked to **discouragement**, **dislike** and **irritability**, but not if **tension** and **satisfaction** are activated (Hasegawa & Yoshimura, 1996). These complex interactions and inter-relationships are based on empirical observations of actual subjects performing in simulator experiments. SYBORG is possibly the first approach of its kind trying to deal with social aspects of a work situation.

There are two other cognitive simulations in particular which relate to the ATM context, as described below.

3.8.6 Modell der Fluglotsenleistungen (Neissen et al., 1997; Neissen & Eyferth, 1999)

A research group called ENCORE (En-Route Controller's Representation), at the Technical University of Berlin, have developed a cognitive simulation called *Modell der Fluglotsenleistungen* (MoFL), which aims to model the controller's 'picture'. This simulation model is based on Anderson's (1993) ACT representation language and has three main cycles of information processing: monitoring, anticipation and problem resolution. The main components of MoFL are shown in Figure 21 which shows the five main components of the model, namely **data selection, anticipation, conflict resolution, update** and **control**. A further module, '**sector knowledge'** is planned. **Data selection** and **anticipation** include mainly diagnostic procedures, whereas **conflict resolution** prepares and directs the controller's interventions. The **control** procedures are particularly important for the sequencing of activities (scheduling) according to time constraints.

In this model the picture is in the working memory, which is seen as an activated part of the long-term memory. Each item in the picture is assigned an activation level. This allows the simulation to represent items which are in 'focal' memory (i.e. the focus of attention) and those which are not ('extra-focal memory'). The model also assumes serial processing, i.e. only one item can be processed at a time. Switching of attention from one item to another is dependent on external events and the executive control procedures.

Clearly, this is a sophisticated model, based on detailed investigations of controllers' thought processes (Neissen et al., 1997), which can simulate an en-route controller's thoughts and resultant actions. The focus on development of a model of the picture, rather than simply being a generic information processing model, is also a significant development, as it means the model is embedded within the context of ATM, and an intuitively plausible mental model of the controller.

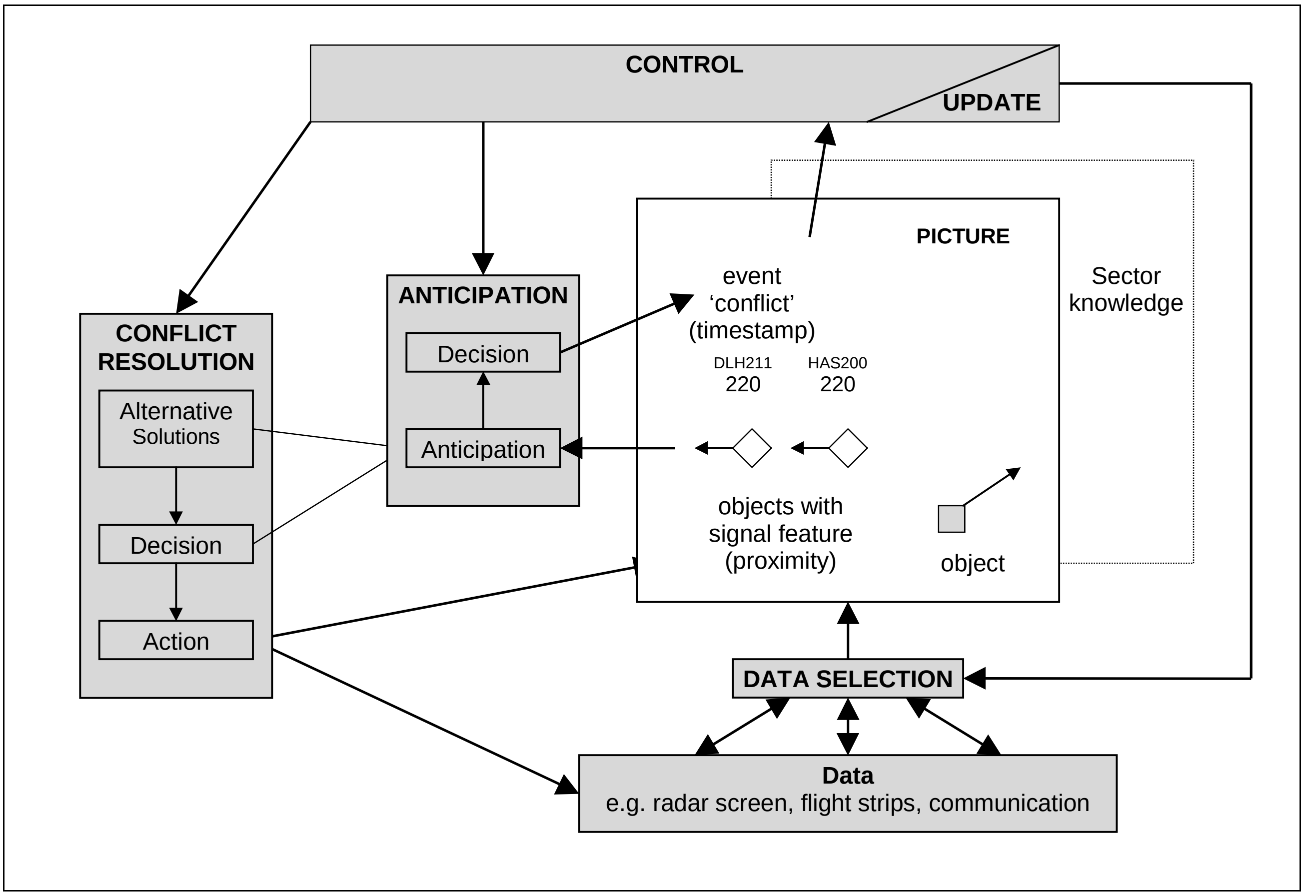

Figure 21: Main components of ENCORE's MoFL (Neissen & Eyferth, 1999)

3.8.7 Man-machine Integration Design and Analysis System (Corker & Smith, 1993; Pisanich et al., 1997; Corker, 1998)

Man-machine Integration Design and Analysis System (MIDAS) is a cognitive simulation with the aim of aiding the designer in developing aviation systems, but also has potential utility for ATM systems development. MIDAS is modular in nature, and not all of the modules need necessarily be active during model execution.

The core of the simulation model is information processing-based, including working memory (Baddeley & Hitch, 1974) and long-term memory, and a limited-capacity central control processor. Also, there is an audio 'rehearsal loop' that helps to memorise and temporarily store communications, and a 'visuo-spatial scratch-pad' for temporary storage of spatial information. Both of these cognitive functions are relevant to an ATM environment and, furthermore, could be useful for modelling errors that may result with the implementation of advanced technology such as data-link and electronic strips.

The system also focuses on scheduling of activities, again relevant to ATM, as the controller must frequently change tasks and determine which is the next priority task, in a dynamic environment.

Memory itself is represented using a ‘semantic net’, which can also aggregate ‘chunks’ of information (so-called **schema,** after Norman, 1981) so that more rapid and expert processing can take place. These schema, or organised information chunks, can be used to consider how errors may occur, e.g. by activation of an inappropriate schema - the controller may be expecting a particular aircraft to ask for a particular route etc., and fails to realise that something else has been requested. However, note that Langan-Fox and Empson (1985) found that Norman’s schema-based error classification system did not appear to be very suitable for ATM. Additionally, like MoFL MIDAS can model focal attention and less focal items, thus modelling forgetting, and ‘intrusion’ of other items in the human’s working memory leading to losing place or forgetting an action, etc.

These and other cognitive simulations represent significant achievements, since these systems are mimicking sophisticated human behaviour, and are largely based on models of human behaviour which have credibility and some validity in the psychological domain. However, many of them remain more research tools rather than finished products, and often they are only applicable to a narrow range of contexts and scenarios. At present, probably their most interesting aspect is the way in which they force the analyst to consider not only that an error mechanism may exist (e.g. tunnel vision), but also to explicate the mechanism of how it must work (e.g. stress affecting the range and mobility of the strategic focus on the working memory). Such insights gained from modelling attempts push back our boundaries of thinking about our own thought and control processes. These insights also raise ideas about how to combat errors (e.g. providing diverse and disconfirming feedback, using team structures and stress training to prevent tunnel vision).

The area of cognitive simulations therefore remains one which should be monitored in the future, in case sufficiently mature simulations arise, but also to gather insights into error mechanism modelling and error reduction strategies.

Lessons for HERA

Whilst the cognitive simulations themselves are not necessarily usable to develop a taxonomy of error for ATM, their attempts at modelling the internal mental functions and mechanisms of error can offer support in error modelling in ATM. The cognitive simulations represent a midway point between an explanative model and a working taxonomy and in some cases provide useful insights into how the one may connect to the other. HERA’s model and the taxonomy developed in WP2 should therefore take information from these simulations, whether in terms of useful constructs in the cognitive architectures (e.g. audio rehearsal loops; focal and extra-focal memory; etc.) which should appear in the model or in terms of the mechanisms of error (e.g. stress affecting the range and mobility of focal memory functions) which may inform the taxonomy.

3.9 Other Domain Approaches

The most significant domain for development of human error taxonomies and techniques has been that of nuclear power production. Even prior to the TMI accident, there had been significant development work ongoing since the early ‘sixties, and most of the work summarised in the foregoing chapters has been developed for, or applied in, the nuclear power field. Because the chemical and offshore industries are also, like nuclear power, essentially process control industries, there has generally been little trouble in adapting human error techniques from nuclear power to these domains. More recently other domains have begun to attract research and application of human error approaches, such as the medical domain and the transport domain (e.g. space and marine transport). Nevertheless, such research in these new application areas is at an early stage, and so this chapter focuses solely on some of the key developments in human error taxonomies in the nuclear power area.

The key developments discussed are as follows:

- Contemporary Accident Theory (Reason, 1998);
- The Human Performance Evaluation System (HPES), a root cause analysis system;
- The Nuclear Computerised Library for Assessing Reactor Reliability (NUCLARR), an early human error database;
- Computerised Operator Reliability and Error Database (CORE-DATA), a human error database;
- Office for the 'Analysis and Evaluation of Operational Data (AEOD)' study, an example of the use of incident analysis results proactively.

3.9.1 Contemporary Accident Theory (Reason, 1998)

It is important to comment here, with respect to multi-causality and the ‘safety-health’ model of a system. Multi-causality means that it is unlikely that a single solution to an error problem leads to an accident. Reason (1990 & 1998) in particular has used the ‘safety-health’ analogy to promote a better understanding of the implications of multi-causality. The analogy is that when a person becomes unhealthy or ill, a number of symptoms may occur. If such symptoms are treated independently, the person will not get better, although symptoms may temporarily subside, others are likely to appear, and in fact health may degrade, since the illness is not being treated and the symptoms are being ‘removed’. This is analogous to a any system including the ATM system in which general problems are arising, which manifest themselves in symptoms (e.g. air misses). If these symptoms are targeted individually, investigators may be missing the bigger picture, until a large accident occurs. Typically, once the large accident occurs, everyone suddenly has perfect hindsight and cannot understand why all the symptoms were not integrated and understood beforehand, and why the larger problem was not appreciated.

Certainly there will be times when a single incident is simply that, perhaps a random failure which occurred in very unusual circumstances, in which a new procedure or training could prevent the error ever recurring. But the irony of advanced and very safe systems, is that such errors will be very rare, because they will have been predicted and dealt with earlier. The company that has been very safe for the past ten years is perhaps the one harbouring serious problems which, unfortunately, are difficult to detect.

The cure to this, to continue the medical analogy, is to examine the types of underlying causes that indicate the general health of the system. Any accident analysis system must therefore have a sound structure of PSFs, and should probably ascertain the status of key PSFs, even when they do not at first sight appear to be relevant to an incident. This is after all what a good doctor does: the doctor does not simply accept the obvious symptoms and what the patient thinks the problem is, but probes other key indicators to establish the patient's general health and ensure there are no deeper underlying pathologies present.

Lessons for HERA

1. An incident analysis approach requires at least two 'levels' of PSF - specific PSFs which will capture the detailed context of an incident in a useful way relevant to ATM operations, and more general or fundamental PSFs which underpin operational performance and together indicate the 'health' of the system.

2. A fundamental set of PSFs should be explored for all incidents, whether or not such PSFs are implicated initially.

3.9.2 The Human Performance Evaluation System

The Human Performance Evaluation System (HPES) was developed originally in the US following a series of incidents in nuclear power plants, and was developed to learn lessons from such incidents. A related development at the time was the creation of the role of the Operational Feedback Engineer, of which one or two are located at most nuclear power stations in the world. Their job is to review incident experience from their own and other plants and determine how to avoid future incidents. This role still exists although many plants no longer use HPES as a data source (countries have often developed their own approaches, e.g. 'K-HPES in Korea [Kim, 1997]). Examples of the application of HPES in the US nuclear power industry can be found in Smith (1988) and in Paradies and Busch (1988). HPES was developed in particular to look for root causes, which were defined pragmatically as follows:

Root Cause: 'The most **basic** cause that can **reasonably be identified** and that management **can fix**'.

Typically HPES was aimed at identifying the most relevant Performance Shaping Factors (PSFs) that contributed to the error/incident, at a fairly detailed level. An example of one version of the approach is shown in Figure 22 below (Paradies & Busch, 1988). HPES focused on such PSFs as training, procedures, communications, supervision, and other general human factors (interface design, work environment, task complexity, etc.), as well as equipment reliability and poor design features.

