Error Management Training

An investigation of expert pilots' error management strategies during normal operations and flight crew training

Study Two: Simulator Study to identify Error Management Training in Current Practice.

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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.

The study for which the results are presented in this report sought to investigate the current approaches to error management training within the context of the simulator-based training program of a commercial airline. 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 skills 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. A total of 40 simulator-based training sessions were observed in this study.

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 Line oriented Flight Training (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). Accordingly, the term “threat” and “training exercise” can be used interchangeably throughout this report. 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.

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, and explored is some detail, 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 instructors' 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 lead to undesired aircraft states were debriefed by the instructor in the simulator significantly more frequently that 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 (aircraft configuration and performance), rather than non-technical (situation awareness, monitoring, or communication), aspects.

Use of the Threat and Error Management Model 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 are 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, 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 airline's 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 skills 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.

CONTENTS

1 INTRODUCTION

1.1 Research Context

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.

Due to the lack of a strong scientific foundation to the design and specification of error management training programs, a major research project has been 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 is to provide the Australian aviation industry with a concrete curriculum package for error management training for flight crew.

In order to achieve this objective, two studies at the University of South Australia were funded by the Commonwealth of Australia through the Department of Transport and Regional Services on behalf of the Australian Transport Safety Bureau. This report presents the findings from Study Two: Study Two: Simulator Study to identify Error Management Training in Current Practice.

The study for which the results are presented in this report sought to investigate the current approaches to error management training within the context of the simulator-based training program of a commercial airline. 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 skills would exist, and the expert instructor would engage in informal forms of error management training as part of their everyday instructional practices. A fundamental premise of the study was that these experienced instructors would have developed over the course of their careers considerable knowledge and skill with respect to error management. 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.

1.2 Background

The safe actions and satisfactory performance of personnel are essential aspects of maintaining safety across all sectors of the aviation industry. Accepted models of accident trajectory typically include both active failures of personnel and systems, as well as latent conditions which may lie dormant in an organisations' operational system for considerable time (Reason, 1990). Closely aligned to the concept of active failures and latent conditions and are the terms *error* and *threat* respectively, concepts which have recently been the focus of considerable research in the commercial aviation setting.

The diagram presented in Figure One outlines a model of accident trajectory. Human error, as described by the term “unsafe acts” is implicated as the final element in accident trajectory. While human error is seen as the most “immediate” contributing factor to accident occurrence, the model emphasises the role of error-producing conditions and the organisational processes which promote error occurrence as essential foci for investigation.

Operational personnel act as the last line of defence in complex operational environments (Reason, 1997). Safety is often maintained through the actions of individuals “at the coal-face” through their response to complex and sometimes ill-defined problems. Accordingly, the management of threat and error has been suggested to be a necessary focus of any organisation's attempts to effectively maintain safety in high-risk operations (Klinect, Wilhelm, & Helmreich, 1999). Furthermore, human error is now accepted as a natural part of everyday performance, and can occur both spontaneously or can be precipitated by a variety of environmental and personal factors such as individual proficiency, workload, fatigue, and team-dynamics.

