ERROR MANAGEMENT TRAINING

Defining Best Practice

ATSB Aviation Safety Research Grant Scheme Project 2004/0050

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EXECUTIVE SUMMARY

Human error remains a significant causal factor in the majority of aviation incidents and accidents. In response to the ubiquity of human error, it has been suggested that a key to maintaining safety in high-risk industries lies in the development of specific error management training programs. However, we are still some way from defining best practice in error management training.

Error management training refers to the structured development of error management competencies through a formal process of training. A critical premise for error management training is that it should not form a separate element of a training curriculum, but rather elements of error management training should be integrated into ground, simulator and line training.

Due to the lack of a strong scientific foundation to the design and specification of error management training programs, a major research project was initiated in order to provide an empirical foundation for error management training programs in the commercial aviation setting. The primary objective of this research project was to provide the Australian aviation industry with a concrete curriculum package for error management training for flight crew.

A *curriculum* typically specifies the major aspects of training, including: 1) a specification of the core knowledge and skills that form the instructional objectives of training and the content of the syllabus; and 2) the instructional approaches adopted in the implementation of the training. This report provides an overview of both of these aspects of an error management training curriculum.

Core Knowledge and Skills

A critical introductory component of the error management curriculum is an understanding of human error. As a necessary developmental step in skill acquisition, building core knowledge is critical for the development of advanced competencies in many tasks. To this end, a comprehensive understanding of human error, and the processes that give rise to the effective management of error, provide a firm grounding for further error management training. Core knowledge identified through this research project includes:

The Nature of Human Error
- Error Genotype
- Error Phenotype

Error Generation
- Error Occurrence and Frequency
- Error Producing Conditions
- Areas of Vulnerability

Error Management Strategies
- Models of Error Management
- The Role of Technical and Non-Technical Skills

The development of tangible skill in the avoidance, detection and response to error must form the keystone of error management training programs in commercial aviation. The results of the two studies undertaken as part of this research project have reinforced the understanding that error management skill is frequently non-technical in nature. Accordingly, it is these non-technical abilities that must be integrated effectively into traditional airline training programs.

Using the findings from the research project, it has been possible to synthesise a number of skill dimensions that appear to be critical in the effective management of error. Core error management skill dimensions identified through this research project include:

Cognitive Skill Dimensions

- Information Management
- Planning and Mental Simulation
- Monitoring and Evaluation

Team and Interpersonal Skill Dimensions

- Communication
- Task Management

The error management skill dimensions that have been synthesised from the results of this project provide the curriculum framework for competency development. While a number of the skill dimensions identified through this project mirror current practice in relation to Crew Resource Management training, the research presented here has provided a number of insights into new cognitive skill dimensions. For instance, the emphasis on mental simulation, and more particularly the *metacognitive* aspects of error management strategies highlight significant new areas for error management training. In light of these findings, further research is required in the development and validation of specific competency specifications for the error management skill dimensions.

Classroom-Based Error Management Training

Traditionally, the classroom environment has provided the primary forum for training with respect to the non-technical aspects of flight crew performance. Crew Resource Management training has evolved within the commercial aviation environment predominantly in a classroom-based format, and with the continued evolution of a non-technical focus on performance, any new error-management training programs are often simply integrated within these existing programs. While the findings of the two studies involved in this research project have reinforced the need for a more "hands-on" format to error management training, the classroom environment does provide a forum for preliminary exploration of error management principles, and the development of core knowledge and attitudes. Critical aspects of classroom-based error management training were identified as:

- Introducing Core Knowledge and Skills
- Using Examples from Real Operations
- Providing Behavioural Models and Exemplars
- Promoting Personal Identification with Error Management Strategies

The classroom environment provides the opportunity for specific knowledge development, and accordingly lays the foundation for the development of appropriate attitudes towards the effective avoidance, detection and response to error. The two studies which underpin this research project have provided a number of insights into how the classroom environment might best contribute to the overall error management training curriculum.

Simulator-Based Error Management Training

While the classroom environment of traditional Crew Resource Management training provides a forum for the development of core knowledge, the process of skill development and maintenance demands more experiential forms of learning. The results of this project have highlighted that error management training cannot be seen just as a "classroom" activity. Rather, in order to explore and develop the wide range of competencies that underpin effective error management, specific experiential forms of training must be used. Critical aspects of simulator-based error management training were identified as:

- Bridging the Divide between Technical and Non-Technical Skills
- Identification of "Gotchas" and Key Error Management Strategies
- Exposure to Error Producing Conditions
- Guided Analysis of Error Events
- Emphasis of Cause and Effect
- Instructional Prompts for Effective Error Management

It is possible to conceive that error management training can be embedded within existing forms of cyclic simulator training without the need for additional time and resources. In other-words, it would be possible to design an Instrument Rating renewal simulator session that adopted an error management training focus. For instance, using an approach that seeks to train and assess the non-technical competencies of error management alongside the technical aspects of exercises, effective error management training can be achieved.

Summary and Conclusions

This project has sought to provide an initial scientific basis for error management training programs. However, this study does not profess to provide all the answers, nor does it profess to provide the *only* curriculum structure for error management. Rather, the report has sought to identify aspects of best-practice, and provide an exploration of the curriculum foundations of error management training.

The next steps in the development of error management training programs involve firstly the development of detailed competency specifications using the knowledge and skill dimensions provided in this initial curriculum framework. Secondly, these competency specifications need to be empirically validated through further research and development. Error management training is an extremely new development. Accordingly, considerable ongoing research and development is required in the evolution of this new approach to training towards safety management.

1 STUDY ONE: INTERVIEWS WITH EXPERTS

1.1 Study Overview

The first of the two studies that formed the overall research project sought to investigate the wide range of individual expertise with respect to the management of errors during normal flight operations, and the development of error management skill in the training environment (Thomas & Petrilli 2004).

The study adopted an interview-based approach to the investigation of the core components of effective error management, and error management training, within the commercial aviation environment. As an explicit objective of the study was to collect data with respect to the tacit knowledge of domain experts, the study was designed within an interpretive framework. Participants were volunteer pilots who each had significant instructional experience, and who were currently working, or had recently worked, in Training and Checking roles within the commercial airline environment. A total of 14 experienced aviators (instructors, check captains, and training captains) were recruited for the study.

1.2 Summary of Findings

The interview data provided a range of insights into the processes of Error Management employed by expert pilots. Error avoidance is the first stage in error management, and adopts the perspective that the minimisation of error is a critical first step in enhancing safety in normal operations. While it is accepted that the task of eliminating human error is an impossible goal, there are certainly a wide range of techniques that can be employed to avoid, and thus reduce the occurrence, of error. Fourteen components of error avoidance were identified from the analysis of interview data, which have been grouped under four broad categories:

Situation Awareness
- Attention, Vigilance and Comprehension
- Pre-action attention
- Self-Monitoring

Multi-Crew functions
- Monitoring other crewmember(s)
- Communication
- Teamwork and Support

Task Management
- Avoidance of Error Producing Conditions
- Active dependence on Standard Operating Procedures
- Planning and Preparation
- Gates
- Deliberate and Systematic Decision-Making
- Review and Evaluation

Attitudinal Factors
- Conservatism
- Diligence

Error detection mechanisms were found to share much in common with the strategies identified above for error avoidance, as effective error detection depends to a large degree on maintaining situation awareness. However, aside from a focus on situation awareness, the interview data suggests that effective error detection also includes a range of multi-crew coordination factors, as well as unique attitudinal factors. A total of nine components of error detection were identified, under three broad categories.