One of the main benefits of HPES in the mid-eighties was that it directed management focus away from blaming the individual, to looking at more systemic factors. HPES is still running, and so represents a successful implementation of a root cause analysis system. The originators are still involved in implementing versions of HPES and training packages for nuclear power stations. At a later date, it may therefore be worth reviewing lessons learned from this domain, in preparation for Phase 2 of the HERA work (i.e. the implementation phase).

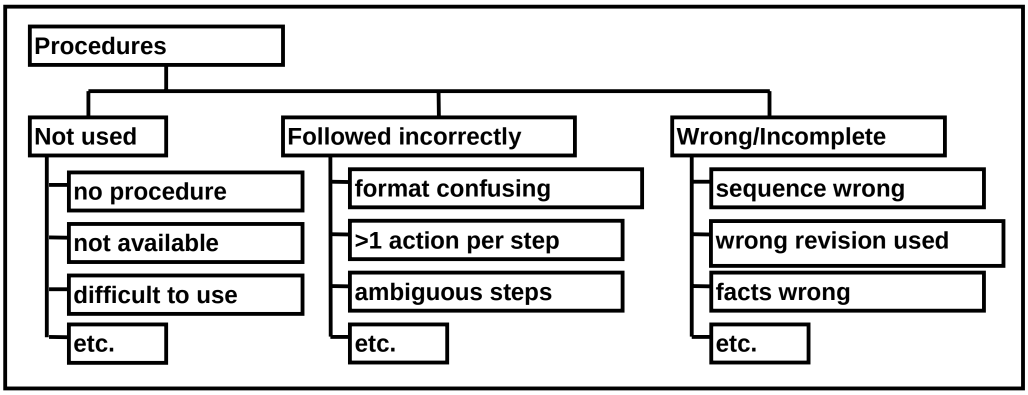

Figure 22: Extract from HPES Root Cause Analysis Implementation (Paradies and Busch, 1988)

3.9.3 The Nuclear Computerised Library for Assessing Reactor Reliability Database (Gertman et al., 1988)

The Nuclear Computerised Library for Assessing Reactor Reliability (NUCLARR) (database Gertman et al., 1988) was developed in the late ‘eighties for quantitative risk assessment support. It contained some human error data which were qualitatively described, and which had the likelihood of occurrence attached to them, and some limited PSF information (e.g. time to complete task). A limited External Error Mode (EEM) classification system was used, but psychological error mechanisms were not used in NUCLARR. However, many of the human error data in NUCLARR were simply re-statements of data from the THERP technique described earlier. Although NUCLARR therefore did not add much that was new, its development contributed to the realisation of the potential benefits of having such a database, and therefore in part led to the motivation to develop the CORE-DATA system, as described next.

3.9.4 The Computerised Operator Reliability and Error Database (Taylor-Adams, 1995; Taylor-Adams & Kirwan, 1995)

The Computerised Operator Reliability and Error Database (CORE-DATA) (Taylor-Adams, 1995; Taylor-Adams & Kirwan, 1995) has been developed over the last six years at the University of Birmingham, to assist UK assessors of hazardous installations such as nuclear, chemical, and offshore installations. It contains approximately four hundred data records describing particular errors that have occurred, together with their causes, error mechanisms and their probabilities of occurrence. Since CORE-DATA is relatively mature and represents a significant developing international database for the nuclear industry, it is described in some detail in this sub-chapter.

In the UK as elsewhere the formal assessment of the safety of a given plant or installation is a major input into the licensing (i.e. regulatory) process. Such safety assessment is increasingly being performed through the use of Probabilistic Safety Assessment (PSA) and Quantitative Risk Assessment (QRA). Within this quantitative framework there is a major requirement to include the human contribution to safety. The general framework for the quantitative assessment of human errors is termed Human Reliability Assessment (HRA) and is concerned with the difficult and complex area of how human error can impact upon risk.

As part of this HRA process, it is not only often necessary to define what human errors can occur, but also how often they will occur, by assigning Human Error Probabilities (HEPs) to the identified human errors. The HEP is defined simply as follows:

$$\text{HEP} = \frac{\text{Number of Errors Observed}}{\text{Number of Opportunities for Error}}$$

Such human error probability data are, in theory, collectable from observations of human errors in real systems during incidents and accidents, and could therefore be collected into a human error database. However, human error data collection, which should arguably underpin the whole approach to quantitative HRA, has generally been an unfruitful area. This has largely been due to;

- confidentiality problems;
- lack of management commitment to data collection;
- lack of a suitable data collection scheme with which to usefully and reliably categorise the data once available.

Nevertheless, in 1991 a recommendation for such a database was made by the Advisory Committee for the Safety of Nuclear Installations (ACSNI, 1991). ACSNI recommended that a 'centralised system and databank for the collection and exchange of data in a standardised form for use in quantitative assessment of the risks arising from human error should be established'. This ‘mandate’ therefore encouraged management commitment in certain companies and, given that theorists such as Reason and Rasmussen had enriched Human Factors sufficiently that suitable taxonomies could be developed, the development of a database was seen as a credible project. CORE-DATA was therefore developed over the next six years. It used the following sources of data to produce its database:

- real operating experience (incident and accident reports),
- simulator data (both training and experimental simulators),
- experimental (performance literature) data,
- expert judgement (e.g. as used in risk assessments),
- synthetic data (i.e. from human reliability quantification techniques).

CORE-DATA focuses on single-operator errors and, although chains of errors could be analysed, this technique tends to ‘fragment’ the analysis. Although the emphasis in CORE-DATA’s usage is different to that of the proposed EATMP taxonomy, the classification of error is likely to be similar. In fact, CORE-DATA was based around the work of Rasmussen, Reason, and Wickens (already discussed above), and had the following basic structure involving five sub-taxonomies:

- EEMs – External Error Modes,
- PEMs – Psychological Error Mechanisms,
- PSFs – Performance Shaping Factors,
- task equipment,
- task actions.

Examples from these taxonomies are shown in Tables 2 to 6.

Table 2: Extract of CORE-DATA’s External Error Mode (EEM) taxonomy

COMMISSION ERRORS
Time Errors
Action Too Early
Action Too Late
Latent Error Prevents Execution
Action Too Long
- Accidental Timing With Other Event/Circumstance
Action Too Short
- Accidental Timing With Other Event/Circumstance
Qualitative Errors
Act Incorrectly Performed
Action Too Much
Action Too Little
Action Repeated
Selection Errors
Right Action On Wrong Object
Wrong Action On Right Object
Information Not Obtained/Transmitted
- Communication Error
Wrong Information Obtained/Transmitted
- Substitution/Intrusion
Sequence Errors
Incorrect Sequence
Action In Wrong Direction
Misalignment/Orientation Error
Extraneous Acts
Rule Violations

Table 3: CORE-DATA’s Psychological Error Mechanism (PEM)Taxonomy

1. Action Prevented
2. Attention Failure
3. Cognitive Overload
    - 3.1 Identification Prevented
    - 3.2 Freeze
    - 3.3 Hyperactivity
    - 3.4 Bounded Rationality
4. Concurrent Plans
    - 4.1 Indecision
5. Encystment
6. Erratic Response
    - 6.1 Motor Variability
        - 6.1.1 Unintentional Activation
7. Incorrect/Incomplete Mental Model
8. Memory Failure
    - 8.1 Mistake Among Alternatives
    - 8.2 Place Losing Error
    - 8.3 Mental Blocks
    - 8.4 Failure to Consider Special Circumstances
9. Misdiagnosis
    - 9.1 Misinterpretation
    - 9.2 Miscuing
    - 9.3 Signal Discrimination Failure
10. Perception Prevented
    - 10.1 Out of Sight Bias
11. Procedure Unfamiliarity
12. Risk Recognition Failure
    - 12.1 Underestimate Demand
    - 12.2 Risk Tolerance
    - 12.3 Overconfidence/Overestimate Abilities
        - 12.3.1 Oversimplification
    - 12.4 Risk Taking
13. Rule Contravention
14. Shared Schema Properties
15. Shortcut Invoked
16. Signal Unreliable/Absent
17. Stereotype Takeover
    - 17.1 Assumptions
    - 17.2 Mind Set
18. Thematic Vagabonding
    - 18.1 Integration Failure
    - 18.2 Availability Bias
19. Topographic or Spatial Misorientation

Table 4: CORE-DATA’s Performance Shaping Factor (PSF) Taxonomy

1. Alarms
2. Communication
3. Ergonomic Design
4. Human-Machine Interface (HMI) Ambiguous
5. HMI Feedback
6. Labels
7. Lack of Supervision/Checks
8. Procedures
9. Refresher Training
10. Stress
11. Task Complexity
12. Task Criticality
13. Task Novelty
14. Time Pressure
15. Training
16. Workload

Table 5: Extract of CORE-DATA’s Task-Equipment Taxonomy

1. Alarms
2. Valves
3. Pumps
4. Fuel Systems
5. Transfer
6. Tanks

Table 6: Extract of CORE-DATA’s Human Action Taxonomy

1. Installs e.g. maintenance operator installs new brake pads into crane.
2. Stops/Starts e.g. operator starts up a computer.
3. Recognises e.g. the shift supervisor notices a bizarre set of alarms in the control room.
4. Diagnoses e.g. operator diagnoses a loss of coolant accident.
5. Responds e.g. control room operator responds directly to an alarm in the CCR.
6. Selects e.g. operators determine which emergency procedure to follow.
7. Communicates e.g. the shift technical advisor informs the maintenance operators what set of valves to close.

CORE-DATA is currently in its final implementation stage, where it will become available to industry. It has also been expanded to include data from other fields including aviation, chemical, offshore and onshore petro-chemical, etc. It is also currently being considered by the International Atomic Energy Agency (IAEA), the nuclear power equivalent of International Civil Aviation Organisation (ICAO)) for more international usage.

3.9.5 The Office for the Analysis and Evaluation of Operational Data Study (US Nuclear Regulatory Commission)

The US Nuclear Regulatory Commission (USNRC) requires all US nuclear power plants to submit Licensee Event Reports (LERs) for significant incidents. These are reviewed as they occur, but additionally there are periodic reviews (e.g. AEOD, 1992) to see what lessons can be learned. One such review was carried out by Barriere et al (1994). This review is mentioned because in particular it identified a new error form of concern for the industry (error of commission, meaning here an unrequired act due either to a slip or a knowledge-based failure [a ‘mistake’ in Reason’s terms]). The review spawned a methodology aimed at tackling such error problems as could occur during low power operations and during shutdown (nuclear power plants are not necessarily safer during such conditions). The review approach therefore represents a model for other industries of early identification of a significant developing problem area, leading to pre-emptive action to avoid the effects of the error.

3.9.6 Human Error-modelling in Maritime Operations

According to virtually all recent maritime research studies and overview reports on incidents and accidents at sea, human error is singled out as the predominant cause of such mishaps (International Maritime Organisation - IMO, 1998). It is estimated that about 80% of accidents at sea - such as collisions and groundings of vessels - are caused by human error. The results may be loss of lives or environmental damage (e.g. oil outflow). Although human error can be considered the greatest threat to safety at sea, little research has been done in the maritime domain in relation to applying human error frameworks as a tool in analysis of maritime incidents and accidents or in risk analysis.

However, an attempt has been made to model human error in maritime risk assessments by Harrald et al. (1998). In this context a human error framework was used to model the impact of human error in a maritime system. The objective was to identify and evaluate both the risk of oil transportation and proposed risk reduction measures. Among other frameworks considered was Reason’s Generic Error-Modelling System (GEMS), but due to lack of detailed statistical accident data from the maritime domain to support the estimation of human error types on such a detailed level (e.g. due to incomplete descriptions of human error in existing accidents and incidents databases), it was not included in the risk model. Instead, a more rough and ad-hoc taxonomy was developed and applied as the basis for the calculation of risk of human and organisational error. The consequence of not having a detailed representation of human error types and causes represented in the risk assessment model was that its ability to assess risks was reduced.

A number of incident databases and compilations have been made within the maritime domain, which potentially could be used as a means to record and learn from human errors (Drager, 1979). However, since the maritime databases do not classify human error types in any detail, they do not provide a sound basis for progress in reducing and capturing human errors. An exception, however, may be a comprehensive database which is in the process of being developed for the US Coast Guard and which IMO members will be able to access directly on the Internet. The database, the *Human Element*, is intended to support investigations of human factors in maritime accidents and in this context the inclusion of a human error taxonomy is considered important. For this purpose, the IMO has developed guidelines on investigation of human factors in maritime causalities and incidents which include a 'Human Element Taxonomy' that contains definitions of specific human factors which may affect performance or give rise to unacceptable or undesirable results. The specific content of the taxonomy is expected to be publicly available in the near future. However, this initiative demonstrates that the use of error taxonomies as a desirable feature of incident and accident database is currently being acknowledged in other domains.

3.9.7 Human Error-modelling in Flight Operations

The need for a model of human error in flight operations becomes clear when we look in detail at accident or incident statistics. In 1985 Sears developed a categorisation of elements found in airline accident statistics for a 24-year period from 1959 to 1983.

He examined in detail 93 major accidents worldwide and developed a classification system with the categories shown in Table 7.

