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Short Report on Human Performance Models and Taxonomies of Human Error in ATM (HERA)

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CONTENTS

DOCUMENT CHARACTERISTICS	ii
DOCUMENT HANDLING	iii
DOCUMENT APPROVAL	iii
DOCUMENT CHANGE RECORD	iv
EXECUTIVE SUMMARY	1
1. INTRODUCTION.....	3
1.1 Human Error in Air Traffic Management.....	3
1.2 Overall Work Plan and Focus of this Report.....	5
1.3 The State-of-the-Art in Human Error Theory and Practice.....	6
1.4 The Need for a Scientific 'Model-based' Approach.....	7
1.5 Structure of the Report.....	8
2. APPROACH.....	11
2.1 Review of Literature	11
2.2 The Present and Future Air Traffic Management Context	20
3. DEVELOPMENT OF A HUMAN ERROR CONCEPTUAL FRAMEWORK.....	25
3.1 Requirements for an Air Traffic Management Human Error Taxonomy and Database	25
3.2 The Conceptual Framework.....	27
3.3 An Enhanced Model of Human Information Processing	28
3.4 External Error Modes, Internal Error Modes and Psychological Error Mechanisms.....	31
3.5 Performance Shaping Factors.....	32
3.6 Contextual or Task-specific Factors	32
3.7 A Flowchart Format.....	33
4. CONCLUSIONS.....	35

REFERENCES 37

ABBREVIATIONS AND ACRONYMS..... 45

CONTRIBUTORS 49

**APPENDIX: TECHNIQUE FOR THE RETROSPECTIVE ANALYSIS OF
COGNITIVE ERRORS..... 51**

EXECUTIVE SUMMARY

This short report accompanies the 'Technical Review of Human Performance Models and Taxonomies of Human Error in Air Traffic Management (HERA)' (EATMP, 2002a), which is the first of three reports dealing, within Phase 1 of the HERA Project, 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 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 of human error 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 abilities 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. The effects of these incidents has resulted in a large body of knowledge on issues such as the errors which 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 to the study of error and its management.

The first technical report (EATMP, 2002a), for which this document represents an extended management summary, reviews the theoretical and practical human error 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 is the subject of the second technical report (EATMP, 2002b) in this project, currently under preparation. The third report (EATMP, 2002c) will summarise the results of a thorough validation of the methodology, demonstrating its application in pan-European ATM incident analysis.

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1. INTRODUCTION

1.1 Human Error in Air Traffic Management

Human error is a major contributor to Air Traffic Management (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 in incidents (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 could be made tolerable to them, then 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 within the ATM 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, the 'at fault' individuals 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, similar events may be prevented. The analysis process is not concerned therefore with the attribution of blame, but rather the analysis of the error and its underlying factors. It is hoped that this will help our understanding of human performance and therefore give us the opportunity to recover and manage occurrences of human error in the future.

One potential engineering solution to the problem of human error is that of automation. However, paradoxically automation can often increase the importance and impact of human error (e.g. Bainbridge, 1987; 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, but it alone 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, which 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 points to the need for the development of an approach to better understand errors, and monitor error trends.

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, this means that most will be learned if all States use the same approach. If a methodology can be developed that can be applied to any European ATM situation, then the European ATM organisation as a whole, and each individual Member State, can maximise learning from all human error events and incidents. Therefore, the European ATM system should become safer and more effective.

1.2 Overall Work Plan and Focus of this Report

The work plan for Phase 1 of the project, the development of a methodology for analysing human errors in incidents in ATM, is divided into three Work Packages (WPs). Phase 2 is not yet fully defined, but will seek to encourage the implementation of the methodology in Europe. Phase 1 has three distinct WPs:

- (i) WP1: Development of a conceptual framework and model of human error in ATM, which will result in Deliverable 1 (see EATMP, 2002a and this additional short report).
- (ii) WP2: Development of a methodology based on WP1 for analysing errors and their causes in ATM incidents and will result in Deliverable 2 (see EATMP, 2002b).
- (iii) WP3: Validation of the methodology developed in WP2 and will result in Deliverable 3 (see EATMP, 2002c).

The 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 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 concerning error classifications from other industries .
- (iv) Models of ATM controller performance.
- (v) Consideration of current and future controller task and behaviour requirements.

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 the methodologies that 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' 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) 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 'naiveté' may not matter. ATM can however borrow from other industry knowledge and experience and from general psychological understanding that has evolved over the past three decades concerned with 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 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 and a better understanding of human errors, 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. One such database, known as CORE-DATA (Computerised Operator Reliability and Error Database - discussed 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 project within ATM.

Details of state-of-the-art human error theory and practice will be reviewed in depth in [Chapter 3](#) of this report and it would appear 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 with regard to human error and why, 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. However the question that should be addressed is why current approaches may not be suitable, and therefore why a new approach is necessary.

Firstly, it is hoped that the new system developed in this project will be seen as adding value to existing approaches. As noted above, concern regarding 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 many thousands of errors in many industries.

Secondly, 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 State Members 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.

Thirdly, 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 that 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 in ATM are introduced across Europe.

Models also need precise definition, so that practitioners can agree a common set of terms and meanings which is particularly important when learning 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 being developed for this project will be tested in the validation stage of the method's development.

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 summarises the overall approach taken in the development of WP1 and in particular summarises the review that was undertaken to support the development of a human error framework.

Chapter 3 develops the set of specific requirements for the framework, based on lessons learned from the review process. A set of generalised criteria for the development of an approach to the classification of human error in incidents, which is applicable to both Phases 1 and 2 of this work, is then described. Finally, a set of requirements that relate to the need for the taxonomy to capture the present and future context of ATM equipment and practices is discussed, and the resultant conceptual framework is then presented.

Chapter 4 presents a number of conclusions derived from WP1.

An Appendix, following the Reference Chapter, contains details of an existing system that satisfies many of the criteria discussed in the main body of the

report. It therefore gives a forward view or 'prototypical template' showing what the 'Human Error in ATM (HERA)' project, to be developed in WP2, might look like.

All Abbreviations & Acronyms used in this document as well as a list of the Contributors to this report can be found at annex.

The structure of the report is summarised in Figure 1.