Situation Awareness
- Maintaining a Mental Model of the Flight
- Monitoring: Scan and Systematic Check
- Detecting Divergence
- Self-monitoring

Multi-Crew Functions
- Monitoring and Cross Checking of other crewmember(s)
- Familiarity with other crewmember(s)
- Communication

Attitudinal Factors
- Expectation of Error
- Comfort Levels and Intuition

Error response is the third phase of error management, and involves the rectification of the error, or the resolution of any problem-state caused by an error. Once the error has been detected, this process should present few problems for the crew who has regained situation awareness. The following discussion highlights areas in which error response can be managed in order to create efficiencies in the error management process and enhance the safety of normal flight operations. From the interview data, a total of nine components of error response were identified under four broad categories:

Situation Awareness
- Information Gathering and Problem Diagnosis
- Projection into the Future and Identification of Alternatives

Task Management
- The Maintenance of Safety
- Deliberate Decision-Making Process

Multi-Crew Functions
- Communication and Information Sharing
- Management of Error Response
- Workload Management

Attitudinal Factors
- Acceptance of Error
- Avoidance of Rumination

Error management training refers to the structured development of error management competencies through a formal process of training. A critical premise for error management training is that it should not form a separate element of a training curriculum, but rather elements of error management training should be integrated into ground, simulator and line training, as well as

inform aspects of ongoing development of expertise in already experienced pilots. Data from the interviews highlighted eight core components of error management training grouped under three broad categories.

Experiential Factors
- Exposure to Error Producing Conditions
- Exposure to Errors and Problem States
- Structured "Hands-On" Training in Error Management and Solutions

Attitudinal Factors
- Understanding Cause and Effect
- Development of Confidence
- Development of Self-Analysis Skills

Debriefing
- Choice of Error-Events to Debrief
- Focus of Error-Event Debrief

This study provided a detailed account of error management, through the analysis of experts' understanding of error avoidance, detection and resolution. From the results of this study, it is evident that elements of error management share much in common with our current understanding of Crew Resource Management (CRM). Aspects such as situation awareness, task management and communication are all common elements of CRM programs in modern airlines. However, this study provides specific new detail with respect to the actual cognitive processes of error management that we commonly group together under such categories as situation awareness. Moreover, the results of this study place significant emphasis on *metacognitive* processes that underlie the more evident cognitive, affective and interpersonal components of error management. The findings of this study reinforce a model of error management that emphasises the process of mismatch emergence as the driver of error detection, problem identification, and error resolution.

This study also provides a wide range of perspectives that in turn can inform a comprehensive curriculum structure for error management training. The study highlights three important new developments for error management training: 1) the need to focus more on cognitive skill development and the affective domain; 2) the need to integrate technical and non-technical skill development; and 3) the need to increase the experiential components of error management training.

2 STUDY TWO: SIMULATOR-BASED TRAINING

2.1 Study Overview

The second of the two studies that formed the overall research project sought to investigate the current approaches to error management training within the context of a commercial airline (Thomas 2005). As error management training is relatively new, it was acknowledged that no formal error management training would be embedded within the simulator-based training program of the airline involved in this study. However, it was anticipated that many tacit approaches to the development of error management skill would exist, and the expert instructors would engage in informal forms of error management training as part of their everyday instructional practices. Accordingly, the objective of this study was to scientifically observe and rigorously document these informal forms of error management training, and identify elements of best-practice that could in turn be used in the development of a scientifically defensible error management training curriculum.

The study adopted an observational design, and utilised trained expert observers for the observation and analysis of the training sessions. The structured performance evaluation methodology was based on the analysis of threat and error events utilised in the Line Operations Safety Audit (LOSA) methodology (ICAO 2002; Klinect 2002). Observers analysed all aspects of the training session, including the briefing, the training session in the simulator itself, and the post-simulator debriefing.

The simulator-based training syllabus of the airline involved in this study was structured around a biannual two-day program. This first day of the program involved a specific training focus, including a LOFT scenario followed by a series of instructional exercises. The second day of the program involved a Proficiency Check and Instrument Rating renewal where required. Each of the exercises contained within the simulator-based training syllabus can be interpreted as "threats" according to the definition within in the Threat and Error Management Model as situations or events that have the potential to impact negatively on the safety of a flight (Helmreich, Klinect & Wilhelm 1999). As with other high-quality airline simulator-based training, the individual threats contained within the program represent a mixture of infrequent, yet high-risk threats such as engine failure or severe windshear encounter, along with more common "everyday" threats such as minor systems malfunctions, in-flight diversions, and different forms of instrument approaches.

2.2 Summary of Findings

Instructional Aspects of Threat Occurrence and Management

As the threat events presented to crews in the simulator-based training environment are each designed as purposeful instructional exercises, the way in which threats are dealt with from an instructional perspective forms a crucial aspect of threat and error management training.

The results of the study highlighted the differing opportunities for instructional interaction with respect to threat and error management during simulator-based training. In relation to briefing, it was found that more comprehensive briefing of exercises occurred prior to simulator-sessions that involved high-jeopardy proficiency checks of crews, rather than prior to sessions that had a more explicit training focus. Conversely, more in-depth interaction between instructor and crews was observed during the simulator-sessions that had a more explicit training focus, than during those sessions that that involved high-jeopardy proficiency checks of crews. These intuitive findings reinforce the need to embed error management training within an appropriate syllabus context, and to promote opportunities for both detailed briefing, as well as interactive feedback and analysis of performance during the simulator-based training itself.

In relation to the informal threat and error management training processes undertaken by the expert instructors, it was found that more than one third of exercises included some discussion of *error prevention*. However, only 14.6% of exercises on day one, and only 4.5% of exercises on day two, included discussion of *general threat and error management* strategies. These findings suggest that the informal threat and error management training undertaken by experienced instructors focuses on error prevention, rather than the generic non-technical skills which underpin effective performance. It was frequently observed during the training sessions that instructors would brief and debrief with respect to the technical and procedural management of a particular exercise, and include little or no focus on non-technical skills or specific threat and error management strategies. Only on rare occasions were important aspects of crew performance such as monitoring and support calls, problem diagnosis, decision-making and situation awareness discussed.

Observers did highlight a small number of noteworthy briefing sessions where instructors focussed on error prevention strategies for particular exercises. This focus on error prevention frequently highlighted the “gotchas” of a particular exercise, which can be best described as the common traps or pitfalls where errors may more readily arise. The focus on error prevention was also evident with respect to the exercises which formed the focus of instructor’s debrief of crew performance. Indeed, exercises in which one or more errors occurred were debriefed significantly more frequently that those exercises in which no errors occurred.