Table 7: Significant accident causes and their percentages 1959-1983

Cause of Accident	%
Pilot deviated from basic operational procedures	33
Inadequate crosschecks by second crew member	26
Design faults	13
Maintenance and inspection deficiencies	12
Absence of approach guidance	10
Captain ignored crew inputs	10
ATC failures or errors	9
Improper crew response during abnormal conditions	9
Insufficient or incorrect weather information	8
Runway hazards	7
ATC /crew communication deficiencies	6
Improper decision to land	6

This methodology can be extremely useful in the operational setting, but as with other similar classifications it says very little about why the crews involved failed to perform the tasks required. Failure to know in detail why a human error occurs makes the development of a solution strategy both difficult and inefficient. Obviously, another problem with these types of classification schemes is that they are only descriptive of behaviour, not predictive. Nagel (1988) continues this discussion in the aviation environment and although not suggesting a model as such, he discusses the need to base such a framework on an information-decision-action model of piloting. This observation is partly based on the work of Card, Moran and Newell (1983) and follows the information processing models of human performance.

Further work, which uses information processing and performance as a framework within which the generation of errors evolve, can be seen in the pilot decision-making research undertaken by O'Hare (1992). He proposed a model that reflected the various types of decisions made on the flight-deck and used it to predict decision-making errors in flight. This model known as the ARTFUL Decision-making Model can be seen in Figure 23.

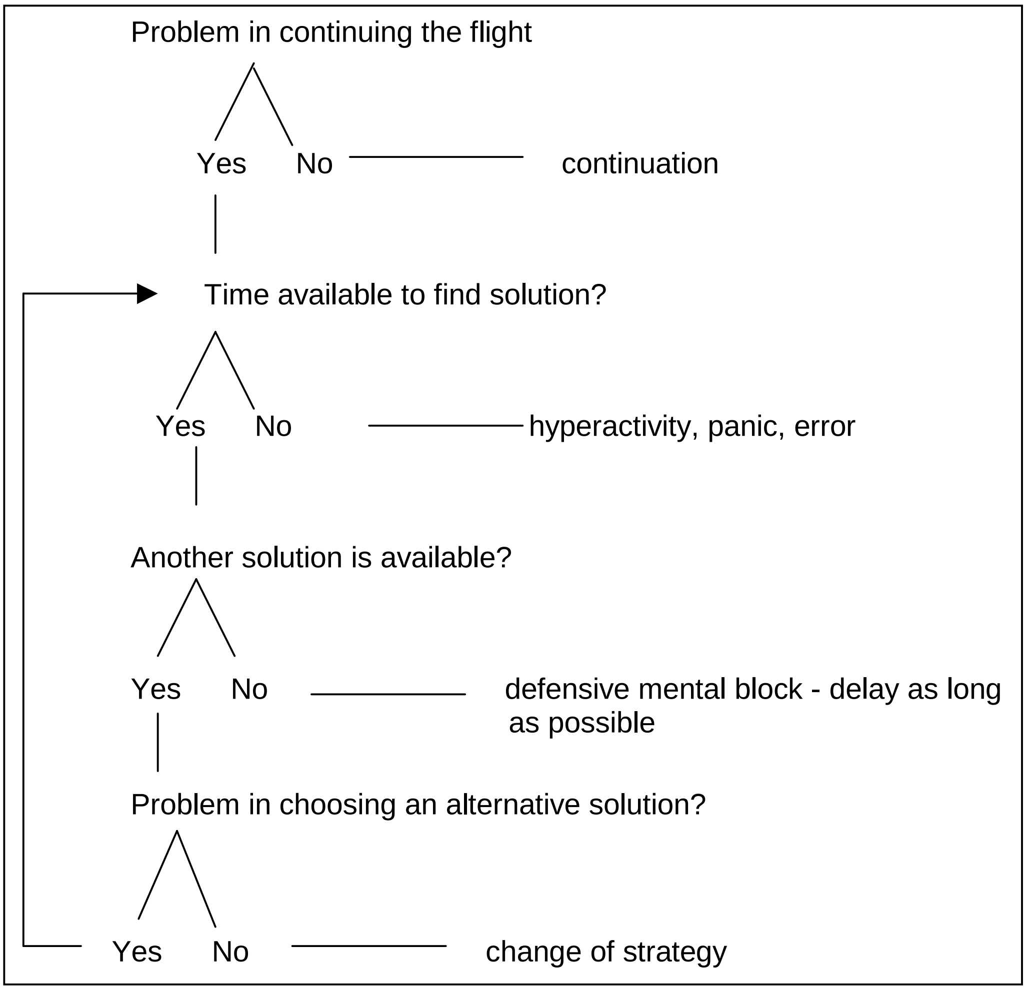

Figure 23: The ARTFUL Decision-making Model O'Hare (1992)

Further work in this environment can also be found in the work by Pariès and de Courville (1994) who discuss errors which arise from the mismatch between the real outside world and the world as it is perceived. This category includes sensory illusions and incorrect images of the world which cause errors to be made. Errors of representation result from the formation of a stable mental image of the environment which is different to the real situation. We have seen that these images, which enhance our Situation Awareness (SA), form the basis of our plans of action and orientate our perception filters. Errors in these areas are therefore self-sustaining and particularly dangerous.

Also, with an erroneous image, we have an incredible ability to ignore contradictory signals from the real world. These concepts were described in one of the few models which address the cognitive mechanisms which underlay errors of image formation. An adaptation of this model can be seen in Figure 24.

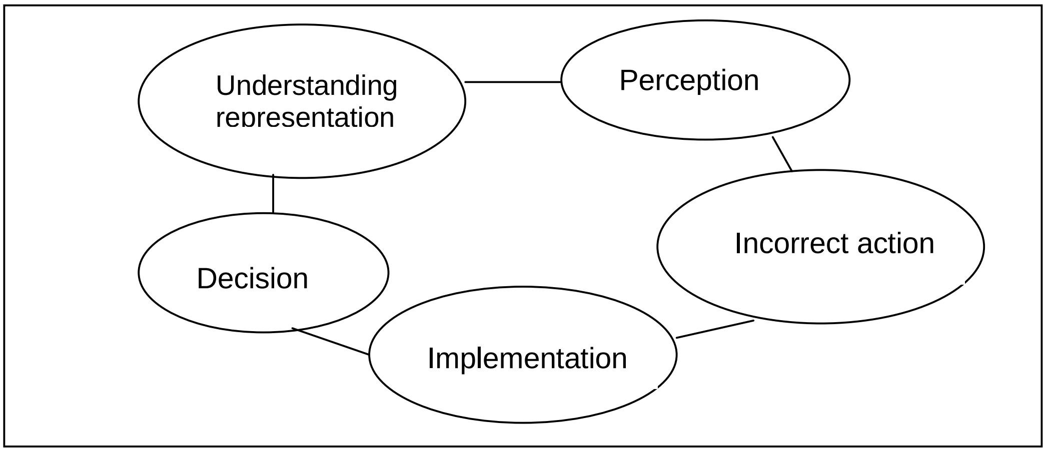

Figure 24: A closed ring model of mental activity leading to errors. Adapted from Pariès and de Courville (1994)

Aviation accident investigations historically identified many technical shortcomings of aircraft and aviation systems, but it is only recently that human performance issues have been adequately considered. This occurred in spite of the fact that ‘pilot error’ traditionally has been identified as the major cause of incidents, with estimates of its contribution generally ranging from 50 to 90 % of all occurrences. By the seventies it became obvious to a number of senior accident investigators that greater emphasis would have to be placed on the behavioural aspects of investigations. By 1980 investigators from the US National Transport Safety Board (NTSB) were not only performing limited human performance analysis, but had revised their investigation format to expand the amount of human factors data gathered during investigation (Diehl, 1980). The US Army at this time also overhauled its aircraft accident investigation procedures, increasing the emphasis on human factors issues (McGehee, Armstrong & Hicks, 1987). However, probably the most comprehensive expansion of any human performance accident investigation was undertaken by the Australian Bureau of Air Safety Investigation (BASI), (Hawkins, 1987 & Lee, 1986).

A fundamental concept which applies to aviation safety was developed by a pioneering industrial safety researcher in the fifties. Heinrich (1959) studied thousands of accidents and documented that for every one major injury accident, there were approximately thirty minor (non-injury) accidents and three hundred hazardous incidents. This helped to formulate the early thinking on the prediction of errors and can be found in some other error models (Isaac, 1995).

Several comprehensive analyses of human performance information in various aviation accident data bases have been established (Jensen & Benel, 1977; Sears, 1985). These are useful as they provide researchers with data for generating detailed conceptual models of human performance issues in the incident causation process. One such model is by Ramsey (1985) and can be seen in Figure 25.

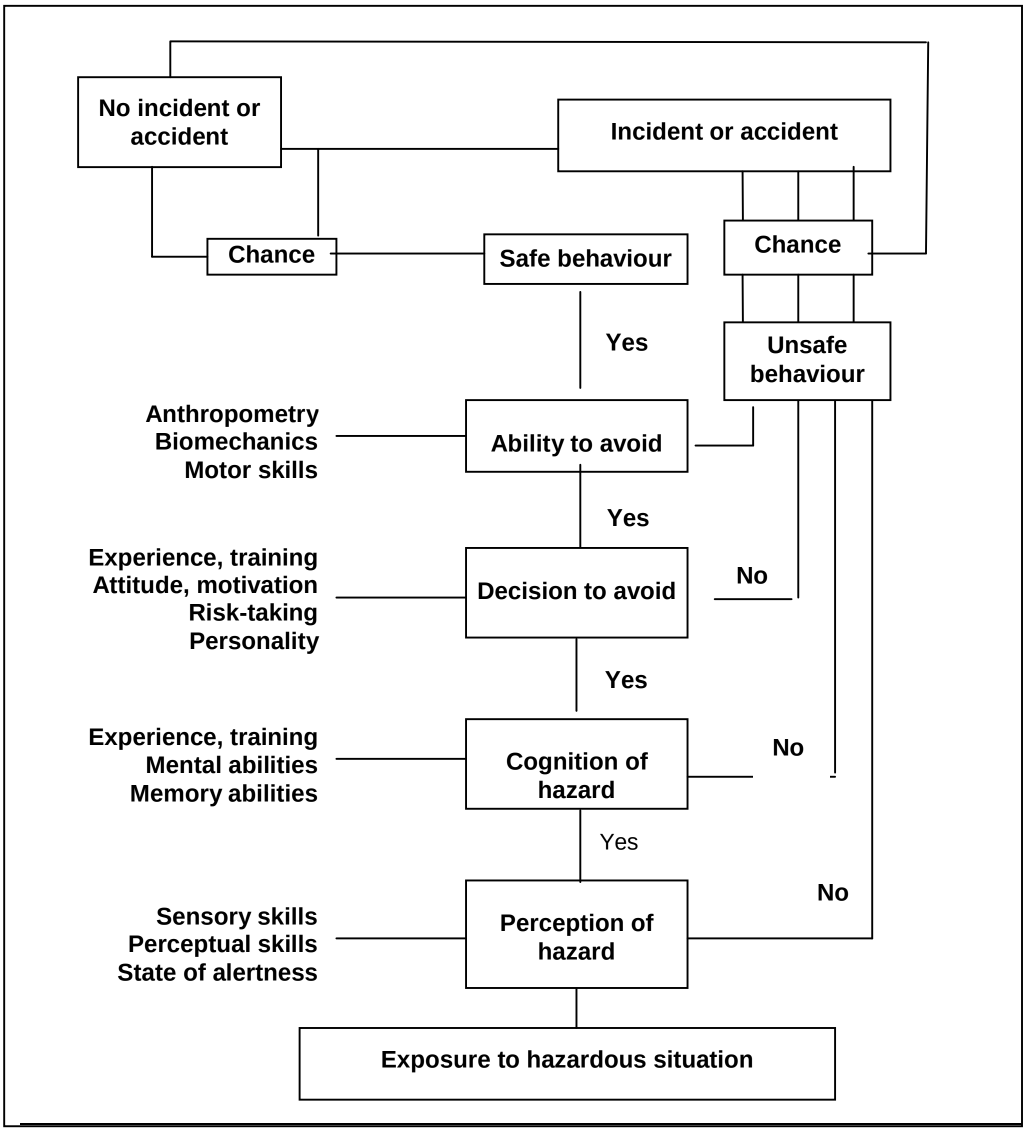

Figure 25: Error in incident sequence model. Adapted from Ramsey (1985).

More recently Wiegmann and Shappel (1997) used three conceptual models of human information processing and human error to reorganise an aviation accident database. The frameworks chosen for the study were:

1. A traditional model of information processing, based on Wickens (1984).
2. A model of internal human malfunction, derived from Rasmussen's (1982) SRK Model.
3. A model of unsafe acts as proposed by Reason (1990).

The investigation revealed that the three taxonomies could account for well over three quarters of the pilot causal factors contained in the database. The reliability of each of the coding systems was assessed statistically and revealed that the Rasmussen and Reason's Models achieved an excellent level of agreement and for the Wicken's Model there was a good level of agreement.

Lessons for HERA

1. Systems like HPES, although limited, can be useful and enduring, helping the classification and reduction of errors in safety critical industries. In Phase 2 (the implementation phase) of this current ATM work, it may be worth investigating lessons learned during the implementation of systems such as HPES, which have stood the test of time.
2. CORE-DATA, a contemporary classification system, shows a potential structure of taxonomies to use in the proposed ATM technique.
3. The nuclear power experience, via initiatives such as the AEOD work, gives the ATM community foresight of how the data could be used constructively and proactively in the future.
4. The initiatives within the maritime environment may have application within this project.
5. Work on the flight-deck, particularly in terms of the creation of mental models and work in errors contributing to decision–making should be considered in this project.
6. Models developed regarding errors found in actual accident analyses will be useful particularly in Phase 2 of this project.