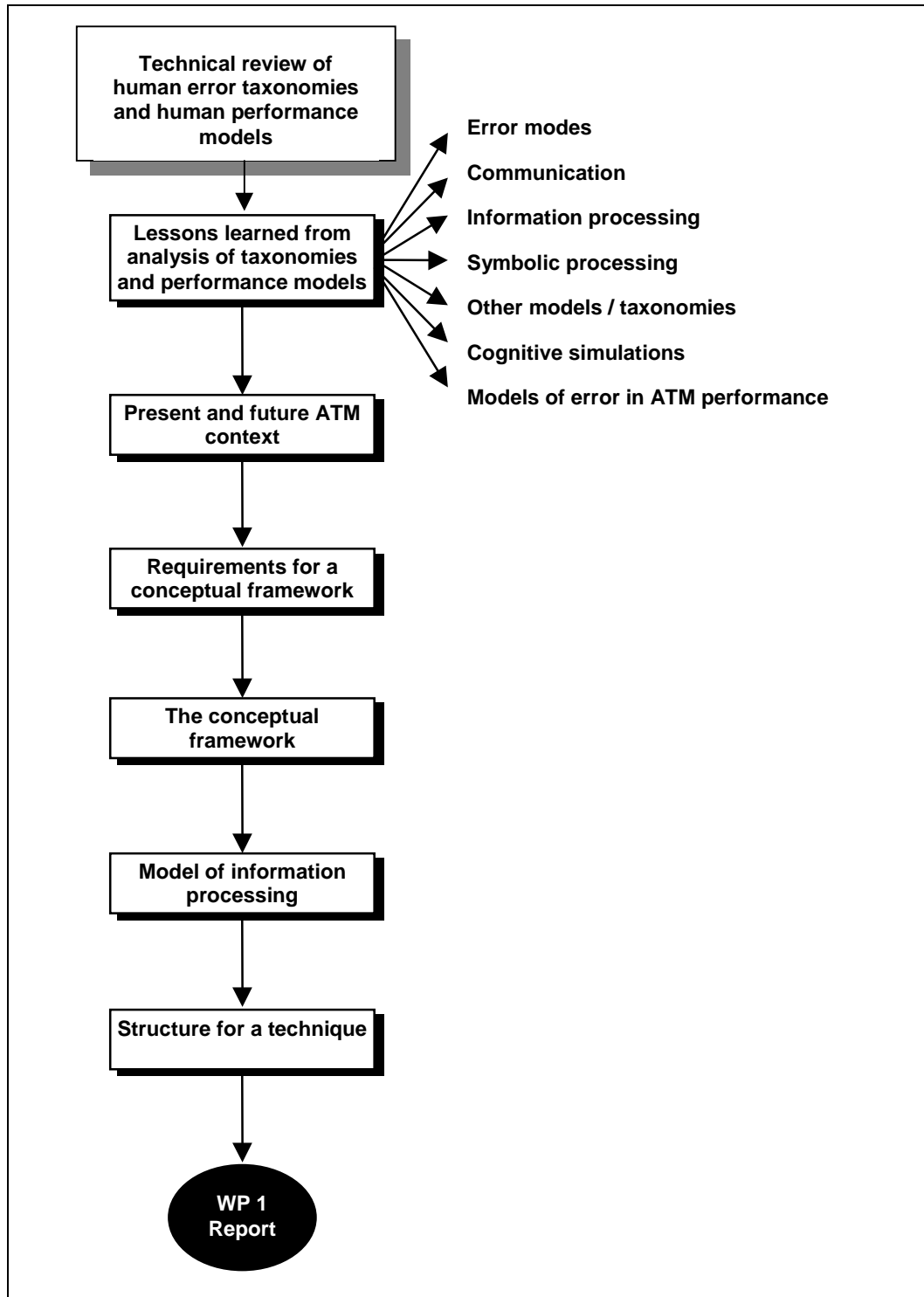


Figure 1: Overall structure of Work Package 1 (WP1) report

2. APPROACH

The approach taken in this Work Package (WP) is to undertake an extensive review of the important factors for creating a human error taxonomy and conceptual framework. Firstly, relevant models of human performance, human error theories and taxonomies and conceptual frameworks were identified and reviewed.

Each classification system, taxonomy, technique and model of human performance is reviewed in the 'Technical Report', and 'Lessons Learned' are summarised for each approach. These 'lessons' have assisted in the development of the conceptual framework for ATM, and will be further utilised to guide and inform the development of the resultant taxonomy in WP2.

A selection of other domain approaches was also explored, since a number of comparable projects were in existence from other industrial domains (e.g. nuclear power). Such experience can provide useful 'benchmarks' for this current ATM project.

The ATM context was also examined, both in terms of present and possible future developments, to provide an insight into what is required to ensure that the developing methodology remains useful and applicable to ATM incident investigators and analysts for some time to come.

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

The resulting conceptual framework will be called:

HERA - Human Error in ATM taxonomy.

2.1 Review of Literature

An extensive review of error taxonomies, models and classifications has been undertaken throughout a variety of literature and it has been established that sixteen areas of human performance and sixty-six approaches within these various areas should be considered within this project. A summary of all the approaches can be found below in [Table 1](#).

Table 1: Review of error taxonomies, models and classifications

Human Error Approaches	Representative Taxonomies, Models and Classifications	Implications for HERA
<p>1. Task-based taxonomies – These classification systems state what happened, e.g. error of omission, fail to detect conflicting aircraft, etc. Such taxonomies can be generic or contextual. They represent useful prompts for an incident analyst.</p>	<p>⇒ Error Modes (Swain, 1982; Swain & Guttman, 1983)</p>	<p>Error mode taxonomies, which state what happened are necessary but not sufficient. This is because they do not give enough causal information on why the incident happened, or how it happened. Ultimately such approaches are necessary, and so HERA must have an ‘External Error Mode’ (EEM) taxonomy within its structure, but EEMs do not go deep enough to render a useful understanding of the human contribution to the incident.</p>
<p>2. System-oriented taxonomies – These taxonomies also determine what went wrong, but are more system-oriented than pure human-oriented approaches (as in (1) above). Errors are considered that can affect the plant during maintenance, prior to an event, during it, those making it worse, and the recovery actions necessary.</p>	<p>⇒ Spurgin et al (1987)</p>	<p>Few single errors lead to significant incidents – more likely there is a concatenation, or a chain of errors and events. HERA must be able to capture the complete chain of events and facilitate a balanced appreciation of the causal contribution of each element in that chain. Also, Currently maintenance or latent errors do not play a significant role in current ATM human errors, but as next generation systems are brought in which are more heavily reliant on software systems, maintenance and latent errors are more likely to play a part in incident causation.</p>

Table 1: Review of error taxonomies, models and classifications (continued)

Human Error Approaches	Representative Taxonomies, Models and Classifications	Implications for HERA
<p>3. Communication system models – A range of models and taxonomies exist on communications, dealing with aspects of the message, the medium and the expectations of the sender and the receiver. It should be noted that communication models and theories do not always sit easily within other larger frameworks such as information processing.</p>	<ul style="list-style-type: none"> ⇒ Lasswell Formula (Lasswell, 1948; Braddock, 1958) ⇒ Linear Model (Shannon & Weaver, 1949) ⇒ Grayson & Billings (1981) ⇒ Cushing (1994/5) ⇒ Helmreich & Merritt (1998) ⇒ Westrum (1995) 	<p>Communication is obviously central to ATM and therefore HERA must be able to focus on this aspect of the task, whether today's task using Radiotelephony (R/T) or the future tasks where there will be more reliance on datalink technology.</p>
<p>4. Information processing models – The information processing tradition has been the dominant model of human performance in psychology and Human Factors for some time, and is perhaps the most useful model for industrial applications. As can be seen from Column 2, the approach has developed over a large number of years. Central to the model is information input to the human, which is perceived, filtered and processed, with 'thought' (e.g. memory, judgement and decision-making) occurring inside the human via memory and other cognitive functions, and then external actions (e.g. physical actions and communications) are the result.</p>	<ul style="list-style-type: none"> ⇒ Fitts (1954) ⇒ Miller (1956) ⇒ Broadbent (1958) ⇒ Welford (1960) ⇒ Payne & Altman (1962) ⇒ Berliner et al (1964) ⇒ Martiniuk (1976) ⇒ Wickens (1984, 1992) ⇒ McCoy & Funk (1991) 	<p>Information processing has proven one of the more useful psychological models of performance to various industries. Its basic emphasis on input, thought, output and feedback is useful for explaining behaviour and also informative for more practical considerations such as designing new displays, etc. For some years the Wickens' version of information processing has become the most accepted version, so that it may provide a good platform upon which to base HERA, if suitably adapted to ATM. The individual components of the information processing model (e.g. working memory) could be used to structure understanding of how errors occur in the human, leading to ways of reducing error potential or increasing recovery potential.</p>

Table 1: Review of error taxonomies, models and classifications (continued)