Instructional Aspects of Error Occurrence and Management

While the occurrence of error is a natural element of even expert performance, the ongoing maintenance of safety relies on the effective management of error. Error management involves firstly the timely detection of an error, and secondly, the effective resolution or mitigation of the possible negative consequences of an error. The development of specific expertise in error management involves a concert of both technical and non-technical knowledge and skill. Accordingly, these crucial elements of error management must form a dual focus for error management training.

Of the 656 exercises analysed during the 40 simulator-based training sessions observed in this study, a total of 277 errors were observed and coded. These errors were found to result from only 30.9% of the instructional exercises,

indicating a relatively low overall rate of error production. The results of the study indicate that the instructor acknowledged the majority of errors committed by crews. In general terms, instructors discussed in detail 52.0% of errors in the simulator, and 50.2% of errors during the post-session debrief, with a total of 77.6% of all errors being debriefed. During day one of the program, instructors debriefed more errors in the simulator during the training session itself, which stands in contrast to day two of the program, where the instructors debriefed more errors in the post-session debrief. Again, this finding suggests that from the perspective of the development of specific skills in error management, the appropriate integration of error management training into the existing simulator-based training curriculum will be critical.

It was found that no significant relationship existed between whether an error was consequential, and the frequency with which the instructor debriefed the error after the training session. However, errors that led to undesired aircraft states were debriefed by the instructor in the simulator significantly more frequently than any errors that were inconsequential. This finding suggests that immediate feedback on a performance that had a potential safety consequence is an important naturalistic instructional process in error management training.

Reflecting the earlier findings that the instructor only infrequently discussed generic detection and management strategies, it was found that less than one in ten of errors led to discussion of strategies for timely error detection, or discussion in relation to generic threat and error management strategies. Much more frequent was the discussion of specific error prevention strategies. Observers again frequently noted that this discussion was dominated by technical, rather than non-technical, aspects such as aircraft configuration and performance.

Threat and Error Management in Training

The use of the Threat and Error Management model in the interpretation and analysis of simulator-based training offers a number of benefits. First, the construction of a simulator-based training syllabus with deliberate reference to the types of operational threats encountered by crews during their everyday line operations ensures that high levels of realism and training efficiency is achieved. Second, the deliberate inclusion of specific operational threats within the simulator-based training syllabus allows for systematic approaches to error management training in the simulator environment. Forewarned with a comprehensive inventory of potential errors that can result from a particular threat event, as well as the technical and non-technical skills which underpin effective performance, the instructor can tailor the training session to focus on the specific application of threat and error management strategies as they apply to defined operational contexts. The process of error management training can then focus on the transfer of general principles to concrete applications within a variety of operational contexts. Finally, exposure to rare, yet high-consequence threats such as engine failure, multiple system failure, severe windshear or traffic avoidance manoeuvres, can assist pilots in the management of events near the boundaries of the safety envelope.

Lessons for the Error Management Training Curriculum

Through the exploration of threat and error management during training, and the instructional approaches to dealing with threats and errors in the simulator-

based training environment, the results of this study have provided a number of useful insights that can in turn inform the development of a formal error management training curriculum.

Firstly, the results of this study have demonstrated where effective opportunities exist for error management training within the structure of a typical simulator-based training curriculum. The study has reinforced the need to position error management training within a context that allows for considerable interaction between instructor and crew, and the ability for crews to explore in some depth both the technical and non-technical aspects of performance. Instructional formats that enable the detailed analysis and debriefing of performance, along with potential for the rehearsal of concrete examples of the non-technical skills that drive effective threat and error management offer considerable advantages in the ongoing expansion of expertise.

One important focus for error management training, which was evident in the survey of current practice, involved a focus on the common traps or pitfalls where errors may more readily arise. The structured analysis of these "gotchas" represents a clear example from current practice of effective error management training. However, as discussed previously, this process could be formalised by an airline to provide instructors with a detailed framework for the analysis of crew performance and tools for the development of tangible skills in threat and error management.

It is therefore likely that one effective approach to error management training would be to provide instructors with systematic inventories of such gotchas, along with key examples of the concrete application of key non-technical skills as they apply to each specific exercise contained within the airlines simulator-based training program.

While this study has provided a number of insights from current practice, the results of this study have also emphasised a scarcity of generic threat and error management foci in current simulator-based training. A frequent commentary on the current use of high-fidelity simulation in the commercial aviation context criticises an almost singular focus on the development of technical skill in the operation of complex aircraft systems (Johnston 1997). Furthermore, a lack of integration of technical and non-technical skill development in current forms of simulator-based training presents a notable deficiency in the appropriate used of advanced technology in training (Hörmann 2001).

This study has demonstrated the need for considerable ongoing development in the effective content, structure and instructional processes involved in error management training within the context of commercial aviation.

3 CORE KNOWLEDGE AND SKILLS

The first component of curriculum development involves specification of core knowledge and skill dimensions. This process serves the dual function of identifying the fundamental objectives of a training program, as well as providing an outline of the syllabus content for a training program. With respect to error management training, a set of core knowledge and skill dimensions were able to be synthesised from the results of the two studies that formed the basis of this project.

3.1 Core Error Management Knowledge

Understanding The Nature of Human Error: "Know your Enemy"

A critical introductory component of the error management curriculum is an understanding of human error. As a necessary developmental step in skill acquisition, building core knowledge is critical for the development of advanced competencies in many tasks. To this end, a comprehensive understanding of human error, and the processes that give rise to the effective management of error, provide a firm grounding for further error management training.

One important aspect of error-related knowledge involves an understanding of *error genotype* – the underlying cognitive causes or "cognitive failure modes" involved in error generation. An understanding of error genotype assists trainees in developing skill in relation to error avoidance, and recognition of areas of personal vulnerability to error such that errors can be detected and managed in a timely manner. For instance, an understanding of our vulnerability to forget critical tasks if distracted at the time of an operational trigger can reinforce the need for systematic checks when a pilot recognises they have been distracted.

Furthermore, knowledge relating to *error phenotype* – the operational manifestation of error, is also critical in understanding and managing error. An understanding of error phenotype can assist trainees in the timely detection of error, particularly with respect to anticipating the occurrence of error as a result of specific operational events. For instance, the susceptibility to erroneously use a VOR in setting up NDB holds and approaches illustrates a common error phenotype. Similarly, an understanding of our vulnerability to slips in the transposition of multiple digit numbers reinforces the need for extra vigilance and the use of gross-error checks for safety-critical clearances or calculations.

A general understanding of error generation and causation can assist in the development of the appropriate attitudinal aspects of effective error management. Understanding the ubiquity of error, and the natural cognitive processes involved in error causation, can assist in the demystification of error. Accordingly, a detailed understanding of the mechanisms behind human error can debunk the common misconception that error is a form of aberrant behaviour or poor performance. As highlighted in Study One, appropriate attitudes towards error, such that error is accepted as a natural part of expert performance, and is to be anticipated and expected during normal flight operations form an important element of effective error management.

Accordingly, error management training should attempt, where possible, to assist in the development of appropriate attitudes towards error.

Error Producing Conditions

An understanding of typical error producing conditions is another critical introductory component of the error management curriculum. A detailed understanding of the types of factors that increase the probability of error generation enables crew to remain wary for the occurrence of error. Accordingly, a sound understanding of error producing conditions can assist in the processes of error avoidance and detection by "priming" pilots to the potential occurrence of error. In turn, this knowledge reinforces the need for effective vigilance, wariness, and disciplined monitoring and cross check strategies.