3.10 Models of Error in Air Traffic Management Performance

Few models of error in ATM performance are currently available. However, two methodologies will be discussed within this chapter: Firstly, the Pyramid Model (Isaac, 1995) used in the modelling of human error in ATM incidents in Australia and, secondly and more importantly for this project, the developed of a human error classification technique to classify errors made in ATM, the

'Technique for the Retrospective Analysis of Cognitive Errors in ATM (TRACEr)' by National Air Traffic Services Ltd (NATS).

3.10.1 Pyramid Model (Isaac, 1995)

In terms of the actual classification of human error within an ATM environment, a composite model has been evolved and used by Isaac (1995). Within this model the issues of individual performance, tasks and the organisation were considered. Figure 26 illustrates this error trend model.

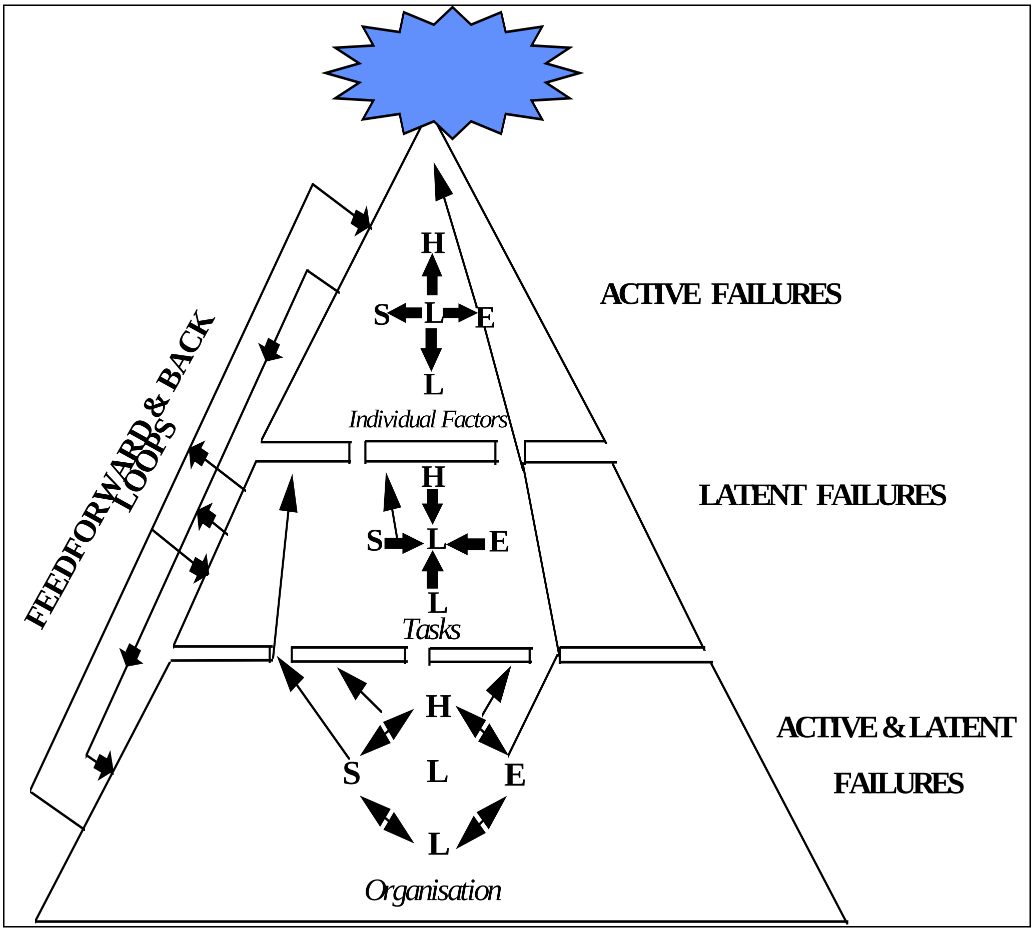

Figure 26: Pyramid Model of error in ATM incident investigation (Isaac, 1995).

The pyramid model takes its name from the shape. The model demonstrates the contribution of many error types within a complex system in the development of an incident. It also illustrates, through the addition of the holes or gaps between each layer, the opportunities at each layer to pass on the errors. The size of each layer is representative of the influence in the incident, and, at the apex, the individual who is in the unfortunate position to make the final error.

As with Reason (1990) the pathway of opportunity is not straightforward. The arrangement of the holes between the layers demonstrates that there is only one direct route and, being a pyramid, these will not line up very often. The model also indicates that there are feed forward and feedback loops from each level and the strength of these loops influences the number of opportunities within the pyramid for failure. The stronger the feedback loops, the fewer the opportunities.

Within each level there is the SHELL icon which is key to the complexity of the interaction within the model. The SHELL icon, developed by Hawkins (1984) indicates the various factors in any system; the Liveware (L) or personnel; the Software (S) or rules and procedures; the Hardware (H) or machines and the Environment (E). It should be noted that the individual appears in all levels as the middle of the SHELL icon but has the most influence in the top level. The three levels of the model indicate the levels of involvement of the variables in any control system; the individual, their tasks and the organisation. Typically, at all levels there are complex interactions which surround the individuals and although there will usually be feedback loops between each level, within each level there are some obvious limitations.

Individual performance factors

At the level associated with individual factors, the interaction between the other SHELL variables is often restricted to the actions of the personnel upon other variables. The ATC system is reliant upon the human operator who will usually process the air traffic in an efficient and safe manner, but, as human performance is fallible, occasionally controllers will commit unsafe acts. As we have already discussed these unsafe acts can be classified as either, attention slips and memory lapses - which involve unintended deviation of actions from a good plan, mistakes - when the action deviates from an adequate plan, or violations - deliberate deviations from regulated codes or procedures. Violations have a motivational basis and can only be properly understood in an organisational context. Usually the incidence of violations can be found in the local factors concerned with attitudes, group norms, rules and morale. These violations can be reduced when the organisation addresses specific issues, such as training, task design, time pressures and the working environment.

In terms of the results of investigations in the ATM environment, the following errors were identified:

- inadequate or no plan for traffic processing,
- failure to maintain SA or the traffic picture,
- reliance on ‘expected aircraft performance’,
- inappropriate use of flexibility to vary procedures,
- inattention to primary task,
- coordination failures,
- flight data processing errors.

Task factors

The middle level of the model illustrates the components of the task. The operator has certain tasks with which they are familiar, skilled and trained. However at this level the components of the SHELL system often impact upon the operator with little or no opportunity to modify the task.

Some of these task-related errors may be linked to the person themselves, whereas others can be directly related to the organisation. However both human and technical failures within the system are not infrequent. Within the organisation there may be several issues concerning management decisions which will create inherent flaws. These decisions are usually associated with a lack of information or resources, time pressure, associated high level decisions or decisions brought about by re-structuring.

In the investigation of the ATM system the following task factors were identified:

- a focus on tactical rather than strategic control,
- excessive use of anticipation,
- workload problems, both minimal and excessive,
- ambiguities regarding service and/or safety,
- acceptance of frequent distractions in the work environment,
- acceptance of working with system deficiencies.

Organisational Issues

The final level, and the foundation of the system, is associated with the organisation in its widest sense. Each part of a large organisation will have various levels of management and responsibility. This model again indicates the relationship between the SHELL variables at this level and indicates that although the personnel are placed in the centre, they are often surrounded by decisions made regarding their working situation in which they have little or no input. This level of the model also incorporates both active and latent failures. This differs from Reason’s earlier model which did not mention active failures at this level. The inclusion of active failures is based on the premise that the organisation does and will create situations within its hierarchy which actively encourage the creation of an error chain. The complexity of such decisions may lie dormant within the system for many years, and it is usually a combination of events or circumstances which allows these fallible decisions to cause an incident or safety critical event.

Those organisational issues which were identified in the investigation of error in ATM included:

- the development of a clear safety philosophy;
- the clarification of service versus safety;
- the development and implementation of an integrated approach to training;
- the establishment of an effective quality assurance function;

- the provision of adequate defences to increase the error tolerance of the ATM system.

This model helped to identify human errors generated by individuals but also focussed on the task and organisation issues. Although useful at a high level the purpose of this project was to narrow the area of concern to human errors generated at the human information performance level.

3.10.2 Technique for the Retrospective Analysis of Cognitive Errors in ATM (Shorrock, 1997; Shorrock & Kirwan, 1998)

The Technique for the Retrospective Analysis of Cognitive Errors in ATM (TRACEr) (Shorrock, 1997; Shorrock & Kirwan, 1998) contains error types derived from three sources:

(i) academic research on human error;

(ii) error types within existing Human Error Identification (HEI) techniques (e.g. the Systematic Human Error Reduction and Prediction Approach (SHERPA) - Embrey, 1986; GEMS - Reason, 1990);

(iii) ATM research and real-time ATM simulations.

TRACEr was created using a formal taxonomic procedure employing the guidance of Fleishman and Quaintance (1984) which ensured that the taxonomy is comprehensive whilst retaining mutual exclusivity and structure.

Wickens' (1992) model of human information processing was used as the underlying model for TRACEr. The stages of the model were translated into five 'cognitive domains' that are applicable to ATM:

- **Perception** and **vigilance**: errors in visual detection and visual search, and errors in listening.

- **Working memory**: forgetting recently heard or seen information, forgetting previous actions, and forgetting what actions were planned for the near future.

- **Long-term memory**: forgetting learned information.

- **Judgement**, **planning** and **decision-making**: errors in making judgements and decisions, and errors in planning.

- **Response execution**: actions or speech 'not as planned'.

In addition, another of Wickens' stages of information processing is represented:

- **Signal reception**: problems associated with the signal itself.

The cognitive domains were used to organise error types according to existing theoretical distinctions of human performance in the literature.

TRACEr also specifies a tripartite distinction between error types - External Error Modes (EEMs), Internal Error Modes (IEMs) and Psychological Error Mechanisms (PEMs).

EEMs describe what error occurred, in terms of the external and observable manifestation of the error. EEMs do not imply anything about the cognitive origins of the error (e.g. intentionality).

IEMs describe the internal manifestation of the error within each cognitive domain (e.g. misidentification, late detection, misjudgement). In order to identify IEMs, cognitive domains were split into further sub-domains within ATM. For instance, the cognitive domain 'Perception and Vigilance' was divided into 'visual' and 'auditory', as well as 'detection' and 'recognition/identification'. IEMs within 'Perception and Vigilance' include 'Hearback error', 'Late detection', and 'Misidentification'. IEMs provide an interface between EEMs, PEMs, and the model of information processing, and are equivalent in concept to Rasmussen's (1992) 'Internal Human Malfunction' classification.

PEMs describe how the error occurred in terms of the psychological mechanism of the IEM within each cognitive domain.

A list of Performance Shaping Factors (PSFs) identifies Human Factors problems that may help to explain why the error occurred.

TRACEr also includes a classification of major ATM sub-tasks (e.g. strip marking and radar monitoring) and a classification of ATM information elements, including aircraft, airspace and airport details. This identifies what it was that was misjudged, forgotten, misperceived, etc. (e.g. call sign, Flight Level, heading, route), and thus provides context for the error. This has provided evidence that the IEMs and the model are comprehensive in accounting for ATM tasks. This classification was developed from ATM Hierarchical Task Analyses (HTA) (see Lamoureux, 1998) and AIRPROX reports.

The relationship between these classification systems is shown in Figure 27.

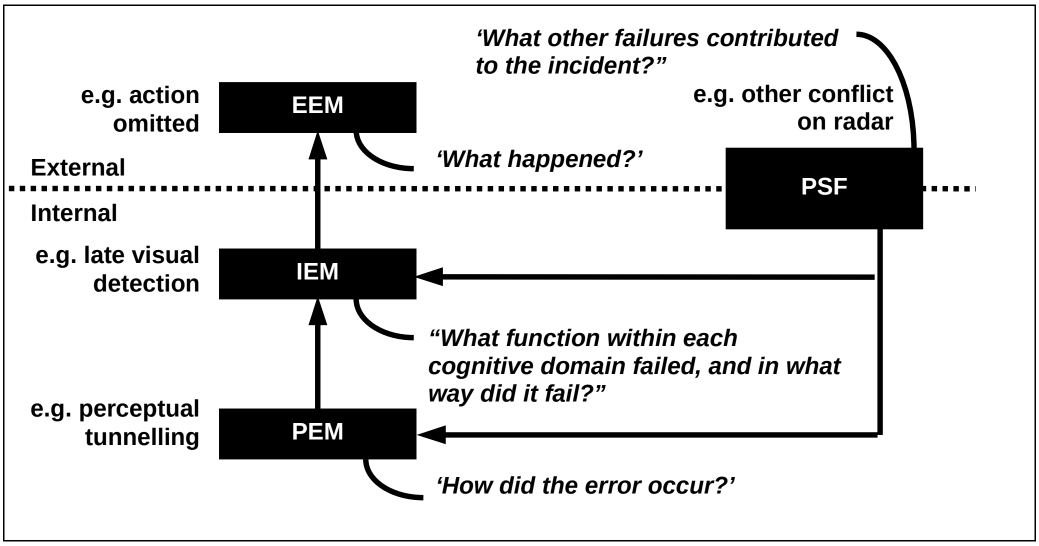

Figure 27: Relationship between TRACEr classification systems

Table 8 shows some example error types from the cognitive domain 'Perception and Vigilance'. Table 9 shows the EEMs within TRACEr.