Human Error Approaches	Representative Taxonomies, Models and Classifications	Implications for HERA
<p>5. Symbolic processing models – This is a rival to the information processing tradition, and considers humans as symbol manipulators. This approach is more ‘cognitive’ in its orientation, and considers the human as having reference ‘mental models’ of the world and how things work, and hence how to perform. This approach has some intuitive appeal in that many controllers do indeed talk of having a ‘mental picture’ which is vital in their moment-to-moment control of the traffic. Symbolic processing theory also underpins the cognitive simulation models described later.</p>	<ul style="list-style-type: none"> ⇒ Newell & Simon (1972) ⇒ Schmidt (1975) ⇒ SRK Model (Rasmussen, 1981) ⇒ Murphy Diagrams (Pew et al, 1982) ⇒ SHERPA (Embrey, 1986) ⇒ Slips, Lapses, Mistakes and Violations (Reason, 1990) ⇒ GEMS (Reason, 1990) ⇒ Action Slips (Norman, 1981) ⇒ Seven-stage Model (Norman, 1986) ⇒ CREAM (Hollnagel, 1993) ⇒ SMoC (Hollnagel, 1993) ⇒ COCOM (Hollnagel, 1993) 	<p>Symbolic processing models have helped several industries ‘unpack’ how errors occur, particularly within the more cognitive aspects of performance, for instance associated with errors such as poor decision-making and misdiagnosis. In particular this theoretic tradition has led to the definition of a set of taxonomies that together explain error: external error modes (what happened?); internal error mechanisms (in which cognitive functional area did the error occur?); psychological error mechanisms (how did the error occur, i.e. in which stage of processing?); and performance shaping factors (what factors caused and contributed to the error?). The symbolic processing models (especially those by Rasmussen et al) have therefore laid the foundation for a set of structured taxonomies, and indeed have informed other industry taxonomic approaches (see CORE-DATA, below). Also, on a practical level, certain techniques (e.g. SHERPA) have shown the utility of having a flowchart-based tool for analysing errors and incidents. Such a tool tends to increase inter-analyst reliability, and general usability of the approach.</p>
<p>6. Situation Awareness (SA) approach – This approach has been influential in aviation systems, particularly military aviation. The approach states that the operator (pilot or controller) needs to have SA to perform their tasks</p>	<ul style="list-style-type: none"> ⇒ Jones & Endsley (1996) 	<p>SA can be seen as either a process (i.e. how is situation awareness maintained?) or a product (what is the controller’s current situation awareness or picture?). This ambiguity of the approach has led to some difficulty in assigning its role in supporting ATM system development, especially since the</p>

Table 1: Review of error taxonomies, models and classifications (continued)

Human Error Approaches	Representative Taxonomies, Models and Classifications	Implications for HERA
effectively. SA comprises three levels: awareness of key elements in the situation; comprehension and integration of those elements to form a coherent understanding (picture) of what is going on and extrapolation of this understanding to the future to allow planning and strategic/tactical decision-making and action. This approach has obvious synergy with ATM and concepts such as 'the picture' of the Air Traffic Controller (ATCO).		product interpretation becomes synonymous with the 'picture' concept already accepted in Europe. What is clear, however, is that some errors do occur which can be neatly explained or categorised by SA approaches. HERA must therefore be able to account for such failures. What HERA may focus on more intensely, however, is how and why such failures occur, and hence how to prevent them or recover from them.
7. Control system models – This set of models uses control theory concepts to describe performance. This set of models is most useful for defining closed-loop continuous performance.	⇒ OCM (Baron & Levinson, 1980) ⇒ PROCRU (Baron, 1984)	These models are of less relevance to ATM performance, which is very open-loop in nature.
8. Perceptually-centred models – This is a special variant of (7) above, as it is a hybrid between control theory and symbolic processing theory.	⇒ Human Control Behaviour (McRuer et al, 1980)	Mainly of academic interest, it is still essentially a closed loop system and therefore has little impact on the HERA approach.
9. Signal detection theory – This approach has grown largely out of the domains of inspection and vigilance. It is a well-proven model in these domains, focusing on the human as a detector of a signal against a background of 'noise'. The human can	⇒ Bisseret (1981)	This approach has partial relevance to ATM, since the controller must detect signals from a relatively noisy background (e.g. the radar screen) and must remain vigilant. ATM systems also now have alarms (e.g. Short-Term Conflict Alert (STCA)) of which a proportion will be false alarms. Whilst the approach has partial relevance, it is too narrow to be used as

Table 1: Review of error taxonomies, models and classifications (continued)

Human Error Approaches	Representative Taxonomies, Models and Classifications	Implications for HERA
also be subject to false alarms, and the rejection of actual signals because they are believed to be false alarms.		a conceptual model or framework for describing all ATM performance. Therefore, rather than informing the HERA model, it is more likely to inform certain elements within the resultant error taxonomies, e.g. instances associated with false alarms of conflict detection tools, etc.
10. Error of commission models – These approaches are trying to address the growing problem of unusual and (usually) unintended acts that have been the cause of a number of incidents in other industries. They also relate to complex and unforeseen interactions in highly complex and otherwise well-defended technological systems.	⇒ PHECA (Whalley, 1988) ⇒ PREDICT (Williams & Munley, 1992) ⇒ EOCA (Kirwan et al, 1994, 1996) ⇒ ATHEANA (Cooper et al, 1996)	Errors of commission may not be a problem in ATM at this stage, but may become more important as ATM system complexity and system inter-dependencies increases with advancing technology and controller support. HERA should therefore ensure that commission error modes and causes are within its relevant taxonomies.
11. Violation taxonomy – Violations are where the operator knowingly contravenes a rule, either because it may be necessary or expeditious to do so, or for other reasons. Violations have caused a number of incidents in other industries. Recently a multi-industry forum produced a violation taxonomy.	⇒ Mason (1997)	Whether or not violations are currently a problem in ATM, since they have been found to occur in most other industries, is not known, but it is wise to ensure that HERA can at least account for them in its taxonomies.
12. Cognitive simulations – These are computerised systems usually based on symbolic processing theory models	⇒ CES (Woods et al, 1990) ⇒ COSIMO (Cacciabue et al,	These models are of interest generally since they take a model to its logical extreme and actually enable the model to become predictive as well as

Table 1: Review of error taxonomies, models and classifications (continued)

Human Error Approaches	Representative Taxonomies, Models and Classifications	Implications for HERA
<p>that mimic human cognitive performance, e.g. monitoring and decision-making in complex environments. For example, MOFL simulates controller performance for a number of en-route- based scenarios (most of the others except MIDAS) are related to the nuclear power domain..</p>	<p>1992) ⇒ CREWSIM (Dang et al, 1993) ⇒ CAMEO-TAT (Fujita et al, 1994) ⇒ SYBORG (Sasou et al, 1996) ⇒ MOFL (Neissen et al 1997; Neissen & Eyferth, 1999) ⇒ MIDAS (Corker & Smith, 1993; Pisanich et al, 1997)</p>	<p>descriptive, possibly even simulating performance in real time. However, they are not generally useful for error analysis at this stage and so will have little impact on HERA in the short term. Nevertheless, the 'architecture' underpinning the models is of interest to the conceptual framework, since some of the models use an information processing framework, and one (MOFL) utilises a dynamic representation of the 'picture' and considers levels of awareness. HERA can therefore consider whether to incorporate such features into its conceptual model and resultant taxonomies.</p>
<p>13. Contemporary accident theory – Recent work in aviation and other domains has been focused on the nature of accidents, and in particular their multi-causality. The main implication is that there is no single 'magic bullet' solution for most accidents, and the antecedents of full-scale accidents are most often deeply rooted in the organisational structure, safety systems and safety culture. Systems such as TRIPOD and BASIS are systems that aim to take information from specific incidents and determine the deeper organisational 'health' problems. Arguably if these can</p>	<p>⇒ Reason (1998) ⇒ Maurino et al (1995) ⇒ TRIPOD (Wagenaar et al, 1994) ⇒ BASIS (O'Leary & Chappell, 1996)</p>	<p>The implications for HERA are complex, since safety culture is still a developing field without clear understanding. It is advisable that HERA should try to incorporate some 'deeper' organisational causes into its structure. However, this may occur in later phases of HERA, when the safety culture field itself can offer more practical guidance on what factors should be included, and how they would interplay with the rest of the HERA model.</p> <p>The degree to which HERA remains focused on determining specific causes rather than deeper factors is a Phase 2 issue, since to determine what the deeper causal factors were would require separate study. It may be that after HERA has been in operation for some time, and data arising has</p>