A range of error producing conditions has been identified throughout the literature, and considerable evidence exists as to the relative influence of various factors on error generation (Wreathall & Reason 1992). An indicative collection of common error producing conditions is as follows:

- Distraction
- Lack of attention
- Loss of Situation Awareness
- Poor Communication
- Stress
- High Workload
- Environmental Conditions
- Fatigue
- Organisational Expectation
- New or Unfamiliar Procedure

Several approaches to enhancing error management developed in recent times have also focussed on segments of flight in which the risk of error generation is increased. These segments have been identified as "areas of vulnerability" during a normal operation (Sumwalt, Thomas & Dismukes 2002). According to this approach, certain operational events and phases of flight place significant and competing workload demands on operators, which in turn act as error producing conditions.

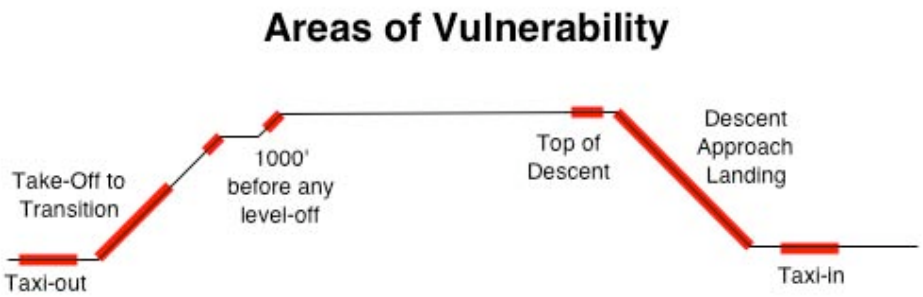

Figure One: Illustration of "Areas of Vulnerability" across a flight

By emphasising the phases of flight in which the risk of error occurrence is increased, as well as unpacking the relationships between error *genotype* and *phenotype* within the operational context, pilots are provided with essential knowledge to be used in the processes of error avoidance, detection and response.

Models of Error Management

An understanding of the processes involved in error management is also an important prerequisite to skill development and effective operational practice. In recent times, models of error management have been developed to provide tools for enhanced understanding and analysis of human error as manifested and managed in operational settings. (Helmreich 2002; Helmreich, Klinect & Wilhelm 1999).

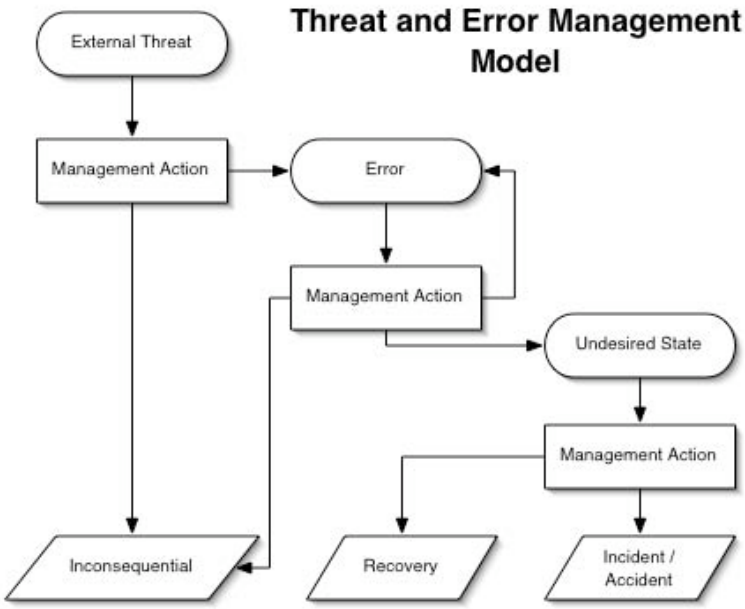

Figure Two: The University of Texas' Threat and Error Management Model

As illustrated in Figure Two, a generic model of error management provides a useful explanatory tool for highlighting the basic processes involved in the management of error. Such a model can be used alongside actual examples of incident and accident reports to highlight the basic components of error management in practice, and illustrate how deficiencies in effective error management can result in adverse outcomes.

The role of non-technical skill and generic strategies was emphasised in both the studies involved in this research project as critical in successful error management. Understanding the types of cognitive and interpersonal processes involved in error management forms another important element of core knowledge. The core knowledge in this area can build directly upon pilots' Human Factors knowledge as developed progressively through the PPL, CPL, and ATPL syllabi, and to this end, pilots are at a distinct advantage over many other high-risk professions as they already have a solid foundation in basic human performance and cognition.

As illustrated in Figure Three, the studies identified, and discussed in detail, a range of cognitive and interpersonal processes at play in effective error management. Together, these cognitive and interpersonal processes form the essential *non-technical skill* and generic *error-management strategies* that enable the effective detection and response to error. An understanding of how

cognitive skills such as situation awareness, vigilance and monitoring, self-regulation, and problem identification contribute to effective error-management, as well as poor performance, constitutes core knowledge for the error management curriculum. Similarly, an understanding of the role of *interpersonal skills* such as communication, negotiation, assertiveness and task management is critical.

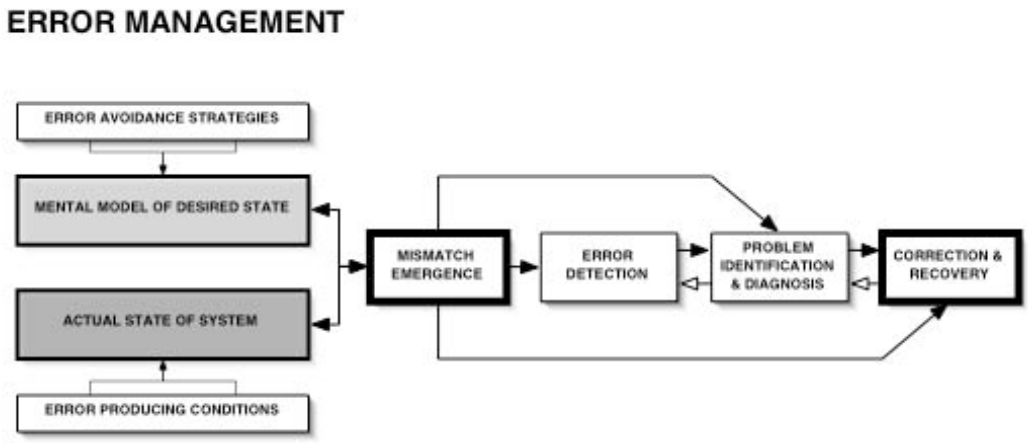

Figure Three: Critical Processes in Error Management

Core knowledge with respect to the cognitive and interpersonal skills of error management appears to be best conveyed with respect to practical application. To this end, an effective error management training program will unpack the abstract notions of a cognitive skill such as situation awareness and explore the specific strategies that can be used in a realistic operational setting. The studies emphasised the need for error management training to be outcome focussed, operationally relevant, and provide pilots with an understanding of the consequences of both effective and ineffective error management performance.