Table 8: Example IEMs and PEMs within TRACEr

Internal Error Modes (IEMs)	Psychological Error Mechanisms (PEMs)
No detection (auditory)	Expectation bias
Late auditory recognition	Association bias
Hearback error	Spatial confusion
Mishear	Perceptual confusion
No detection (visual)	Perceptual discrimination failure
Late detection (visual)	Perceptual tunnelling
No identification	Out of sight bias
Misidentification	Stimulus overload
Misread	Vigilance failure
Visual misperception	Visual search failure
	Monitoring failure
	Preoccupation

Table 9: EEMs within TRACEr

External Error Modes (EEMs)	
Omissions	Communication errors
Omission	Unclear information transmitted
Timing	Unclear information recorded
Action too long	Information not transmitted
Action too short	Information not recorded
Action too early	Incomplete information transmitted
Action too late	Incomplete information recorded
Sequence	Incorrect information recorded
Action repeated	Incorrect information transmitted
Mis-ordering	
Quality	**Rule contraventions**
Action too much	(additive categories)
Action too little	Unintended rule contravention
Action in wrong direction	Exceptional violation
Wrong action on right object	Routine violation
Selection	General violation
Right action on wrong object	

TRACEr is represented as a series of decision flow diagrams. Decision flow diagrams were selected because they increase the usability of the technique, increase inter-analyst agreement, and increase the need for specification of the relationships between errors, which is the principal difference between a taxonomy and a list. Decision flow diagrams have been used previously in HEI techniques (e.g. Embrey, 1986).

The first diagram identifies the cognitive domain. The analyst then locates the diagram for the EEM. Once an EEM has been selected, the analyst refers to the decision flow diagram for the IEM for the identified cognitive domain. Finally, the analyst uses the PEM diagram for the same cognitive domain. These diagrams employ a ‘Yes’/’No’ question and answer routine, leading to the error types. Other questions direct the analyst to another cognitive domain, where the previous answers indicate that the analyst has located the wrong cognitive domain. TRACEr is also represented as a set of tables for quick reference. These tables contain examples of the error types from ATM and references for error types from the literature.

The method of using TRACEr is shown in Figure 28. The decision flow diagram for the cognitive domains is shown in Figure 29. An example ATM incident and the associated TRACEr classifications are shown in Figure 30.

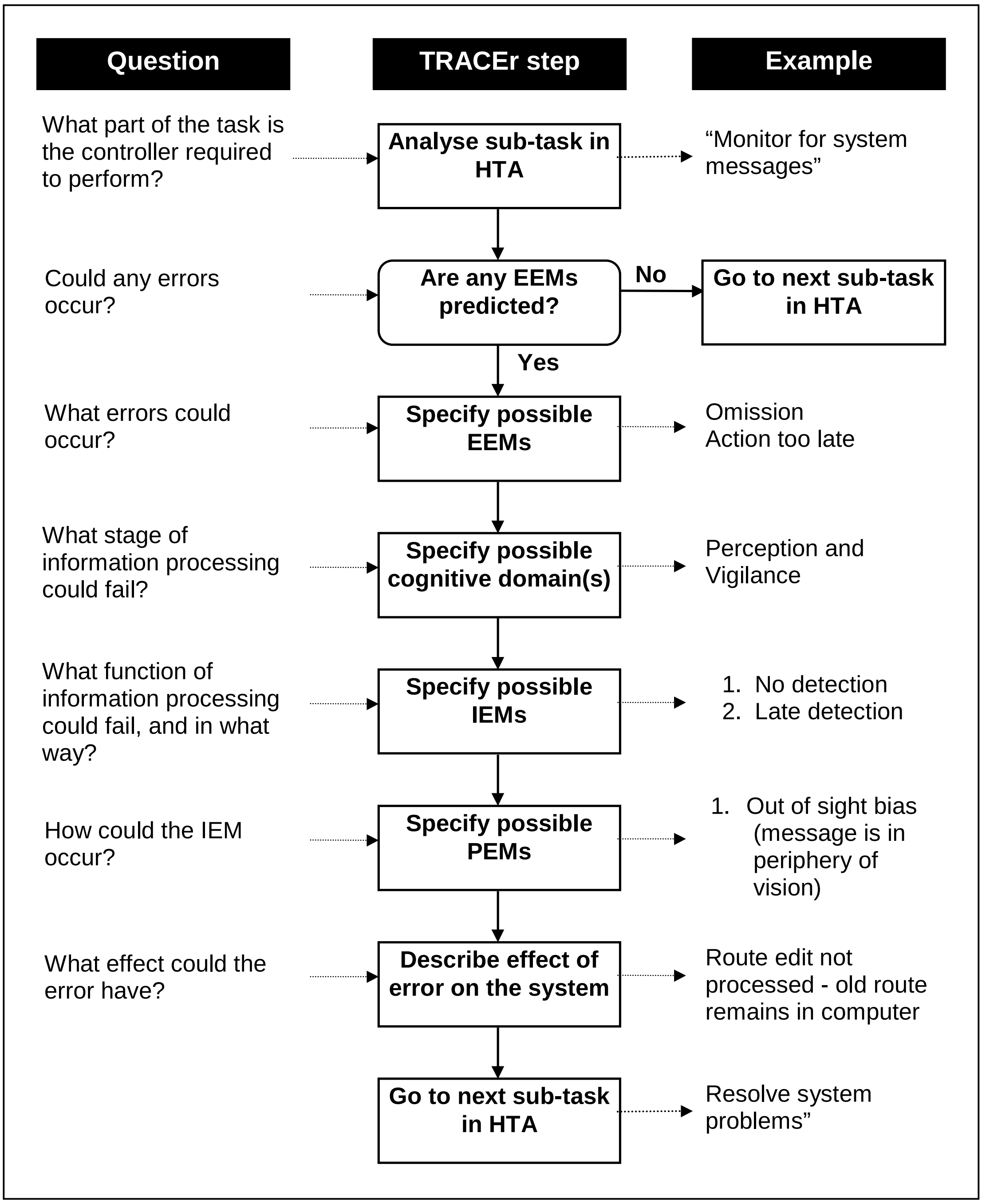

Figure 28: Method for using TRACEr

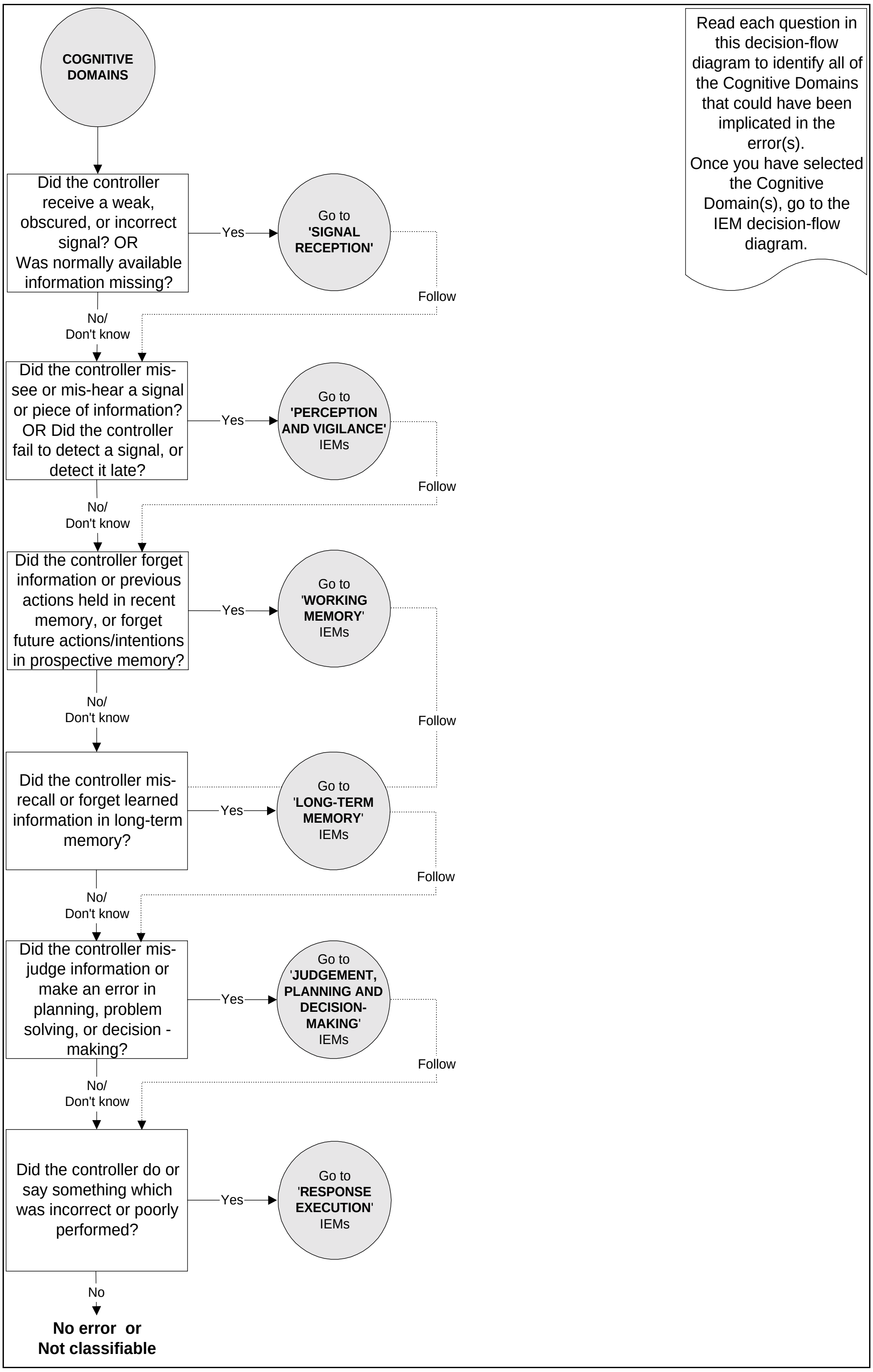

Figure 29: TRACEr Cognitive Domains decision flow diagram

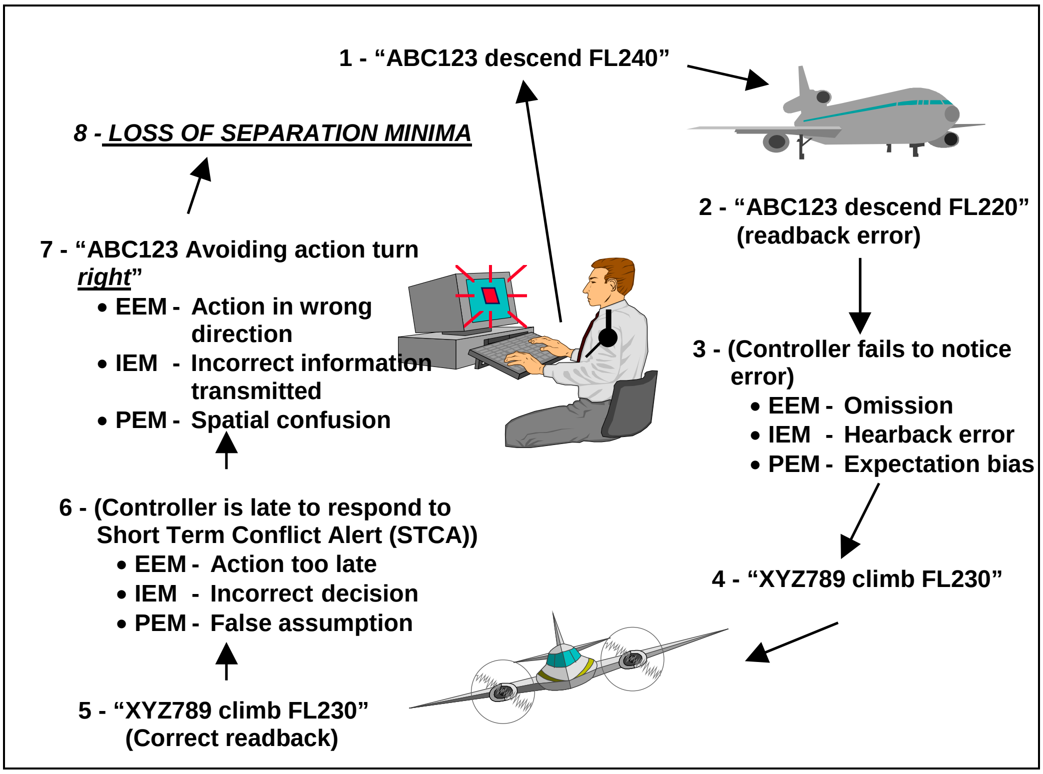

Figure 30: Pictorial description of an ATM incident and associated TRACEr error classifications

Evaluation and Development Study

An evaluation and development study was carried out on an earlier version of TRACEr (Shorrock, 1997). This version of TRACEr did not distinguish between EEMs, IEMs and PEMs. Nine Human Factors analysts independently classified individual events within AIRPROX reports. Over 98 % of the classifications used error types within TRACEr. An agreement level of 67 % was achieved for cognitive domains and 56 % for error types.[1]

This study demonstrated a reasonable level of inter-analyst agreement in the classification of cognitive domains and error types, and revealed good user opinion on the evaluation criteria. The study led to the further development of TRACEr, including the modelling of cognitive domains, the distinction between PEMs and IEMs and the reduction of sources of variance within TRACEr. These developments should improve analyst agreement.