Table 1: Review of error taxonomies, models and classifications (continued)

Human Error Approaches	Representative Taxonomies, Models and Classifications	Implications for HERA
<p>be identified and rectified, then not only can the specific incident's recurrence be prevented, but other, as yet unseen potential incidents, can also be prevented.</p>		<p>been analysed across incidents and even across different ATM providers, then the deeper set of recurrent factors would become apparent.</p>
<p>14. Other domain approaches – A number of specialised taxonomies have been developed which have a similar or at least related mission to that of HERA. HPES and NUCLARR are both nuclear power related and CORE-DATA is multi-industry in its application.</p>	<p>⇒ HPES: Paradies & Busch (1988); Kim (1997)</p> <p>⇒ NUCLARR (Gertman et al, 1988)</p> <p>⇒ CORE-DATA (Taylor-Adams & Kirwan, 1995)</p>	<p>HPES has been fairly successful in its implementation and impact, and it is likely that Phase 2 of the work could learn useful lessons from HPES. CORE-DATA represents one of the main systems under development at the moment, and is also information-processing-based and utilises a set of interrelated taxonomies. HERA should therefore be able to learn from such an approach. In particular, CORE-DATA utilised an equipment taxonomy and a task or action taxonomy, and its causal factor listing was hierarchical (two levels), making it easier to use.</p>
<p>15. Other transportation approaches: Maritime and Flight crew models – Although most practical error insights and resultant techniques have been gained from the heavy industries such as nuclear power, chemical and offshore petrochemical industries, work has also occurred in other transportation areas, such as maritime, space, and aviation. The European Space Agency developed an initial approach to human error, and there</p>	<p>⇒ Drager, (1981) Analysis of Shipping Collisions and Groundings</p> <p>⇒ ARTFUL Decision-maker (O'Hare, 1992)</p> <p>⇒ Closed Ring Model (Pariès & de Courville, 1994)</p> <p>⇒ Error in Incident Sequence (Ramsey, 1985)</p> <p>⇒ Wiegmann & Shappell</p>	<p>Most of the work in these areas has been very focused on its own industrial context. ATM is to an extent however, a unique industry, since it has some properties which are similar to process control, and others which are more similar to dynamic transportation systems. It is unlikely therefore that models from these other transportation areas would directly fit the needs of an ATM model. Nevertheless, HERA should review such work to see if there are any general lessons, model features, or taxonomic elements that should</p>

Table 1: Review of error taxonomies, models and classifications (continued)

Human Error Approaches	Representative Taxonomies, Models and Classifications	Implications for HERA
has been significant analysis of shipping casualties over the years. Also flight models and taxonomies, usually contextual in nature, have been forthcoming.	(1997)	be incorporated into HERA.
<p>16. Air traffic management models – Only two models of human error were identified which were specifically focused on the ATM domain. The first was a model of incident causation, following on from workers such as Reason (1998). This model presents a useful framework for considering how incidents happen and the interrelationship between different levels of causes. The other model is a specific taxonomic set designed to analyse the error contribution to UK-based ATM incidents. This technique followed in the footsteps of systems such as CORE-DATA and SHERPA, and is based around an information processing framework. It has already been applied to the analysis of incidents in ATM.</p>	<p>⇒ Triptych Pyramid Model (Isaac, 1995; Isaac & Ruitenbergh, 1999)</p> <p>⇒ TRACER (Shorrock, 1997; Shorrock & Kirwan, 1998)</p>	<p>The Pyramid Model usefully relates some of the contemporary accident theory specifically to ATM, including the role of latent errors and organisational culture issues. The TRACER Model is information-processing-based, has several taxonomies of errors derived from human error theory and tested in the UK ATM environment, and therefore certainly represents a model and taxonomy worth considering as a detailed platform for the development of HERA.</p>

2.2 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 (Taylor-Adams & Kirwan, 1995) reviewed in [Table 1](#) 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 datalink, 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 the following three aspects of the error/event/incident must be systematically recorded:

- What the controller was trying to do (the **ATM function**);
- How the controller 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, then the resulting error database will be far more useful to those concerned with determining error trends and patterns, and on 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.

2.2.1 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.

2.2.2 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' 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.

2.2.3 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 bay, 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 radiotelephone;
- headsets,
- etc.

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

2.2.4 Implications for Human Error in Future Air Traffic Management Systems

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 example, 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, 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 External Error Modes (EEMs), Psychological Error Mechanisms (PEMs) and the Performance Shaping Factors (PSFs). 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.

More generally, 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;
- 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 when a new technology is brought in gradually or in stages. An example would be datalink, since some aircraft will have datalink capabilities before others. The controller may then have two additional tasks: determining which aircraft have datalink and which do not, then selecting the appropriate medium for communication. Although this sounds trivial it 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 only see just one innovation at a time becoming operational; there may also be several implementations happening at the same time, e.g. datalink together with certain tools, and the elimination of paper or even electronic strips could occur at the same 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 working during the transition period will have a challenging time, with significant impact on their cognitive resources (e.g. on working and long-term memory). 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.

3. 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 WP2. The emphasis of this chapter is therefore twofold. First, a set of requirements for the operational taxonomy are presented, which will become the guiding principles for the taxonomy in terms of its performance, validity and utility, and some of these requirements will actually become measures that will test HERA during the third WP, 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; 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 overall requirements for the taxonomy to make it **useful** in error analysis and reduction in ATM;
- the best model to make it **relevant** to the ATM context;
- the best practical dimensions and format to make it **usable** by relevant ATM personnel.

3.1 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 were cross-referenced to the lessons learned (i.e. sub-section 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 (see [Table 2](#)). However, these requirements are secondary in nature compared to the main objective, which is the development of the HERA taxonomy itself.

Table 2: HERA requirements

REQ 1: Usable by specialists other than Human Factors specialists	The taxonomy should be usable, after an introduction of a few hours, by experienced ATC operators and the type of staff who customarily classify incidents. It is expressly not intended that the users of the taxonomy have a professional background in human factors or psychology.
REQ 2: Robustness	The taxonomy, in combination with its user guidelines, should produce reports with little variation - so, the same case ought to result in the same classification no matter where, when and by whom it is classified.
REQ 3: Comprehensiveness	The taxonomy should be comprehensive in the sense that it should be able to 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 principle error categories in order to provide insight (see REQ 4).
REQ 4: Insightful	In terms of practical error reduction strategies, the taxonomy should be capable of providing not only a breakdown of causes and factors (human errors, technical and organisational elements) but must also be able to aggregate similar error forms to determine trends and patterns in the data, leading to more prompt warning of errors, and/or better ways of defending against certain errors.
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.
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.