In summary, comprehensive knowledge in relation to error occurrence and management forms the first critical learning objectives for an error management training program. Knowledge relating to error and its management provides a solid foundation from which dedicated skill development can proceed. In general, three broad areas of core knowledge have been identified by this research as critical within an error management training curriculum: 1) the nature of human error; 2) error generation; and 3) models of error management.

3.2 Core Error Management Skills

The development of specific tangible skill in the avoidance, detection and response to error must form the keystone of error management training programs in commercial aviation. The results of the two studies undertaken as part of this research project have reinforced the understanding that error management skill is frequently non-technical in nature. Accordingly, it is these non-technical abilities that must be integrated effectively into traditional airline training programs.

The specific focus on non-technical skills is by no means a new addition to aviation training. With increased awareness of the human contribution to incidents and accidents, training programs were developed to focus on aspects of performance that were not directly related to the technical expertise or procedural skills involved in aircraft operation. Crew Resource Management (CRM), defined as the crews' effective use of all available resources to achieve safe and efficient flight operations, emerged as an important part of efforts to reduce the impact of human error and enhance safety (Lauber 1987; Wiener, Kanki & Helmreich 1993). The primary focus of CRM was the development of discrete non-technical skills such as communication, leadership, decision-making, conflict resolution, as well as stress and fatigue management (Helmreich & Wilhelm 1991). Through an evolutionary process, new generations of CRM have emerged, and recently CRM has been re-conceptualised explicitly as the development of threat and error countermeasures (Helmreich, Merrit & Wilhelm 1999). Recent research has emphasised the role of a wide range of non-technical skills in error management, and has provided critical insights into the relative influence of non-technical performance in various aspects of error detection and response (Thomas 2004).

It has been argued that one of the major problems facing non-technical skill development by flight crew is that the traditional approaches to training are largely ineffective (Trollip 1995). Recent analyses of airlines' training programs in the broad area of non-technical skill development have demonstrated a lack of coherence in different operator's approaches. Significant difference has been found in relation to a focus on attitude or behavioural development, as well as in relation to the specific labels, descriptions and representations of the attitudes or skills that are the focus of training (Salas, Rhodenizer & Bowers 2000).

The results of the studies undertaken under the current research project identified a range of specific components of effective error management, which in turn suggest the existence of a complex amalgam of error management *skill* that are used by crews. The individual reports for Study One (Thomas & Petrilli 2004) and Study Two (Thomas 2005) provide detailed analyses and specification of the underlying components of error management, as well as detailed explanation of how these components are applied in an operational sense.

In synthesising the findings of the research studies, two broad categories of error management skill can be differentiated. Firstly, a set of specific *cognitive skill dimensions* provide mechanisms for the important processes of information management, planning and evaluation. Secondly, a set of specific *interpersonal skill dimensions* provides a framework for the communicative and support functions necessary for effective error management.

Cognitive Skill Dimensions

The core cognitive skill dimensions identified in this research as critical to effective error management can be grouped under three broad categories: 1) information management; 2) planning and mental simulation; and 3) monitoring and evaluation.

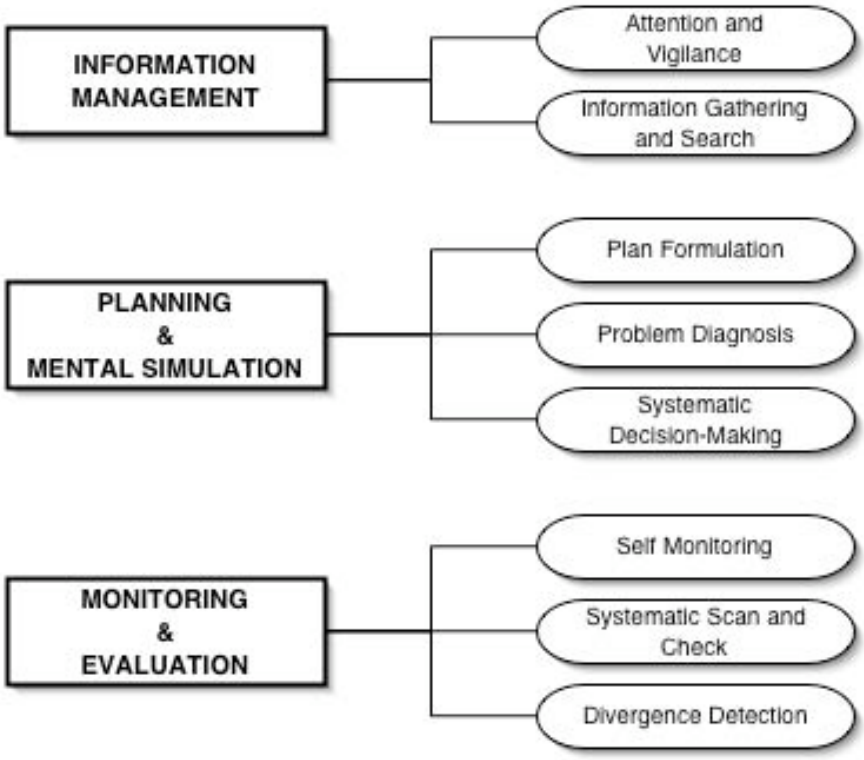

Figure Four: Core Cognitive Skill Dimensions of Error Management

Information Management: The first group of cognitive skill dimensions identified as critical to effective error management performance can be termed *information management*, and involves a range of cognitive processes concerned with the acquisition of information. First, the studies that formed the foundation for this report identified cognitive processes of *attention and vigilance* as of primary importance in error management. These processes form the first stage of Situation Awareness, and relate to the constant acquisition of information from the environment for use in subsequent higher-order cognitive processes such as monitoring, planning and evaluation. A second, yet related, process is that of purposeful *information gathering and information search*. This form of information acquisition is driven by particular situational needs, and is simply more directed and purposeful in nature.

It is likely that effective training of these cognitive skill dimensions involves the development of *metacognitive* processes that are used in the regulation of information acquisition, hence the use of the term information *management*. The term metacognition refers generally to awareness of our own cognitive processes and mental states. More specifically, metacognitive regulation refers to our ability to monitor and control our cognition. Accordingly, the development of enhanced skill in this area enables pilots to more effectively control the acquisition of information, critical to ongoing situation awareness and hence the process of error management.

Key Competencies: A set of underlying error management competencies can be identified in relation to *information management* and the underlying metacognitive processes which direct information acquisition. Specific

competencies are likely to include: 1) control of attention, 2) alertness management, and 3) directed information search.

Planning and Mental Simulation: The second group of cognitive skill dimensions can be termed *planning and mental simulation*. Three quite distinct cognitive skill dimensions are grouped under this category. The first of these, *plan formulation*, involves the creation of plans, including specified goal states, and a series of actions that specify the method for achieving or maintaining the goal-state. From an operational perspective, the processes involved in *planning and mental simulation* enable the specification of key parameters of the operation. Firstly, the planning process involves the creation of "fences", which define the broad envelope of safety for the operation. Secondly, the planning process involves the specification of "gates", which are predefined points in space and time where pre-determined parameters must be met. The process of plan formulation demands significant mental simulation, with the parameters of safe system operation projected into the future. This process of projection into the future also demands the definition of critical cues to be used to evaluate whether the ongoing operation of the system lies within the "fences" of safe operation.