The task of the Air Traffic Controller (ATCO) is characterised by a number of cognitive skills. TRACEr is a comprehensive HEI technique that captures the potential failures in these cognitive skills. The technique is structured and

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[1] The number of analysts who independently selected the mode cognitive domain and error type was calculated for all 23 events. The median of these values was six for cognitive domains (67 % agreement) and five for error types (56 % agreement).

usable with a strong error-reduction focus. Wicken's Model of information processing along with the tripartite distinction between error types has proved successful in analysing errors to derive measures for their reduction or their adverse effects. TRACEr marks a shift in emphasis away from the 'knowledge-based' errors that feature heavily in other error analysis tools, to better reflect the visual and auditory nature of ATM, judgement of current and projected radar separation, rapid decision-making and communication.

The Internal Error Modes (IEMs) have reintroduced a concept that has been lost from several HEI techniques that are not model-based. IEMs add value to error analysis because they provide an intermediate step between PEM and EEM analysis. It is not always possible to define the PEM, whereas it will usually be possible to derive the IEM. For instance, it might be clear that a misjudgement has occurred (IEM), but less clear whether this was due to the 'False assumption' (PEM). Thus, IEMs bring the analyst closer to error reduction than EEMs alone.

3.11 The Present and Future Air Traffic Management Context

The proposed system (HERA) which will be used to determine error contributions to incidents, must be able to classify the complete range of errors that can occur in ATM. This applies not only to current ATM, but also to the developments that are likely to be implemented in the medium term future (e.g. over the next 10-15 years).

The CORE-DATA system reviewed in Chapter 3.9 utilised not only error descriptors, but also descriptions of the tasks, behaviours and equipment involved in the error scenario. Such considerations can add context to the classification and become potentially useful when trying to learn from incidents. For example, a HERA system user may wish to investigate all information on errors associated with paper strip marking, input to electronic strips or data-link, or colour displays, etc. Alternatively, when examining incident trends for an operational centre, it may be found that most errors are occurring with respect to conflict detection or planning of taxi routes, or that certain significant errors are concerned with electronic strip manipulation (e.g. premature deletion of strips). Gaining such insights relies on classifying the incidents *according to their ATM context* in the first place. This effectively means that three aspects of the error/event/incident must be systematically recorded:

- what the ATCO was trying to do (the ATM ***function***),
- how the ATCO was trying to achieve it (the ATCO ***behaviour***),
- what the ATCO was using to achieve it (the ***device***).

If these three aspects are systematically recorded the resulting error database will be far more useful to those concerned with determining error trends and patterns, and on the improvements needed in system performance and safety. An additional benefit of such contextual classifications is that they allow a taxonomy to be adapted and updated with new technology and controller roles. This is important, since ‘psychological’ taxonomies should not change, unless new important psychological research findings have implications for HERA.

3.11.1 Current Air Traffic Management Functions

For current ATM systems in Europe, this means that the HERA system must generally be able to deal with the following ATM **functions**:

- traffic management and conflict detection,
- conflict resolution,
- inter-sector coordination,
- handling of emergencies,
- advice to aircraft (e.g. on meteorological conditions),
- management of pilot-initiated communications,
- management of aircraft in stack,
- guidance (on airports),
- arrival management,
- clearance delivery,
- planning of taxi routes,
- departure management.

3.11.2 Current Air Traffic Controller Behaviours

Air Traffic Controller (ATCO) **behaviours** can be considered firstly at a high level:

- anticipation,
- planning,
- situation assessment,
- monitoring,
- detection,
- evaluation,
- resolution,
- communication,
- verification,
- decision-making.

These are the main behaviours in ATM, currently. It may however be more useful to go to a more detailed level, such as the following:

- accept,
- acknowledge,
- acquire,
- adjust,
- aggregate,
- analyse,
- approve,
- assess,

- assign,
- brief,
- broadcast,
- calculate,
- etc.

Such a detailed ‘verb taxonomy’ (as was Berliner’s 1964 taxonomy, cited earlier in 3.5.1, for the nuclear power field) may render the resulting error database more sensitive to particular behavioural failures. Such information might be of particular use to training departments, for example, who could then re-direct efforts towards particular behaviours or skills (e. g. vectoring, phraseology, etc.). The only ‘downside’ of such detailed behavioural analysis is of course that it takes longer, and more care must be exercised when classifying the error. The decision of how ‘deep’ to go in terms of behavioural classification will be addressed in a later report, as it in part depends on achieving a degree of coherence between the EEM/PEM descriptive level and the behavioural descriptive level. The determination of the appropriate behavioural level will therefore be developed in the second work package report.

3.11.3 Current User Devices

The typical working position of the controller contains one or more of the following *devices*:

- a radar screen;
- ancillary screens (meteorological information; screens of other controllers’ strip bays; traffic flow information; etc.);
- computer;
- a touch input device;
- a pointing device (mouse; track ball, light pen);
- a paper strip board (and strip printer);
- panels associated with telecommunications;
- telephone and R/T;
- headsets;
- etc.

Devices will vary from one centre and country to another, and the device classification part of HERA should probably be kept relatively small and generic, as otherwise little generalisation of lessons can take place, as each device appears to be different from another. Large equipment or device taxonomies usually prove to be unwieldy and not particularly helpful.

3.11.4 Future Air Traffic Management- Implications for Human Error in Air Traffic Management Project

The future ATM environment will lead to changes or a shift in the human's role and tasks. However, it is not clear whether this shift will result in new functions or behaviours. Instead, future impacts may simply result in different emphases; for instance, electronic strips and datalink will generally have the same functions as current paper strips and datalink, with some additional functionality (e.g. enabling electronic coordination between tactical and planner; enabling the ATCO to understand better the aircraft's intent via datalink interrogation of the aircraft's Flight Data Processing System (FDPS); etc.). This extra functionality will generally be subsumed within current functions such as management of traffic and conflict detection, using conventional (i.e. current) behaviours (e.g. anticipation, evaluation, etc.).

The significant difference with some of the more advanced functionality is that the function may shift from being a human-implemented function to a computerised one, with the development of conflict detection support being a prime example. In such cases, although the function is the same, the role has changed. This may be best represented in the database either via categorisation of such tools as devices, or via noting which functions were 'automated'.

What will clearly change, however, are the procedures and the interface (the devices), and therefore the 'device' part of the HERA classification system must be adaptable to consider future devices. Descriptors such as electronic strip display, track-data-block object-oriented display, and up-link message window, and others, may therefore be likely to appear in the HERA classification system.

The above two paragraphs almost give the impression that future automation will have little net impact on the classification system, whereas there is general and genuine concern that such future systems will indeed affect human performance significantly (although hopefully for the better). Such impacts on human performance will generally be classified in the error parts of the HERA system, e.g. in terms of the EEMs, PEMs, and the PSF. For example, a fundamental Human Factors concern over future automation is the degree of trust that controllers will have in such systems. Trust will therefore be an important PSF with respect to future systems.

Similarly, future data-link systems will be likely to entail more visual tasks than are currently the case (and correspondingly less audio tasks), and the impact on human cognitive resources will need to be sensitive to such changes (e.g. via appropriate PEMs and/or PSF). Additionally, there may be more emphasis on teamwork in the future, so this aspect must be accountable in the error classifications, probably in terms of EEMs, PEMs, and PSF. The concept of teamwork can also be applied to the automation itself as part of the team, so that considerations can be made, for example, in failure to rely on the machine's suggestions (e.g. due to a lack of trust). Furthermore, whilst most ATM tasks are not 'knowledge-based' in Rasmussen's terms, future systems (e.g. 2015 and beyond) may require a more supervisory role, and more knowledge-based failures may start to appear. The PEMs and EEMs must be able to accommodate such changes in error patterns.

The HERA system must therefore be sensitive to the following evolving aspects of ATM:

- the shifting role of the controller (with respect both to automation and pilot autonomy);
- changes in the controller's picture and impact on Situation Awareness (SA);
- issues of trust and complacency with respect to automation;
- the potential shifts towards knowledge-based errors;
- team and organisational aspects.

Additionally, a significantly difficult time for ATM evolution will be what can be classified as the 'transition period'. This is when new technology is brought in gradually, or in stages. An example would be data-link, since some aircraft will have data-link capabilities before others. The controller may then have an additional task of determining which aircraft have datalink and which do not, and of then selecting the appropriate medium for communication. This sounds trivial, but is not, since the controller will have to keep switching from one 'mental modality' to another, often under significant workload pressures.

Moreover, the transition period, e.g. from 2005-2010, will not see just one innovation at a time becoming operational, but there may be several implementations happening at the same time – e.g. data-link together with certain tools, and the elimination of paper or even electronic strips could occur at the same or similar time. For the new controllers coming on-line in 2015 this will not be a problem, since they will only know the new system. But the controllers during the transition period will have a challenging time, with significant impact on their cognitive resources (e.g. on working and long-term memory, for example). HERA must be sensitive to such potential problems, most likely by indicating familiarity with the system (as a function of length of operational experience), and perhaps even having 'transition effects' as a PSF.

Since there is significant uncertainty over exactly what the impact of future systems and developments will be, such aspects of HERA will initially need to be relatively flexible rather than 'cast in concrete'. What is important however, is that as such systems are brought into operational usage, the key lessons should be learned from them via HERA as soon as possible. If such learning is prompt, this will help to avoid catastrophic problems, forewarn other future systems nearing implementation, and possibly even inform future operational strategy. Such 'early warning' of possibly serious human error problems will be particularly important during the 'transition phase' of implementing new technology and operational practices.

Lessons for HERA

1. In summary, the proposed HERA classification system would benefit from contextual classifications. These classifications enable the descriptions of the error to capture the relevant nature of the work environment at the time of the error, in terms of what the ATM function was, how it was being achieved (the behaviour) and what devices or equipment were being used. This will maximise the amount of useful learning that can occur on real and specific systems, which could lead to insights into how to improve system performance and safety.
2. Future ATM will offer significant and as yet uncertain challenges to the controller. HERA must remain sensitive to the impacts of future developments, to the changing role of the controller, to the sharing with automation (and ultimately even the pilot) of previously manual functions, to the transition period impacts and to the changes in work practices that will accompany such changes. This sensitivity will be achieved by enriching the set of EEMs, PEMs and PSFs associated with current ATM to account for such impacts. This will maximise early learning with future developments.

4. DEVELOPMENT OF A HUMAN ERROR CONCEPTUAL FRAMEWORK

This chapter integrates the results of the literature review in the development of a conceptual framework for the HERA taxonomy, so that the taxonomy itself can be developed in Work Package (WP2). The emphasis of this chapter is therefore twofold. First, a set of requirements for the operational taxonomy are presented. These requirements will become the guiding principles for the taxonomy in terms of its performance, validity and utility. Some of these requirements will actually become measures that will test HERA during WP3 where HERA will be validated. However, these principles are generally high level and will not help to define the detail or even necessarily the structure of HERA.

The second aspect of this chapter concerns the conceptual framework or model itself that HERA will be built around. Having reviewed a number of alternatives, one must be selected or adapted which will best help HERA to capture human errors and their causes in an ATM environment.

Within the conceptual framework a further aspect of this chapter is to define an appropriate structure and format of HERA in terms of what ‘dimensions’ HERA must contain and its overall format. This is key to gaining a consistently usable taxonomy and the structure of HERA will be based on lessons learned from the review of other taxonomic systems detailed in Chapter 3.

This chapter is therefore the spring board for WP2 since it defines the following three overall requirements:

- for the taxonomy to make it **useful** in error analysis and reduction in ATM;
- for the best model to make it **relevant** to the ATM context;
- for the best practical dimensions and format to make it **usable** by relevant ATM personnel.

4.1 Requirements for an Air Traffic Management Human Error Taxonomy and Database

This chapter identifies key requirements for the proposed taxonomy which will be developed in WP2. Each of these requirements, developed partly from the literature review and partly by the authors’ deliberations on the intended use of the taxonomy, cross-refers to the lessons learned (i.e. sub-chapter numbers) where appropriate.

Requirements primarily concern the taxonomy of human error. An additional potential outcome of this work, however, is a prototype database of analysed incidents. Such a database can be analysed to show the utility of classification using the taxonomy and, therefore, is useful as a demonstration for Phase 2 of the HERA Project, where ATM providers will be encouraged to use and apply HERA. Requirements for the database are therefore also included in this chapter, but these are secondary in nature compared to the main objective, which is the development of the HERA taxonomy itself.

In the **first** column of Table 10, under 'Priority', each requirement has been assigned a number between 1 (high) and 3 (low). When a priority number is put inside parentheses it indicates that the corresponding requirement is judged to be difficult to achieve. In the **second** column of the table each requirement is characterised in terms of its significance for either the Taxonomy (T) or the potential Database (D) or both products. The order of the letters T and D refers, when both apply, to the order of significance for the two products of the specific requirement. Finally, the **third** column refers to the specific 'lesson' that reflects the specific requirement in that row. The lessons are referred to by the number of the sub-chapter in which they appear. Whenever individual numbered statements of the text box lessons need to be identified, the number of that lesson is specified; for instance, when the requirement column says '3.7.1(2)' in the REQ1 (first) row this refers to the text box lesson, item 2, in Chapter 3.7.1.