Table 2: HERA requirements (continued)

REQ 7: Consistent with approaches in other domains	The taxonomy should be consistent with classificatory 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.
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 authors anticipate that a comprehensive set of rules governing confidentiality, access of use and publicity will be elaborated after the first phase of the project.

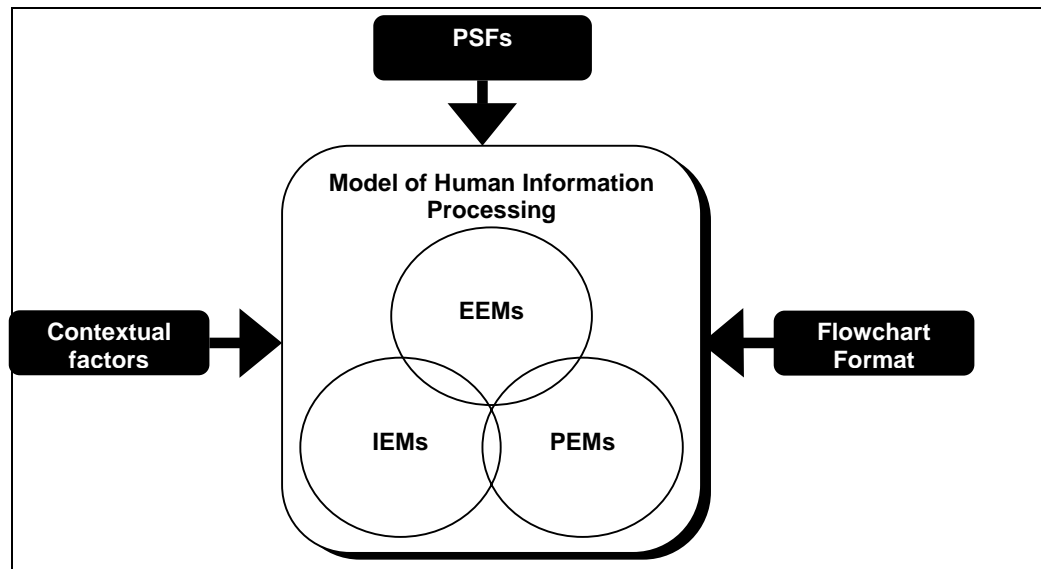
3.2 The Conceptual Framework

The literature review has derived the following several core components of a human error conceptual framework:

- **A human information processing model** - Appears to be the most relevant model of human performance for ATM, as it encompasses all relevant ATM behaviours and also allows a focus on certain ATM-specific aspects such as 'the picture' and situation awareness.
- **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)** - Additional factors relating to error causes which 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 because 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 2](#).



[Figure 2](#): Proposed conceptual framework of HERA

3.3

An Enhanced Model of Human Information Processing

The model of human information processing provides a good underlying model around which to base a human error classification system. Wickens' influential model of information processing (1992) appears to be the most suitable model, if suitably adapted to make the model more applicable to ATM. Wickens' model comprises a number of information processing stages and functions. These stages and functions, along with the adaptations to the model, are briefly described in the following paragraphs and illustrated in [Figure 3](#).

Reception and sensory processing

This stage involves the initial reception and sensory processing of external information (e.g. an R/T call from a pilot) and internal information (e.g. the 'feel' of a foot switch). In ATM visual and auditory sensory data are of primary importance. Information from each sensory modality can be retained for a very short period of time (less than eight seconds) and, without any attention, in a 'short-term sensory store'.

Perception

Sensory information is detected, then identified or recognised, based on an association with long-term memory – a large store of relatively permanent information. Thus, a controller may detect an aircraft ‘blip’ on the radar display, and then identify the aircraft by using other information, such as call sign. Example errors of perception include misidentifying an aircraft on a radar display or a paper flight progress strip, or failing to detect a pilot ‘readback error’, where a pilot fails to correctly read back a controller’s instruction.

Working memory

Working memory refers to the temporary encoding, storage and retrieval of verbal and spatial information. For example, working memory is used to retain the contents of a pilot’s transmission or a conversation with another controller, to perform mental arithmetic, or to remember to do something in the near future (called ‘prospective memory’).

In the enhanced model of human information processing used in HERA, working memory follows ‘sequentially’ from perception. This is a departure from Wickens (1992) model which 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 often automatic in the first instance. People may then decide how long to try to hold information in working memory for a specific time period, or decide to try to recall something at a specific time in the future. Working memory is thought to contain part of what is traditionally referred to as ‘the picture’, (i.e. the controller’s 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 and how situationally aware they feel. In the enhanced model this is termed ‘self-picture’.

Example errors of working memory include forgetting to transfer an aircraft to the next sector controller and forgetting the details of a coordination with another controller.

Picture update process

The ‘picture update process’ represents the flow of information used to update the controller’s ATM picture. Information from perception, long-term memory, judgement, and from 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. recalled procedures, previous briefings.
- Information from **judgement, planning and decision-making** - e.g. judgements regarding climbs, descents, and turns, decisions about whether to split a sector or act on a conflict alert.

Long-term memory

Long-term memory is a 'storehouse of facts about the world and how to do things' (Wickens, 1992, p. 211). This 'storehouse' includes information derived from training, procedures and briefings. An error of long-term memory may occur following a change in procedures, when a controller can incorrectly revert to the previous and well-learned procedure.

Mental model update process

The 'mental model update process' is the flow of information from working memory to long-term memory. The controller's mental model is updated by new information from working memory, judgement, planning and decision-making.

Judgement, planning, and decision-making and response selection

Wickens (1992) Model contains an information processing stage called 'decision and response selection'. This has been divided into two separate renamed processes as described below:

- 'judgement, planning and decision-making': these reflect more explicitly the processes of judgement, projection, prediction and planning used in ATM. 'judgement' here refers to judging the required heading, climb, descend or speed, etc., to achieve separation. A controller may, for example, misjudge a required climb. An example of an incorrect decision may be to ignore a conflict alert deliberately based on the assumption that it is a false alert.
- 'response selection': once the controller has made a decision a response is selected.

Response execution

Response execution involves the physical actions or speech that are used to effect a decision. Hence, errors of response execution include 'slips' such as writing or saying an unintended Flight Level.