The second cognitive skill dimension grouped under planning and mental simulation involves the process of *problem identification*. This process involves the identification of problem states within the system, and occurs after the operator has detected a mismatch between the desired and actual state of the system. Broadly aligned with the second stage of situation awareness, that of the comprehension and understanding of a situation, *problem identification* draws upon stored knowledge about the system, as well as information gathered from the current situation. Accordingly, problem identification serves a diagnostic function within the process of error management.

The third cognitive skill dimension grouped under planning and mental simulation involves the process of *systematic decision-making*. The results of the study determined that a systematic approach to decision-making was critical in both the avoidance of error, and the ongoing management of error when it spontaneously occurs. A deliberate and methodical process to decision-making defends against the occurrence of error when circumstances demand that operational decisions are made to guide the actions of the flight crew. A deliberate decision-making mnemonic such as GRADE (gather, review, analyse, decide, evaluate) builds defences against rushed and ill-considered decision-making. Similarly, while still operating within the time constraints placed on crews through operational requirements, it is ideal to adopt a deliberate and considered approach to the resolution of errors, or error-related problem-states. Rushed or hasty attempts in the rectification of error have the potential to further exacerbate any negative consequences of errors.

Key Competencies: This second set of cognitive skill dimensions is the point where technical and non-technical skill must be effectively integrated. A set of underlying error management competencies can be identified in relation to *planning and mental simulation* and relate to the second and third stages of situation awareness concerned with comprehension and projection into the future. Specific competencies are likely to include: 1) the creation of plans; 2)

comprehension of normal and non-normal systems states; and 3) systematic decision-making.

Monitoring and Evaluation: The third group of cognitive skill dimensions can be termed *monitoring and evaluation*, and involve a set of cognitive processes concerned with a constantly watching and scrutinising the operating state of the system.

The first cognitive skill dimension grouped under monitoring and evaluation is that of *self-monitoring*, and involves the metacognitive processes involved in maintaining an awareness of one's own cognitive state. The process of self-monitoring involves awareness of one's own performance, and the ability to detect when there is a degradation in performance, or a degradation in mental state though such factors as task overload or distraction. Another critical process involved in self-monitoring is the detection of self disengagement from the task or situation. Often referred to using terms such as "getting behind the aircraft" or "zoning out", self-disengagement can have a wide variety of genotypes, including a lack of experience or external factors such as personal stress. However, self-disengagement from the task or situation is an important trigger for loss of situation awareness, and thus subsequent error. The ability to detect the onset of self-disengagement, or loss of situation awareness, is therefore a crucial aspect of error avoidance.

The second cognitive skill dimension grouped under monitoring and evaluation is that of *systematic scan and check*, and involves systematically scrutinising the current status of the system. This process involves a conscious analysis of the work-environment, searching for the presence of an error.

The third cognitive skill dimension grouped under monitoring and evaluation is that of *divergence detection*, and involves the detection of any divergence from the anticipated system state. Possibly the most critical component of error detection is the ability to identify divergence from plans, or a mismatch against one's mental model of the situation. This process brings together the mental model of the situation that has been built through a combination of expertise, planning and the establishment of "gates", along with the process of monitoring and systematic check, such that the actual "reality" of the operation is evaluated against the ideal mental model. The literature on error detection has identified a process of "mismatch emergence" whereby conflict arises between the expected state of the work system and the actual observed state of the system as the critical point in the error detection process (Rizzo, Ferrante & Bagnara 1995). This process was highlighted in the studies as the critical component in the detection of error.

Key Competencies: A set of underlying error management competencies can be identified in relation to *monitoring and evaluation*. Specific competencies are likely to include: 1) awareness of one's own mental state; 2) scrutinising the current state of the system; 3) evaluation of current system states against planned or anticipated system states; and 4) detecting divergence between current system states and planned or anticipated system states.

Interpersonal Skill Dimensions

The core interpersonal skill dimensions identified in this research as critical to effective error management can be grouped under two broad categories: 1) communication; and 2) task management.

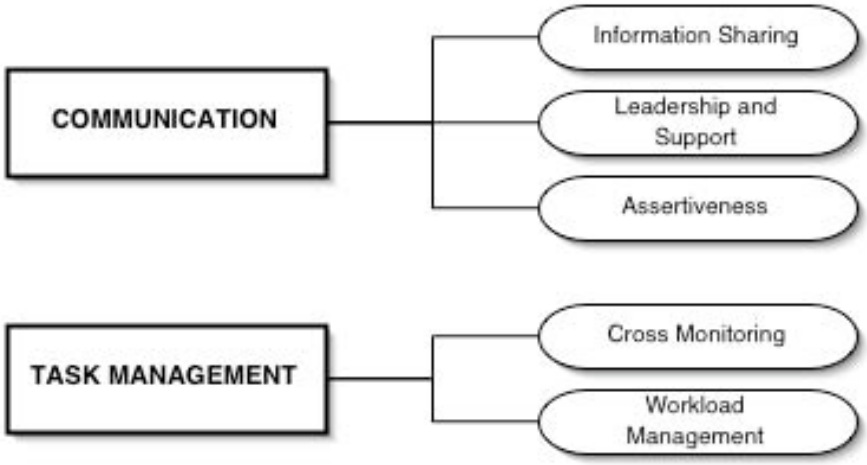

Figure Five: Core Interpersonal Skill Dimensions of Error Management

Communication: The first group of interpersonal skill dimensions can be termed *communication*, and involves a set of interpersonal skills used in the exchange of information, and the maintenance of an operationally effective group dynamic within the multi-crew environment.

The first interpersonal skill dimension grouped under communication is that of *information sharing*, and simply involves the effective exchange of information. Results from the study suggest that all stages of error management depend on the timely, clear and appropriate exchange of information between crew-members. Effective communication in this context refers to avoiding both communication underload and communication overload. The maintenance of an appropriate flight-deck environment for the open exchange of information is also a critical component of information sharing, such that any errors can be detected in a timely fashion, and any concerns can be easily voiced without fear of sanction.

The second interpersonal skill dimension grouped under communication is that of *leadership and support*, and involves maintaining an appropriate flight-deck authority gradient. The flight-deck gradient is comprised of two main aspects. First, an appropriate level of command is necessitated, which is neither authoritarian in nature, nor is it ineffectual. Second, an appropriate level of support is necessitated, which includes the provision of support through good information flow, the offering of suggestions, and identifying a potential or actual errors made by other crew-members.

The third interpersonal skill dimension grouped under communication is that of *assertiveness*, and involves the ability to be confident, or appropriately forceful, in stating a position. The requirement for assertiveness in error

management has been embodied in a number of airline's Standard Operating Procedures with respect to the call "Captain, you must listen…". This call highlights the potential gravity of a situation, and is used to necessitate the formal evaluation of plans when a commander has not adequately addressed the concerns of other crewmembers. While this is one formalised aspect, the general communication processes involved in assertiveness are required to be used by both crew-members and also take a variety of informal forms such as repeating information, indicating discomfort, or making a special request for the re-evaluation of a plan.