Table 10: HERA requirements

Priority	T/D	Lesson	Requirement number and description
1	T	3.7.1(2) 3.6.5(1)	*REQ 1: Usable by non - human factors specialists*. The taxonomy should be usable, after an introduction of a few hours, by experienced ATC-operators and the kind of staff who customarily classify incidents. It is expressly *not* intended that the users of the taxonomy need to have a professional background in human factors or psychology.
1	T		*REQ 2: Robustness.* The taxonomy, in combination with its user guidelines, should produce reports with little variations, so the same *case* ought to result in the same classification no matter where, when and by whom it is classified. If not, the output of the taxonomy will depend on uncontrolled and typically undocumented circumstances of use; this in turn will seriously jeopardise the quality of the database that results from the use of the taxonomy. REQs 2.2-2.3 expand on this criterion.
2	T	3.5.2	*REQ 2.1: Theoretically sound.* The taxonomy should go beyond a mere empirical classification of data and be based on generally accepted theories of human performance and cognitive processing in real-time domains. In contrast an empirically derived classification scheme is liable to be sensitive to differences in samples (cases on which it is built).

Table 10: HERA requirements (continued)

Priority	T/D	Lesson	Requirement number and description
(1)			*REQ 2.2: Inter-cultural reliability*. Ideally, the taxonomy should yield the same classification in terms of types of errors and causes when the same case is treated by different incident investigators belonging to different operational cultures within the EUROCONTROL area. This requirement constrains the user guidelines and the associated brief introductory training.
1	T		*REQ 2.3: Validated.* The taxonomy should not only be robust and consistent in use across different users and occasions of use, but it should demonstrate this.
1	T	3.3.1 3.3.2 3.6.5(1) 3.6.6 3.6.7 3.6.8 3.6.9 3.7.2(1,3)	*REQ 3: Comprehensiveness*. The taxonomy should be comprehensive in the sense that it should have a classification label for all relevant *types* of human error in the ATM domain; at the same time, it should aggregate errors in terms of principled error categories in order to provide insight (see REQ 4).
(1)	T D	3.3.2 3.6.5(2)	*REQ 3.1: Inclusive of ATM functions and equipment.* The taxonomy should prompt users to identify failures and errors not only in terms of psychological mechanisms but also in terms of the tasks (functions) and devices or equipment that were being used. Similarly, the database should support queries by reference to the latter terms.
(1)	T	3.3.1(3)	*REQ 3.2: Comprehensive of human-system interaction failures*. The taxonomy should allow for classification of human-system interaction failures when relevant (e.g. occurrence of 'mode error' with respect to specific automated equipment).
(1)	T	3.3.2 3.6.9 3.9.1	*REQ 3.4: Descriptive of errors in terms of work situation.* The taxonomy should be able to capture analysts' description of the human elements involved in incidents in terms of the actual conditions of work (e.g. handover; high workload) and PSFs.
1	T	3.4.5	*REQ 3.5: Sensitive to single operators, team and interactional aspects.* The taxonomy should be sensitive to errors (and error-capturing behaviours) at the level of the single operator and at the level of the team; it should therefore also be able to classify communication failures.

Table 10: HERA requirements (continued)

Priority	T/D	Lesson	Requirement number and description
(1)	T		*REQ 4: Insightful in terms of practical error reduction strategies.* It is not uncommon that 'human error classification schemes' provide detailed breakdowns of the determinants of incidents/accidents and yet their output is met with a 'and now what?' reaction. The taxonomy should be capable of providing not only a breakdown of causes and factors (human errors, technical and organisational elements) but must also, by virtue of its theory-based character (see Chapter 3), aggregate 'minute human error causes' in terms of larger and operationally meaningful categories. Similarly, it should be able to capture recommendations by general and not just locally meaningful, categories.
(1)	T/D		*REQ 4.1: Enhance the discovery of trends, i.e. early warnings.* The database resulting from the use of the taxonomy should enable end-users of the database to identify trends and suspected trends.
(2)	T	3.3.2(2)	*REQ 4.2: Sensitive to error detection behaviour.* The taxonomy should prompt users (classifiers) to record when and by whom irregularities and errors were discovered ('Who discovered the error; how, why, when?'). It is well-known from a range of field studies in process industry and aviation that far more errors are made than are allowed to influence system behaviour. The errors that are caught are, at their root, typically no different from the errors that are not. It is therefore important to gain knowledge into error detection strategies and factors which enhance their potency. This requirement will shape the fine grained structure of the taxonomy aimed at classifying behaviours observed during simulated or observed sessions.
(1)	T		*REQ 5: Adaptive to future developments.* The taxonomy should aim to be comprehensive with respect to future developments in technical and procedural systems (e.g. free routes) and should be able to accommodate future ATM developments.
(1)	T		*REQ 5.1: Allow new ways of categorising data and at the same time stay 'historically robust'.* While the taxonomy should allow for the introduction of novel distinctions in terms of future ATM functions and equipment, the taxonomy should be

Table 10: HERA requirements (continued)

Priority	T/D	Lesson	Requirement number and description
			'historically robust' in the sense that cases which are classified by an older version of the taxonomy should be comparable with cases classified by a newer version. There will be a trade-off between adaptability (ability to incorporate novel distinctions and categories) and historical robustness.
(1)	T		*REQ 5.2: Customisable to different ATM environments yet allowing for the integrity of the database.* The taxonomy should allow for the possibility that different ATM environments can adapt parts of it (by expansion) to local requirements. The user guidelines shall carefully document how novel (local) categories may be introduced so as not to jeopardise the consistency of data input into the database - see Req. 5.3.
(1)	T		*REQ 5.3: Consistency*. While the taxonomy should allow for local adaptations and expansions the interpretation of data should remain invariant across local variations. A given category should not vary in meaning across different entries (compare Req. 2.2, which says that similar or indistinguishable observations should result in identical categorisations).
1	T/D		*REQ 6: Analytic power:* The potential database resulting from the application of the taxonomy, or alternatively an analysis of grouped data, should support many different types of queries and analyses to be performed in order to maximise what can be learned from the database.
1	T/D		*REQ 6.1: The taxonomy and potential resulting databases should support queries across combinations of error categories.* For example, a user should be able to make queries such as ‘What incidents involved electronic strips and were also influenced by time of day effects?
3	T	3.9.7	*REQ 7: Consistent with approaches in other domains.* The taxonomy should be consistent with classification schemes used in other domains, especially in aviation and process control. There are several motives behind this requirement. One is to produce a taxonomy which follows the 'industry standard', another is to allow for comparisons between the ATM domain and especially aviation and other process control areas in order to identify possibly abnormally high rates of specific error categories.

Table 10: HERA requirements (continued)

Priority	T/D	Lesson	Requirement number and description
(2)	T		*REQ 7.1: Both incident report inputs and data from real time simulations and field studies.* The taxonomy should be able to provide a theory-based classification scheme for not only (a) incident and accident reports from different ATM environments but also (b) data and observations derived from real time simulations or operational sessions. This Requirement entails that both the observations made by experienced incident analysts (not necessarily human factors trained) and observations made by, typically, human factors analysts, must be accommodated within the same classification scheme.
1	T/D		*REQ 8: Confidentiality.* The taxonomy should not invite the pillorying of specific sites, organisations or persons. It is important that issues of confidentiality and anonymity are addressed at an early point when the taxonomy and its database are offered to member states. This is not just a point about ethics - numerous taxonomies and reporting schemes have foundered due to a lack of anonymity in their application. The partners anticipate that a comprehensive set of rules governing confidentiality, access of use and publicity will be elaborated after the first phase of the project.

4.2 The Conceptual Framework

The literature review has derived several core components of a human error conceptual framework. These core components are listed below.

- **A human information processing model** - Appears to be the most relevant model of human performance for ATM because it encompasses all relevant ATM behaviours and allows a focus on certain ATM-specific aspects such as ‘the picture’ and Situation Awareness (SA).

- **External Error Modes (EEMs), Internal Error Modes (IEMs) and Psychological Error Mechanisms (PEMs)** - Appear to be the main structural aspects that enable a constructive (precise and helpful) analysis of human errors and they have proven their worth in other industries.

- **Performance Shaping Factors (PSFs)** - Are additional factors that relate to error causes, that will be necessary for error reduction analysis.

- **Contextual or task-specific factors** – These task (e.g. strip-marking), information (e.g. flight level) and equipment (e.g. strip) factors must be embedded within the HERA technique, as they make HERA focus on the ATM context, and enable analysis of error trends across errors from various operational units and practices.

- **A flowchart format** – Appears the most usable and robust format to error classification, as shown in other industries.

These core components are shown in Figure 31.

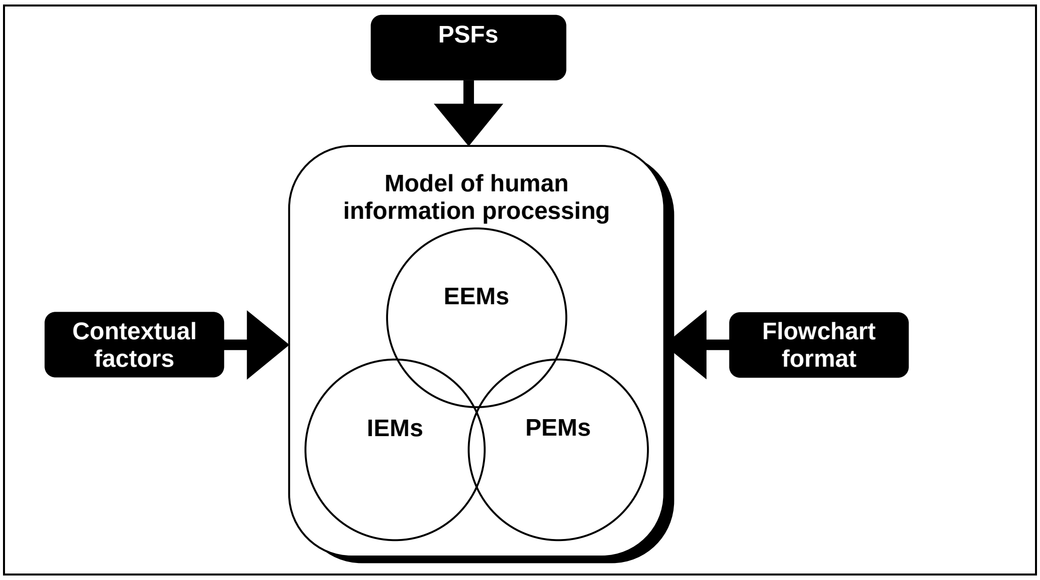

Figure 31: Proposed conceptual framework of HERA

4.3 An Enhanced Model of Human Information Processing

The model of human information processing provides a good framework around which to base a human error classification system. Wickens' (1992) Information Processing Model appears to be the most suitable model, if suitably adapted. Therefore, a number of modifications, which are listed below, are required to make the model more applicable to ATM.

'Working memory'

'Working memory' should however follow from 'perception'. Wicken's (1992) model shows 'decision and response selection' as following from perception. Wickens' rationale for this is that people decide to store information in working memory or to select a response. However, whilst people may have to decide to select a response, committing information to working memory is automatic in the first instance. However, people may then decide how long to try to hold information in working memory for a specific time period or decide to remember something at a specific time in the future.

‘Working memory’ is thought to contain what is traditionally thought of as ‘the picture’, i.e. the controllers mental representation of the traffic situation. In the enhanced model, this is termed ‘**ATM picture’.** However, controllers also have thoughts about themselves and their ability to cope with the traffic situation. This includes factors such as confidence, perception of workload, how situationally aware they feel, etc. In the enhanced model, this is termed ‘**self-picture’**. These factors can change dynamically with the ATM situation and so are located in working memory.

‘Decision and response selection’

‘Decision and response selection’ is divided into two separate renamed processes:

‘Judgement, planning and decision-making’ - This reflects more explicitly the processes of judgement, projection, prediction and planning used in ATM. ‘judgement’ here refers to judging the heading, climb, descend or speed, etc., to achieve separation.

‘Response selection’ - Once the controller has made a decision a response is selected.

‘Mental model update loop’

The ‘mental model update loop’ is the flow of information from working memory to long-term memory. The controller’s mental model is updated by new information from perception as well as information from judgement, planning and decision-making. However, all updates to the mental model arrive directly from working memory. Since past decisions and responses as well as perceived information must be processed in working memory initially.

‘Picture update loops’

The ‘picture update loops’ represent the flow of information used to update the controller’s ATM picture. Information from perception, long-term memory, and judgement, planning and decision-making is used to update the picture.

- Information from **perception,** e.g. current aircraft movements on the radar display, flight progress strip markings and current pilot transmissions.

- Information from **long-term memory,** e.g. previous transmissions to pilot and recalled procedures.

- Information from **judgement**, **planning** and **decision-making,** e.g. judgements regarding climbs, descents and turns, and decisions about whether to split a sector to act on a conflict alert.

‘Attentional resources'

An important part of the model is the limited pool of attentional resources. There are four types of attention which can be considered:

- selective (scanning selected channels),
- focused (on one channel with a particular signal),
- divided (over different, simultaneous tasks),
- sustained (over long periods, i.e. monitoring and vigilance).