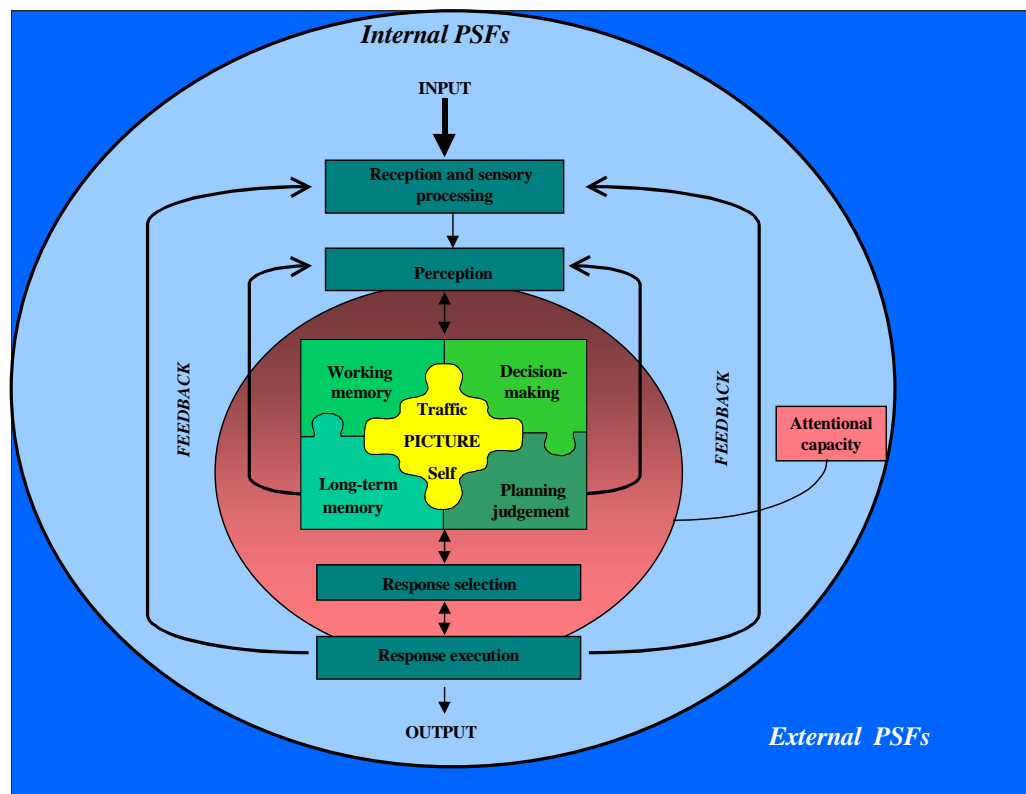


Figure 3: An enhanced model of information processing

Attention

Most of the processing that occurs following reception and sensory processing require attention to function efficiently. Attention is shown as the shaded area in Figure 3. Wickens (1992) describes attention both as a 'searchlight' that selects information sources to process and as a commodity of 'limited availability'. Learning and practice reduce the demand for attention resources.

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

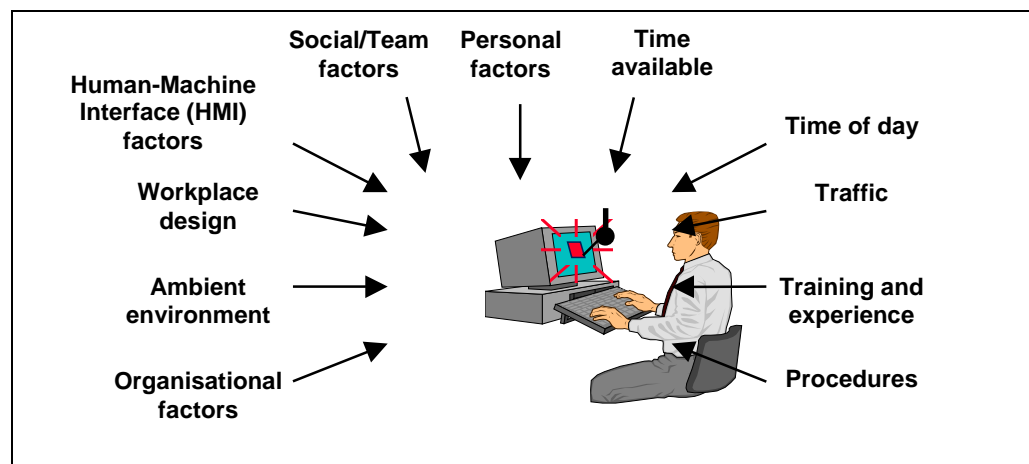
The Human Error in ATM (HERA) Project will adopt an internal structure consisting of:

- 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 incidence 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 even if there are the most difficult 'level' to classify because there is often insufficient information to determine the PEM.

3.5 Performance Shaping Factors

A set of ATM Performance Shaping Factors (PSFs) will be included within the conceptual framework. These are depicted either as external PSFs such as organisational factors, or as internal PSFs such as traffic or the ambient environment. Clearly, some of the factors have a two-level impact; for instance, **procedures** which, at an international level, would be recognised as an external PSF using aviation English but which, at a local level, could be regarded as an internal PSF using approved instructions at a military base. All possible major groups of PSFs are shown in [Figure 4](#).



[Figure 4](#): Possible major groups of Performance Shaping Factors (PSFs)

The above therefore represents the conceptual framework and can account for (albeit at a high level of description) the different human performance aspects seen in current and future ATM. Such a framework is then the basis for the actual technique that can be used to determine precisely what the human error contribution to an incident is and what the causes are. The next section describes in some detail the selected prototype for the future HERA system.

3.6 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 may 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;
- the equipment keyword 'keyboard' to find out what errors have been made using a keyboard;
- the information keyword 'heading' to determine the types of errors made when making heading changes.

3.7 A Flowchart Format

A structured format is required to ensure improvements in the ease of use and reliability of HERA. Flowcharts have been used successfully with some previous systems, such as SHERPA (the Systematic Human Error Reduction and Prediction Approach) and the SRK (Skill, Rule, Knowledge), PEMS. Flowcharts can increase the consistency with which the technique is used by leading different analysts with the same information to the same classification.

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4. CONCLUSIONS

This report has presented a short 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 - Human Error in ATM taxonomy.

However, the other approaches reviewed in this report will significantly influence the developing taxonomy. In particular, techniques such as SRK, SHERPA, GEMS (Generic Error Modelling System) and CREAM (Cognitive Reliability Error Analysis Method) 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 first describe TRACER more fully. Then it will detail the further development, refinement and broadening of TRACER to create HERA. The HERA technique will be presented and will then be validated in WP3.

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ABBREVIATIONS AND ACRONYMS

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

AIRPROX	Airproximity
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
BASIS	British Airways Safety Investigation System
CAA	Civil Aviation Authority/Administration
CAMEO-DATA	Cognitive Action Modelling of Erring Operator Task Analysis Tool
CENA	Centre d'Etudes de la Navigation Aérienne (<i>France</i>)
CES	Cognitive Environment Simulation
COCOM	COntextual COntrol Model
CORE-DATA	Computerised Operator Reliability and Error DATAbase
COSIMO	COgnitive SImulation MOdel
CREAM	Cognitive Reliability Error Analysis Method
CREWSIM	CREWSIMulation
DIS	Director(ate) Infrastructure, ATC Systems & Support (<i>EUROCONTROL Headquarters, SDE</i>)
DIS/HUM	See 'HUM (Unit)'
EATCHIP	European Air Traffic Control Harmonisation and Integration Programme (<i>now EATMP</i>)
EATMP	European Air Traffic Management Programme (<i>formerly EATCHIP</i>)
ECAC	European Civil Aviation Conference
EEM	External Error Mode

EOCA	Error of Commission Analysis
EWPD	EATCHIP/EATMP Work Programme Document
FAA	Federal Aviation Administration
FDPS	Flight Data Processing System
GEMS	Generic Error-Modelling System
HEA	Human Error Analysis
HEI	Human Error Identification
HERA	Human ERror in ATM (Project)
HFSG	Human Factors Sub-Group (<i>EATCHIP/EATMP, HUM, HRT</i>)
HMI	Human-Machine Interface
HPES	Human Performance Evaluation System
HRA	Human Reliability Assessment
HRS	Human Resources Programme (<i>EATMP, HUM</i>)
HRT	Human Resources Team (<i>EATCHIP/EATMP, HUM</i>)
HSP	Human Factors Sub-Programme (<i>EATMP, HUM, HRS</i>)
HTA	Hierarchical Task Analysis
HUM	Human Resources (Domain) (<i>EATCHIP/EATMP</i>)
HUM (Unit)	Human Factors and Manpower Unit (<i>EUROCONTROL Headquarters, SDE, DIS; also known as 'DIS/HUM'</i>)
IAEA	International Atomic Energy Agency
ICAO	International Civil Aviation Organization
IEM	Internal Error Mode
K-HPES	a Korean version Human Performance Enhancement System
MIDAS	Man-machine Integration Design and Analysis System
MOFL	MOdell der FluglotsenLeistungen
NASA	National Aeronautics and Space Administration (<i>US</i>)
NATS	National Air Traffic Services Ltd (<i>UK</i>)