Key Competencies: A set of underlying error management competencies can be identified in relation to *communication*. Specific competencies are likely to include: 1) effective information exchange; 2) creating and maintaining an appropriate flight-deck authority gradient; and 3) adopting appropriate levels of assertiveness.

Task Management: The second group of interpersonal skill dimensions can be termed *task management*, and involves a set of interpersonal processes involved in the effective allocation and distribution of workload within the multi-crew environment.

The first interpersonal skill dimension grouped under task management is that of *cross-monitoring*, and involves a constant process of monitoring and evaluating the actions of the other crew-members. This process does not mean that the other crew-members are constantly "under the microscope" and subjected to unfair scrutiny and challenge. Rather, it refers to a constant underlying process of "keeping an eye out" for potential or actual errors.

The second interpersonal skill dimension grouped under task management is that of *workload management*, and involves the appropriate distribution and delegation of workload, such that critical tasks are prioritised, tasks are appropriately shared between crew-members, and sufficient workload resources remain for ongoing monitoring, evaluation and metacognitive processes which also form crucial elements of error management.

Key Competencies: A set of underlying competencies can be identified in relation to *task management*. Specific competencies are likely to include: 1) effective cross-monitoring; 2) workload distribution and delegation; and 3) ensuring workload "reserves" exist for monitoring, evaluation and metacognition.

The error management skill dimensions that have been synthesised from the results of this project provide the curriculum framework for competency development. While a number of the skill dimensions identified through this project mirror current practice in relation to Crew Resource Management training, the research presented here has provided a number of insights into new cognitive skill dimensions. For instance, the emphasis on mental simulation, and more particularly the *metacognitive* aspects of error management strategies, highlights significant new areas for error management training. In light of these findings, further research is required in the development and validation of specific competency specifications for the error management skill dimensions.

4 ERROR MANAGEMENT TRAINING - CLASSROOM

Traditionally, the classroom environment has provided the primary forum for training with respect to the non-technical aspects of flight crew performance. Crew Resource Management training has evolved within the commercial aviation environment predominantly in a classroom-based format, and with the continued evolution of a non-technical focus on performance, any new error-management training programs are often simply integrated within these existing programs. While the findings of the two studies involved in this research project have reinforced the need for a more "hands-on" format to error management training, the classroom environment does provide a forum for preliminary exploration of error management principles, and the development of core knowledge and attitudes.

The classroom environment provides the opportunity for specific knowledge development, and accordingly lays the foundation for the development of appropriate attitudes towards the effective avoidance, detection and response to error. The two studies which underpin this research project have provided a number of insights into how the classroom environment might best contribute to the overall error management training curriculum.

Introducing Core Knowledge and Skills: The classroom environment provides the opportunity for core error management knowledge to be developed by crew. For instance, the classroom provides the perfect environment in which the details of error generation, error genotype and error phenotype can be introduced, such that crew can develop a better understanding of the nature of human error, and how error is manifested in during normal flight operations. Similarly, the classroom environment is the appropriate forum for the introduction and discussion of the core error management skills, both with respect to the cognitive and interpersonal competencies identified as critical to effective error management.

Examples from Real Operations: One of the most important aspects of classroom-based error management training is the use of real examples of error occurrence, preferably both from the context of the airline in which the training is taking place, and from the context of notable incidents and accidents worldwide. These examples should be used to illustrate each of the aspects of core error management knowledge and highlight both outstanding and poor crew performance.

The technique of illustrating theory with practical examples is critical in the demystification of a topic, and also the development of a meaningful understanding of the nature of error. For instance, introducing the term error genotype without a clear illustration of the very real differences between a slip, a lapse and a mistake, would be extremely counter-productive. The results of this study have emphasised the need for crew to develop a better understanding of the nature of human error, and accordingly, the most effective and meaningful mechanism to achieve this is through the use of relevant examples.

Providing Behavioural Models and Exemplars: Extending the notion of the use of real examples, providing participants with behavioural models, or

exemplars of best-practice, is a critical component of classroom-based elements of the error management curriculum. To this end, the use of accident recreations to illustrate not only the technical failures of crew, but also the non-technical performances that contributed to error occurrence and poor error management, provides an example of how this process might unfold.

The use of video, transcripts from cockpit voice recorders, incident and accident reports, as well as examples from other industries are all essential resources in the classroom-based error management curriculum. These resources serve to bring the theory of human error to life, and are critical in facilitating the understanding of core error management knowledge and skill.

Promoting Personal Identification: Allowing participants to develop a personalised understanding of both general error management principles, and the benefits of effective error management strategies is perhaps the keystone of a simulator-based error management training program. To this end, the classroom-based error management training curriculum should provide the opportunity for crew to identify and discuss notable errors that have occurred during their own operations. Such personal identification of error management behaviours might be guided by the following types of question:

- Were any error producing conditions present?
- What type of error(s) occurred?
- Could anything have prevented the error?
- Were you aware of your own workload or stress levels?
- Was the error detected, and if so, how?
- Could the error have been detected more quickly?
- How did you respond to the error?
- How did you manage the multi-crew environment?
- What did you learn from this event?

This approach provides the forum for the personal analysis of error events in a guided and structured format such that crew can make personal meaning of the theory of error management. Moreover, this approach allows for the sharing of personal expertise, and the tacit strategies that expert crew utilise themselves in the error management processes. As experts develop their own personal strategies to manage error, and no error management training curriculum is going to be able to provide all the possible solutions, this informal exchange of expertise forms a critical component of the error management training curriculum.

5 ERROR MANAGEMENT TRAINING – SIMULATOR

While the classroom environment of traditional Crew Resource Management training provides a forum for the development of core knowledge, the process of skill development and maintenance demands more experiential forms of learning. The results of this project have highlighted that error management training cannot be seen just as a "classroom" activity. Rather, in order to explore and develop the wide range of competencies that underpin effective error management, specific experiential forms of training must be used.

Just as technical skills in areas such as aircraft handling and automation management require "hands-on" approaches to skill development and maintenance, the non-technical skills that underpin error management require practical forms of training that are embedded within a realistic operational context. The exposure to a wide range of conditions, and error-related events, during training is an essential element of developing effective skills in the management of error. Accordingly, error management training must have a significant experiential focus. In order to achieve this goal, it is apparent that both simulation and line training should include a specific structured focus on the generic non-technical skills that form the foundation of error management.

Over the last few decades, simulator-based training has come to form the bulk of experiential training in commercial aviation. The high fidelity full flight simulator provides the perfect environment for the exploration and development of error management competencies alongside the operational conditions in which error naturally occurs.

It is possible to conceive that error management training can be embedded within existing forms of cyclic simulator training without the need for additional time and resources. In other-words, it would be possible to design an Instrument Rating renewal simulator session that adopted an error management training focus. For instance, using an approach that seeks to train and assess the non-technical competencies of error management alongside the technical aspects of a raw data NDB approach, effective error management training can be achieved.