With a shift from passive reception to active collection of information attention becomes more focused. Attention can be insufficiently focused in the case of distraction or preoccupation, to too focused in the case of 'visual tunnelling'. A limited pool of attention is shared between perception, working memory, decision and response selection, and response execution. If perception demands a large supply of attention performance of other functions deteriorates. The role of attention is represented in TRACEr's cognitive domains.

Figure 32 shows the enhanced human information processing model.

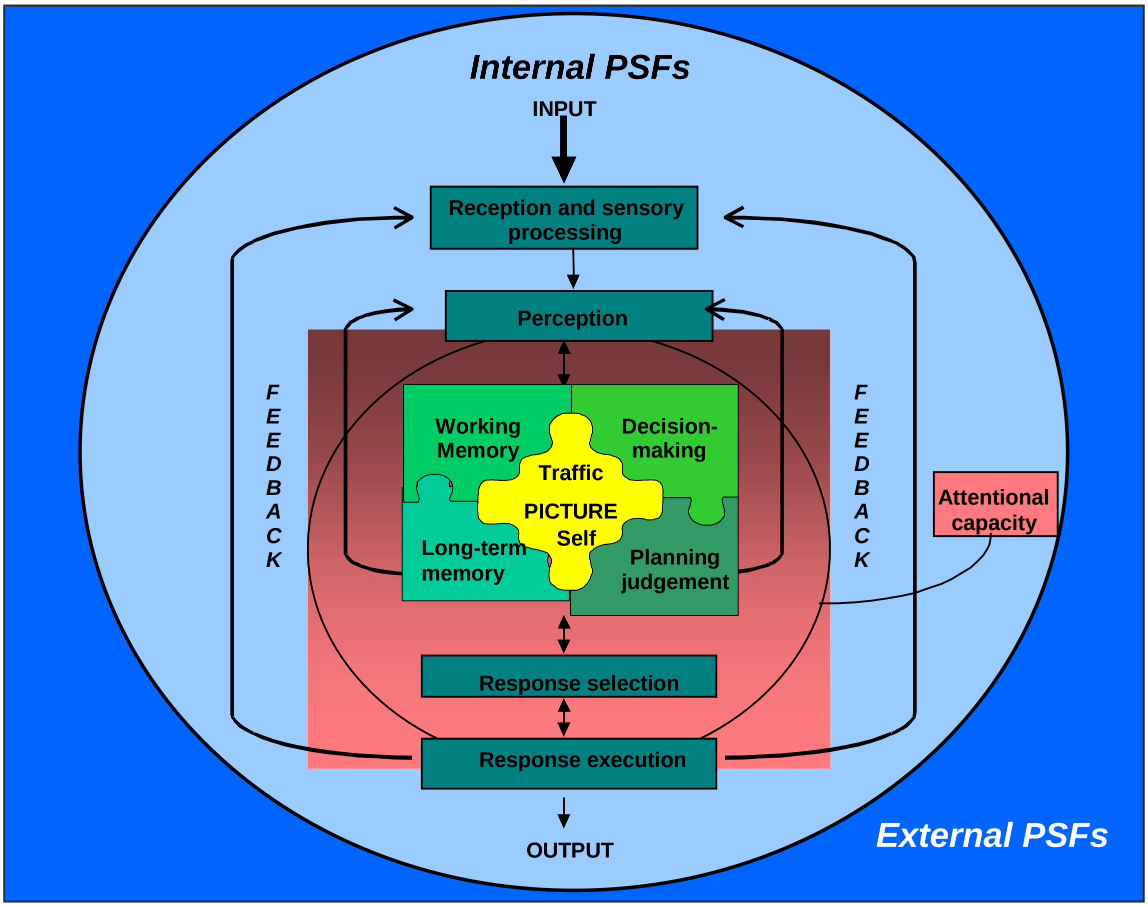

Figure 32: An enhanced model of information processing

4.4 External Error Modes, Internal Error Modes and Psychological Error Mechanisms

HERA will adopt an internal structure of:

- External Error Modes (EEMs) - The external manifestation of the error (e.g. omission).
- Internal Error Modes (IEMs) - The internal manifestation of the error within each cognitive domain (e.g. late detection).
- Psychological Error Mechanisms (PEMs) - The internal mechanism of the error within each cognitive domain (e.g. perceptual tunnelling).

This internal structure allows the analyst or incident investigator to classify errors at three levels of detail. There will always be sufficient information to classify the EEM, and usually there will be enough information to classify the IEM. PEMs add value to the analysis, but are the most difficult 'level' to classify, because there is often insufficient information to determine the PEM.

4.5 Performance Shaping Factors

A set of ATM Performance Shaping Factors (PSFs) will be included within the conceptual framework. Possible major groups of PSFs are shown in Figure 33.

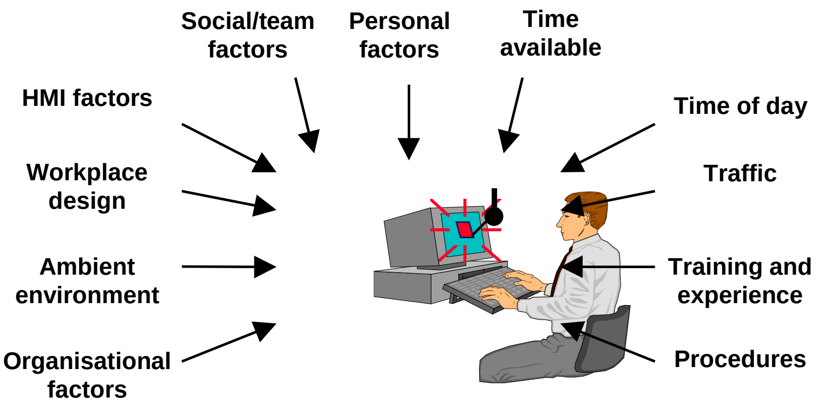

Figure 33: Possible major groups of Performance Shaping Factors (PSFs)

4.6 Contextual or Task-specific Factors

Contextual factors describe aspects of the task that the controller was performing at the time of the error. These aspects will include:

- Task - *What was the controller doing at the time of the error?,* e.g. handover, takeover, aircraft observation (tower only), coordination, communication, radar monitoring, relief briefing, strip marking, computer input.
- Equipment - *What equipment was the controller using* - e.g. radar display, strips, mouse, keyboard, switch panel.
- Information - *What information was the subject of the error?* - e.g. flight level, heading, speed.

Such contextual factors allow easier retrieval of information from a database of incident data. For instance, a search could be made using the task keyword ‘strip marking’ to derive a record of strip marking errors. Second, a search could be made using the equipment keyword ‘keyboard’ to find out what errors have been made using a keyboard. Third, a search could be made using the information keyword ‘heading’ to determine the types of errors made when making heading changes.

4.7 A Flowchart Format

A structured format is required to ensure the ease of use and reliability of HERA. Flowcharts have been used successfully with some previous systems, such as SHERPA and SRK’s PEMs. Flowcharts can increase the consistency with which the technique is used by leading different analysts with the same information to the same error classification.

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5. CONCLUSIONS

This report has presented an extensive review of the relevant models of human performance, human error theories and taxonomies, and conceptual frameworks from several diverse theoretical areas and industrial domains. The report described approaches to performance modelling and error analysis from several traditions, such as early taxonomies of error modes, communication models, information processing, symbolic processing, errors of commission and cognitive simulations. The review also described an ATM-specific error analysis technique called 'Technique for the Retrospective Analysis of Cognitive Errors in ATM (TRACEr).

The review finds that human information processing is the most appropriate model for an ATM error taxonomy. Furthermore, TRACEr has been selected as an appropriate ‘baseline’ for the developing technique called:

HERA - **H**uman **E**rror in **A**TM taxonomy.

However, the other approaches reviewed in this report will significantly influence the developing taxonomy. In particular, techniques such as SRK, SHERPA, GEMS and CREAM are likely to inform HERA.

When taken together, this combination of human error and performance modelling research, techniques and frameworks from other industrial domains, new developments, and ATM context lead to a new conceptual framework for error analysis in ATM. This framework includes:

- a model of human information processing,
- a set of EEMs, IEMs and PEMs,
- a set of PSFs,
- contextual factors such as classifications of task, equipment and information,
- a flowchart format to create a structured technique.

Work Package 2 (WP2) of this project will fully develop HERA based on the work reviewed in this report, and will refine and broaden the technique by applying it to a range of actual incident reports from several ECAC States. The resultant HERA technique will be presented in the second technical report as the main deliverable for WP2. The HERA system will then be validated in WP3, and if successful the work will then proceed to Phase 2, where its implementation across Europe will be encouraged and supported.

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ABBREVIATIONS AND ACRONYMS

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

ACSNI	Advisory Committee on the Safety of Nuclear Installations
AEOD	Office for the 'Analysis and Evaluation of Operational Data
AI	Artificial Intelligence
AIRPROX	Airproximity
ASRS	Aviation Safety Reporting System *(US)*
ATC	Air Traffic Control
ATCO	Air Traffic Control Officer / Air Traffic Controller *(UK/US)*
ATHEANA	A Technique for Human Error ANAlysis
ATM	Air Traffic Management
ATMDC	Air Traffic Management
BASI	Bureau of Air Safety Investigation *(Australia)*
CAA	Civil Aviation Authority/Administration
CAMEO-TAT	Cognitive Action Modelling of Erring Operator Task Analysis Tool
CENA	Centre d’Etudes de la Navigation Aérienne *(France)*
CES	Cognitive Environment Simulation
COCOM	COntextual COntrol Model
CORE-DATA	Computerised Operator Reliability and Error DATAbase
COSIMO	COgnitive SImulation MOdel
CPCs	Common Performance Conditions
CREAM	Cognitive Reliability Error Analysis Method

CREWSIM	CREWSIMulation
CRM	Crew Resource Management
DIS	Director(ate) Infrastructure, ATC Systems and Support *(EUROCONTROL Headquarters, SDE)*
DIS/HUM	See ‘HUM (Unit)’
EATCHIP	European Air Traffic Control Harmonisation and Integration Programme *(now EATMP*)
EATMP	European Air Traffic Management Programme *(formerly EATCHIP)*
ECAC	European Civil Aviation Conference
EEM	External Error Mode
ENCORE	En-Route COntroller’s REpresentation
EOCA	Error Of Commission Analysis
EWPD	EATCHIP/EATMP Work Programme Document
FAA	Federal Aviation Administration
FDPS	Flight Data Processing System
FMAQ	Flight Management Attitudes Questionnaire
GEMS	Generic Error-Modelling System
HEA	Human Error Analysis
HEI	Human Error Identification
HEP	Human Error Probabilities
HERA	Human ERror in ATM (Project)
HFRG	Human Factors in Reliability Group *(UK)*
HFSG	Human Factors Sub-Group *(EATCHIP/EATMP, HUM, HRT)*
HMI	Human-Machine Interface
HPES	Human Performance Evaluation System
HRA	Human Reliability Assessment
HRS	Human Resources Programme *(EATMP, HUM)*

HRT	Human Resources Team *(EATCHIP/EATMP, HUM)*
HSE	Health and Safety Executive *(UK)*
HSP	Human Factors Sub-Programme *(EATMP, HUM, HRS)*
HTA	Hierarchical Task Analysis
HUM	Human Resources (Domain) *(EATCHIP/EATMP)*
HUM (Unit)	Human Factors and Manpower Unit *(EUROCONTROL Headquarters, SDE, DIS; also known as 'DIS/HUM')*
IAEA	International Atomic Energy Agency
ICAO	International Civil Aviation Organization
IEM	Internal Error Mode
IMO	International Maritime Organisation
K-HPES	a Korean version Human Performance Enhancement System
LER	Licensee Event Report
LISP	LISt Processing
MAQ	Management Attitudes Questionnaire
MIDAS	Man-machine Integration Design and Analysis System
MOFL	MOdell der FluglotsenLeistungen
NASA	National Aeronautics and Space Administration *(US)*
NATS	National Air Traffic Services Ltd *(UK*)
NTSB	National Transport Safety Board *(US)*
NUCLARR	NUclear Computerised Library for Assessing Reactor Reliability
OCM	Optimal Control Model
PEM	Psychological Error Mechanism
PHECA	Potential Human Error Cause Analysis
PREDICT	Procedure to Review and Evaluate Dependency In Complex Technologies
PROCRU	Procedure-Oriented Crew Model

PSA	Probabilistic Safety Assessment
PSF	Performance Shaping Factor
QRA	Quantitative Risk Assessment
R/T *or* RT	RadioTelephone/y
REP	Report *(EATCHIP/EATMP)*
REQ	Requirement
RISØ	RISØ National Laboratory (Denmark)
SA	Situation Awareness
SDE	Senior Director, Principal EATMP Directorate *or, in short,* Senior Director(ate) EATMP *(EUROCONTROL Headquarters)*
SHELL	Software, Hardware, Environment and Liveware
SHERPA	Systematic Human Error Reduction and Prediction Approach
SMCR	Source, Message, Channel, Receiver
SMoC	Simple Model of Cognition
SOR	Stimulus-Organism-Response
SRK	Skill, Rule, Knowledge
STCA	Short-Term Conflict Alert
STSS	Short-Term Sensory Store
SYBORG	SYstem for the Behaviour of the OpeRating Group
TMI	Three-L-Mile Island
TRACEr	Technique for Retrospective Analysis of Cognitive Errors in ATM
USNRC	United States Nuclear Regulatory Commission
WP	Work Package *(EATCHIP/EATMP)*

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