NUCLAAR	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
REP	Report (<i>EATCHIP/EATMP</i>)
REQ	Requirement
RISØ	RISØ National Laboratory (Denmark)
R/T	Radio Telephone <i>or</i> Radio Telephony
SA	Situational Awareness
SDE	Senior Director, Principal EATMP Directorate <i>or, in short</i> , Senior Director(ate) EATMP (<i>EUROCONTROL Headquarters</i>)
SHERPA	Systematic Human Error Reduction and Prediction Approach
SMoC	Simple Model of Cognition
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-Mile Island
TRACEr	Technique for Retrospective Analysis of Cognitive Errors in ATM
USNRC	United States Nuclear Regulatory Commission
WP	Work Package (<i>EATCHIP/EATMP</i>)

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APPENDIX: TECHNIQUE FOR THE RETROSPECTIVE ANALYSIS OF COGNITIVE ERRORS

The Technique for the Retrospective Analysis of Cognitive Errors in ATM

The Technique for the Retrospective Analysis of Cognitive Errors in ATM (TRACER) (Shorrock, 1997; Shorrock and 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. 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' Model of Human Information Processing (1992) 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 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 are 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. intentions).

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 are split into further sub-domains within ATM. For instance, the cognitive domain 'perception and vigilance' is 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 (1982) 'Internal Human Malfunction' classification).

PEMs describe how the error occurs 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 occurs.

TRACER also includes a classification of major ATM sub-tasks (e.g. strip marking, radar monitoring) and a classification of ATM information elements, including aircraft, airspace and airport details. This identifies what is misjudged, forgotten, misperceived, etc. (e.g. call sign, Flight Level, heading and route), and thus provides context for the error. This provides 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 5](#).

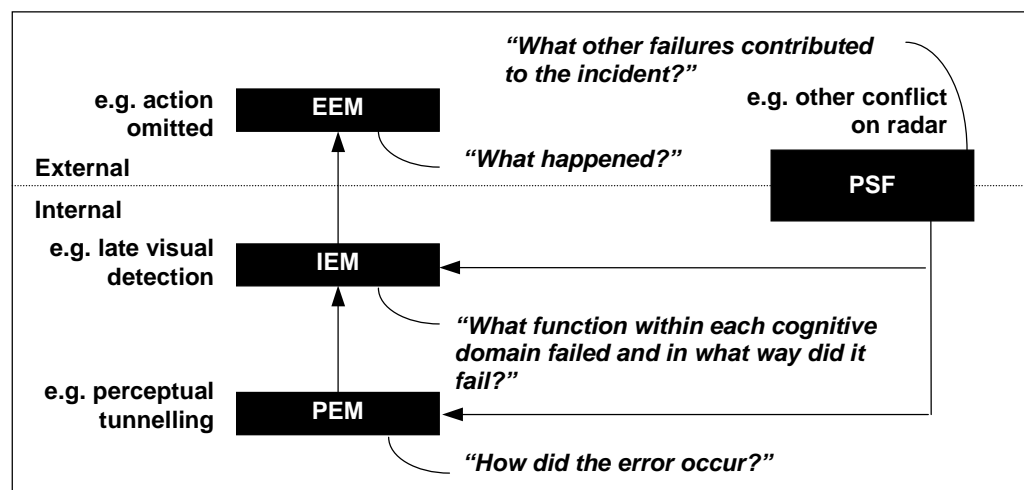


Figure 5: Relationship between TRACER classification systems

[Table 3](#) shows some example error types from the cognitive domain 'Perception and Vigilance'. [Table 4](#) shows the EEMs within TRACER.

Table 3: Example of IEMs and PEMs within TRACER

Internal Error Modes (IEMs)	Psychological Error Mechanisms (PEMs)
<ul style="list-style-type: none"> • No detection (auditory) • Late auditory recognition • Hearback error • Mishear • No detection (visual) • Late detection (visual) • No identification • Misidentification • Misread • Visual misperception 	<ul style="list-style-type: none"> • Expectation bias • Association bias • Spatial confusion • Perceptual confusion • Perceptual discrimination failure • Perceptual tunnelling • Out of sight bias • Stimulus overload • Vigilance failure • Visual search failure • Monitoring failure • Preoccupation

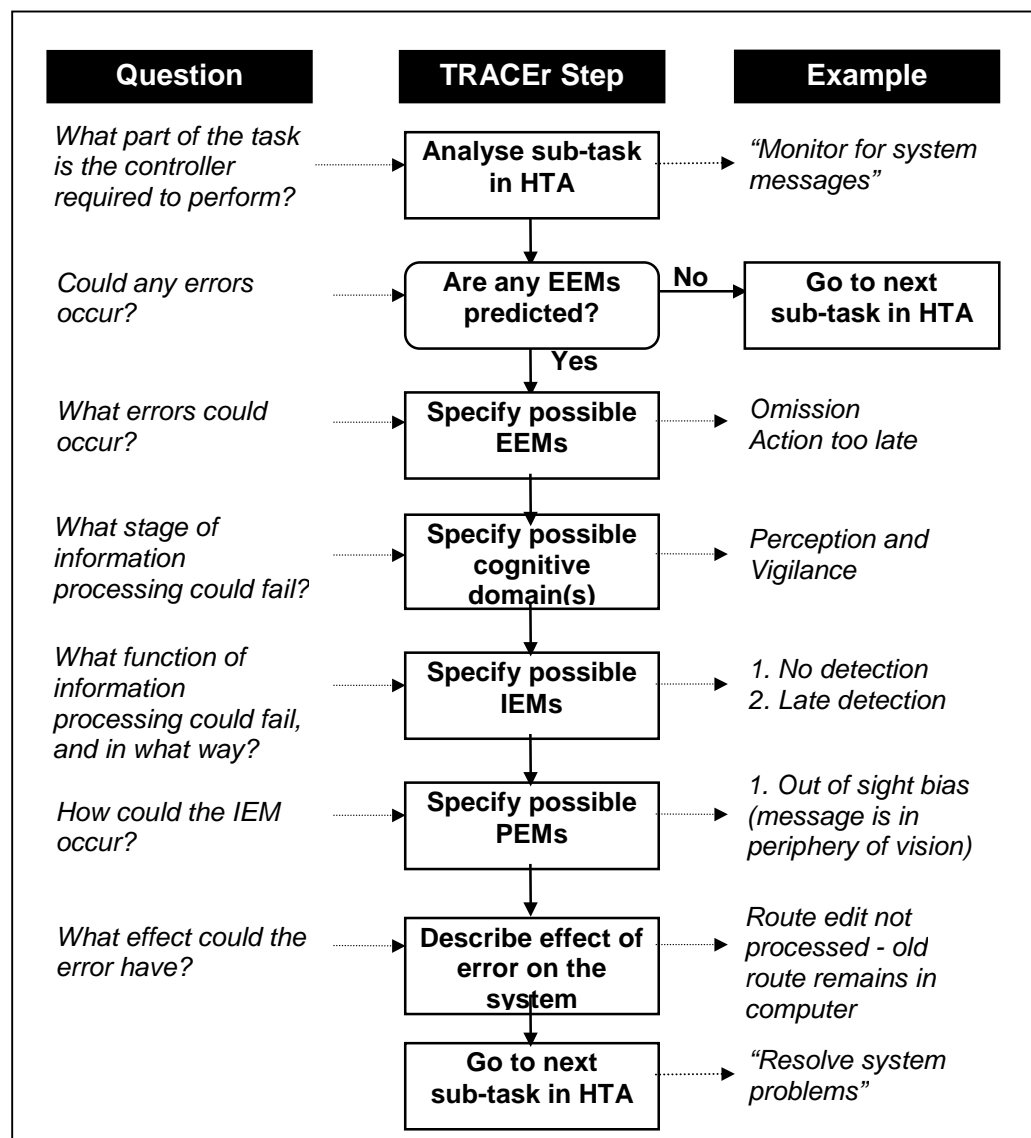
Table 4: EEMs within TRACER

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

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 6](#). The decision flow diagram for the cognitive domains is shown in [Figure 7](#). An example ATM incident and the associated TRACER classifications are shown in [Figure 8](#).