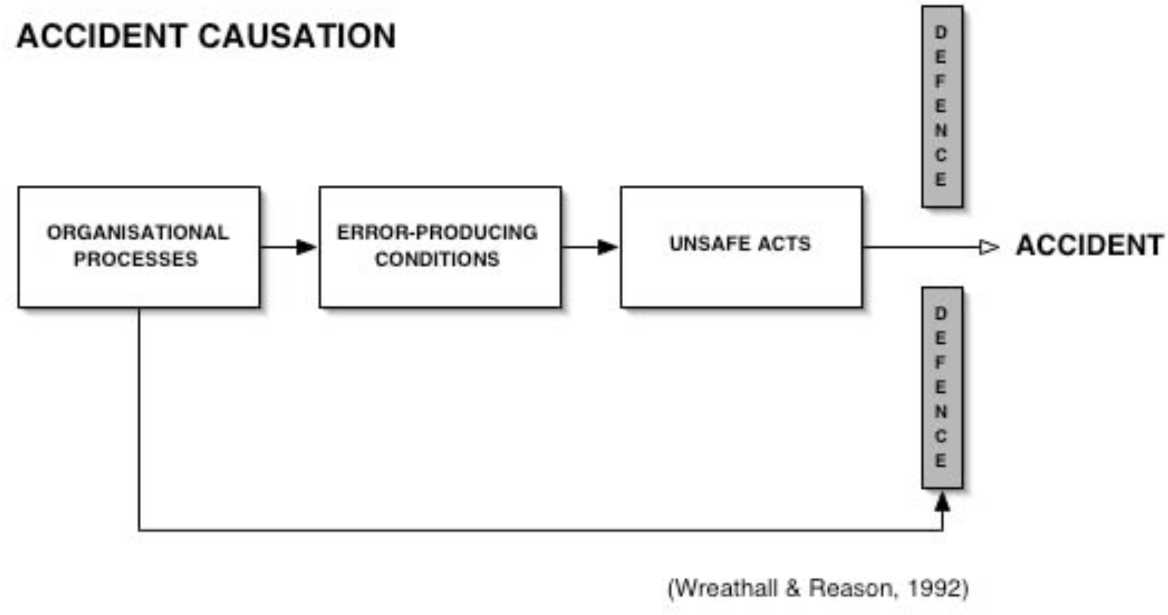


Figure One: A Model of Accident Causation

As Helmreich (2000) suggests, given the ubiquity of human error, and the wide range of factors which promote error, a key to safety lies in effective error management by operational personnel. In response to the increasing sophistication in our understanding of the role of error management in enhancing operational performance and safety, error management training programs are becoming innovative new elements of many airline's training systems (Phillips, 2000). However, recent research has highlighted a number of challenges facing effective error management training programs. Thomas (2003a), in a study of Line Training in the commercial airline setting, highlights the difficulties associated with the effective detection of error events during training, and the lack of instructor debrief and analysis of errors as they occur. Current error management training practices lack large-scale empirical investigation, and existing evidence suggests that they may require considerable refinement and improvement.

Indeed, the continued findings of low levels of error detection during audits of normal operations suggest that error management training is an area requiring urgent investigation. This project seeks to investigate effective strategies for error management training.

1.3 Error Occurrence in Normal Flight Operations

Considerable research has demonstrated that there is a consistent and systematic underlying rate of error during normal flight operations. Error is both a natural element of human performance, and even the most highly trained, skilled and experienced operators naturally and frequently make errors. New observational audit methodologies, such as the Line Operations Safety Audit (LOSA) have demonstrated that crews make on average between one and five errors per flight sector (Klinect, 2002). The vast majority of errors are inconsequential within the environment of commercial airline operations, given the multi-layered systemic safety defences employed within this high-risk environment. However, it has also been demonstrated through the systematic observational analysis of normal operations that up to half of the errors committed by crews remain undetected (Thomas, 2004; Thomas, Petrilli, & Dawson, 2004)

Considerable existing research examining the general occurrence of human error across a wide range of everyday and work environments has informed systems for the classification of error. Through the classification of error, we risk creating an illusion of understanding the causal factors involved through a simplistic process of re-labelling and grouping similar types of error. However, it is possible to build effective mechanisms for safety-related change through analyses of error that de-emphasise the construction of cause and focus on the identification of patterns in error occurrence. These "genotypical mechanisms of failure" elucidate the means by which operators create safety in practice, and map universal patterns of safety breakdown (Dekker, 2003).

1.3.1 Errors in Planning and Errors in Execution

The most common system for the classification for errors involves the differentiation between errors committed in the planning of actions, and errors committed in the execution of actions.

The term *mistake* is used to describe the errors that occur in the planning of actions and involve errors where the plan for specific action is deficient or fundamentally flawed. In this instance, an operator might execute a plan of action flawlessly, but not achieve the desired outcome due to an inherent problem with the plan of action itself. As Reason (1990) suggests, mistakes frequently occur through the failures of higher-order cognitive processes involved in judging the available information, setting objectives, and deciding on the means to achieve a desired outcome. This type of error relates directly to Rasmussen's (1986) knowledge-based behaviours, which involve conscious reasoning during problem-solving activities. Accordingly, these errors are frequently referred to as *knowledge-based mistakes*.

However, mistakes are frequently also observed with respect to less conscious or deliberate planning processes. Termed *rule-based mistakes*, these forms of error involve the incorrect initiation of actions in response to existing behavioural routines. Frequently, rule-based mistakes involve an automatic response to misdiagnosed problem, or the automatic misdiagnosis of a situation. Rule-based mistakes occur through the interference of biases or quasi-automatic intervention of more familiar rules, and can occur in relation to both the identification of a situation and the selection of action (Rizzo, Ferrante, & Bagnara, 1995).