Bridging the Divide between Technical and Non-Technical Skills: As the sophistication in our understanding of error management training increases, it is likely that the supposed distinction between technical and non-technical skills will need to be deconstructed for the purposes of *integrated* modes of training. Indeed, it should be argued that the distinction between technical and non-technical skill is in fact a false division of what are in truth integrated elements of competency which combine in the form of expertise. However, the current distinction between technical and non-technical skills does serve a purpose of highlighting individual competencies and core knowledge which come together in effective error management.

The results of this study highlight the important role of non-technical skills in error management. Such skills as situation awareness, construction of accurate mental models and mental simulation, anticipation and contingency planning,

self-monitoring, and deviation detection are all generic cognitive processes that have been identified as critical components of error management.

Accordingly, any successful error management training program should develop an explicit focus on the development of these skills in pilots. This task is somewhat more difficult than the training of technical skills relating to areas such as systems knowledge, procedures, and aircraft handling. This difficulty is primarily because these types of cognitive skills are not directly observable, and in many respects difficult to define as they generally involve complex and multi-faceted thought processes. However, the task is by no means impossible, and the Human Factors research agenda for the near future can contribute considerably by providing new insights into areas such as:

1. The development of competency specifications for cognitive skills; and
2. Identification of the types of training interventions that enable the development of cognitive skills.

The error management competencies identified in these studies are all context-driven, and likely to be affected themselves by a range of error producing conditions such as high-workload, stress and distraction. Accordingly, the task management elements of effective error management dictate a need to embed an error management training focus within existing experiential forms of training in commercial aviation.

Identification of "Gotchas" and Error Management Strategies: One important aspect of simulator-based error management training relates to the identification of common "gotchas" in a given exercise, and highlighting the appropriate error management strategies that can be used to avoid, detect and respond effectively to error. The expectation of error, and more specifically being forewarned with respect to the common error genotypes and phenotypes related to a specific exercise or operational event, can assist crews in the targeted development of enhanced error management skills.

Exposure to Error-Producing Conditions: Another allied aspect of effective error management training involves an emphasis on the awareness of, and exposure to, conditions that increase the likelihood of error. The ability to detect error producing conditions were found to be essential elements of effective error management. Accordingly, guided exposure to aspects of normal operations where errors frequently occur is a primary element of error management training. Awareness of "areas of vulnerability" is best demonstrated through exposure to these aspects of the operation, and first-hand experience of the increased error-rate during these times. Aspects such as distraction, multiple and conflicting tasks and other areas of high workload should therefore be experienced and analysed from the perspective of error occurrence and management.

Accordingly, best practice in simulator-based error management training might promote enhanced awareness of error producing conditions, through asking crew to reflect on the inherent "traps" in a given exercise, and identify the propensity for certain error producing conditions to arise within the context of a particular exercise or operational event.

Guided Analysis of Error Events: Error management training must provide an instructional environment in which a range of errors is subjected to detailed

analysis. This analysis should occur in a manner that not only investigates the technical aspects of the errors, but also the non-technical and generic error avoidance, detection and response strategies as explored in previous sections of this report.

Take for example a circling approach that has become destabilised due to the crew's failure to commence descent with the turn onto base. A common way in which this might be debriefed in current practice would be to indicate to the crew the need to commence descent at a pre-determined point, and reinforce a the rough "rule of thumb" to guide crew in calculating the best descent point. However, from the perspective or error management training, an instructor might ask the following types of questions to prompt the crew to explore best practice in error management:

- What was your plan?
- Did you set a "gate" for the descent point?
- What do you think caused the error?
- What "gotcha" in that exercise?
- What distracted you from your plan?
- Did you evaluate your plan - did you see any mistakes?
- What alerted you the error of leaving the descent too late?
- What could you have done to detect the error earlier?
- Were you aware of a distraction or narrowing of attention?
- How did the pilot monitoring support the pilot flying?
- Did you communicate the critical pieces of information?
- Were you both monitoring effectively?
- How did you manage the error?
- Did you work well as a team?

Obviously, if each error were analysed in complete detail, it would be easy to spend a four-hour simulator session in the analysis of the first error that occurred in the first exercise flown. However, by asking open-ended questions to the crew with respect to the crucial elements of error avoidance, detection and response, a process of self-analysis is promoted with respect to error management. To this end, one or two of such questions asked of crew for a few of the consequential errors made in any one training session would provide an enhanced framework for the analysis of error events. Over the course of a recurrent training program, it would be ideal for crews to analyse aspects of error generation, error avoidance, error detection and error response. Furthermore, such approaches to error management training can be undertaken in a planned manner such that the generic non-technical strategies for error avoidance, detection and response can be explored in specific detail. To this end, resources can be created for instructors that provide guidance with respect to the common errors that are made in a specific exercise, and how the generic error management skills might be best applied for the training sequence.

Emphasising Cause and Effect: The need to develop a clear understanding of "cause and effect" with respect to the management or mismanagement of error was highlighted during the studies as a critical component of error management training. The exposure to the real consequences of poorly managed error, as well as the effectiveness of error management strategies, facilitates the development of healthy error management attitudes.

This understanding of "cause and effect" forms an important part of experience, and is captured in the informal process of "learning from mistakes". This process of learning from experience can be formally embedded into an error management training program. Such an approach can complement, as well as "short-cut", the informal aspects of learning from experience, and can be achieved within a more controlled environment. For instance, allowing crew in the training environment to see a safety-critical outcome of their errors highlights the inherent danger of poor error management. This process of controlled transgression through the safety envelope is a powerful learning mechanism, and has been formally adopted in military training environments (Naikar & Saunders 2003).

Instructional Prompts for Effective Error Management: The inclusion of specific instructional prompts during exercises in the simulator-based training syllabus provides an instructional environment in which crews are supported in the development of specific error management skills. Such instructional prompts are as follows:

- Have you missed anything?
- What is your plan?
- What "gates" have you set here?
- How is your workload?
- How are you feeling?
- When did you get distracted?
- What are some of the traps or "gotchas" here?

Such instructional prompts are designed to promote the use of each of the core error management skills described in the earlier sections of this report.

Rehearsal and Drill: The final aspect of experiential modes of error management training involves structured and guided training to specifically develop the non-technical skills used in error avoidance, error detection and error response. Just as technical procedures are frequently learnt through drill and rehearsal, so too can the generic non-technical skills that form the basis of error management. Processes described in this report such as the "systematic check", "building gates", "detecting divergence", "pre-action attention" and "using metacognitive prompts" can all be specifically trained and rehearsed during simulator and line training. Even through these skills are frequently described as generic non-technical skills as they are specifically cognitive in nature, they are nonetheless *competencies* that can be defined, specified and drilled during training.

6 SUMMARY AND CONCLUSIONS

This project has sought to provide an initial scientific basis for error management training programs. However, this study does not profess to provide all the answers, nor does it profess to provide the *only* curriculum structure for error management. Rather, the report has sought to identify aspects of best-practice, and provide an exploration of the curriculum foundations of error management training.

The next steps in the development of error management training programs involve firstly the development of detailed competency specifications using the knowledge and skill dimensions provided in this initial curriculum framework. Secondly, these competency specifications need to be empirically validated through further research and development. Error management training is an extremely new development. Accordingly, considerable ongoing research and development is required in the evolution of this new approach to training towards the enhancement of safety.

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