[Figure 6](#): Method for using TRACER

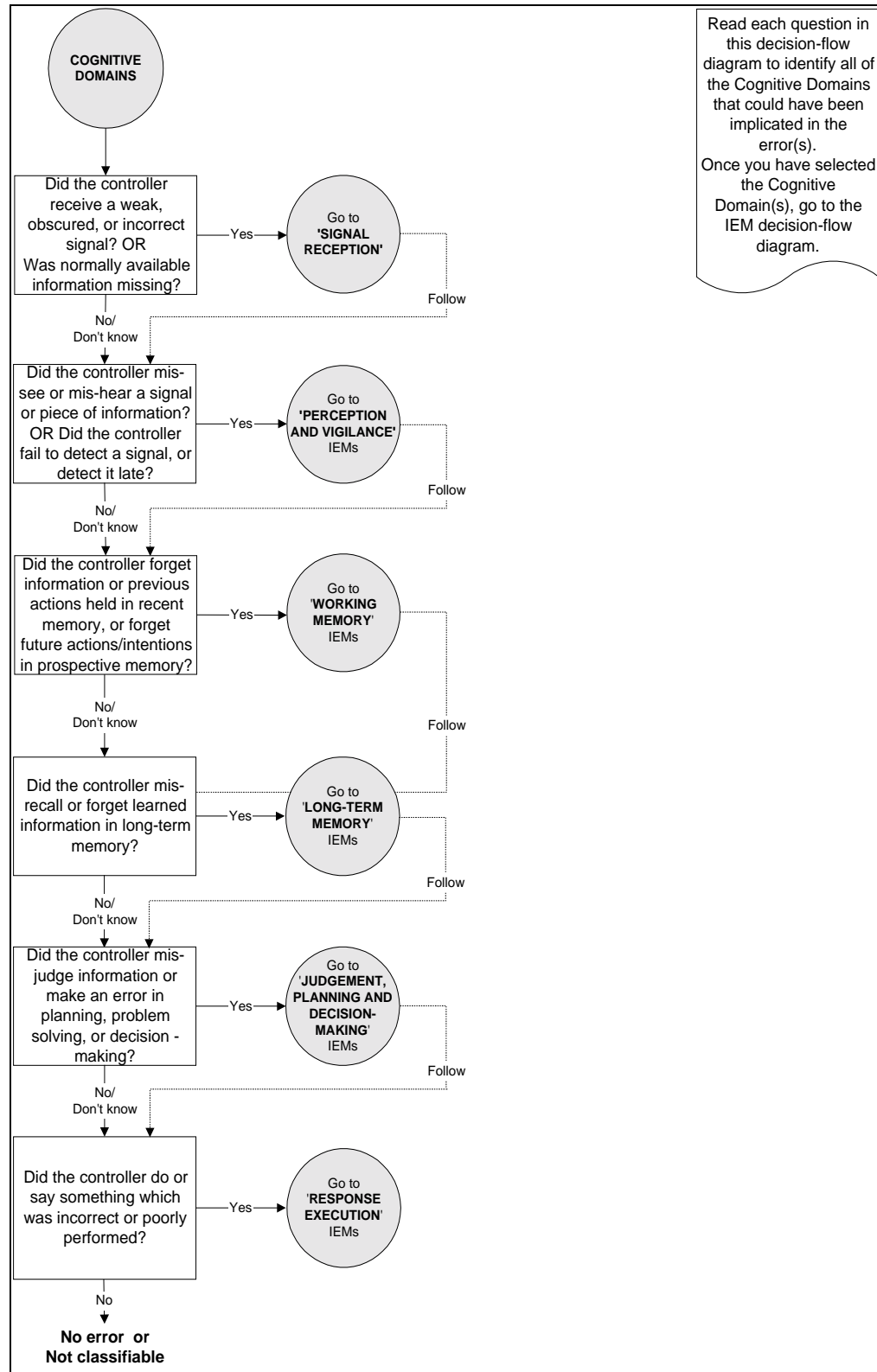


Figure 7: TRACER 'cognitive domains' decision flow diagram

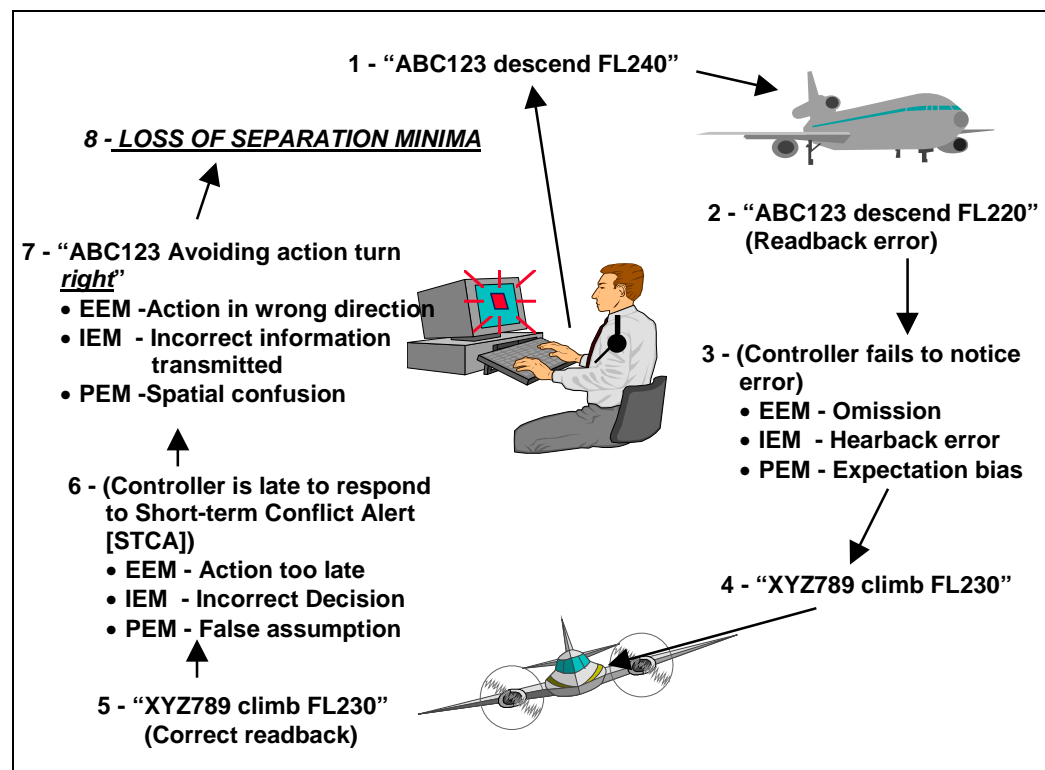


Figure 8: Pictorial description of an ATM incident and associated TRACER error classifications

The task of the 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 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 the reduction of 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 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 may 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.