Similarly, two broad types of error can be categorised at the execution stage. Firstly, *slips* involve unintentional actions or active failures in the execution of a plan. In these situations, the intended action is appropriate, but due to low level attentional failures in highly practiced and automatic behaviours, incorrect action is executed (Norman, 1981). For instance, simple errors in psychomotor performance such as moving a lever forward instead of backward typify slips.

Secondly, *lapses* are defined as errors that occur as a result of memory failures, and most frequently involve forgetting a procedural step or planned action. For instance, a task, or individual task step, is omitted through a failure in memory processes. Again, it has been suggested that attentional failures, or diversion of attention through distraction, are important mechanisms in the production of lapses.

1.3.2 Unintentional Errors, Violations and Unsafe Acts

A fundamental problem facing the construction of a robust classification system for error involves the distinction between unintentional errors and the wilful deviation from rules, procedures or regulations. The most strict use of the term error does not include the notions of violations, intentional non-compliance or wilful deviations. By definition, error is unintentional and does not include actions in which the operator has consciously and deliberately chosen to deviate from required practice.

However, frequently the outcome of both an unintentional error and a violation are the same, and at both can have the same negative impact on safety. For instance, either a lapse in concentration or the intentional disregard for a speed restriction can lead a car travelling more than 10kms above the sign-posted limit. In the majority of cases, the law does not differentiate between unintentional error and the violation, with both actions leading to a speeding fine.

In order to adequately capture both the intentional and the unintentional types of human error, Reason (1997) uses the term *unsafe acts* to describe both errors and violations. Unsafe acts describe a wide variety of human behaviours and include both unintentional errors and intentional acts of non-compliance with policies, procedures or regulations. The figure below provides a detailed diagrammatic representation of the classification of errors in relation to unintended and intended actions.

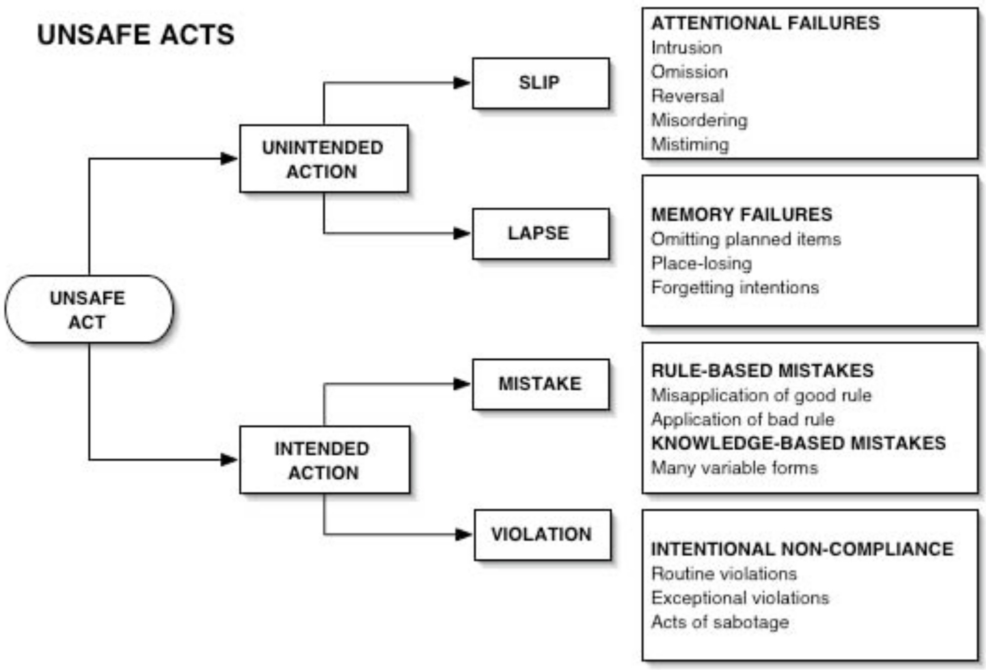


Figure Two: Classification of Unsafe Acts (Reason 1990).

1.4 Error Management – Fundamentals and Current Knowledge

As Wreathall and Reason (1992) have put so elegantly, "the history of accidents and their analysis is also the history of human contribution to accidents". Illustrated in Figure One above, it is the unsafe acts of human operators that are often primary factors in accident causation. However, rather than treating the variety of error events, captured by the term "unsafe acts", as aberrant mental processes which need to be eradicated, it has become accepted that systems-based approaches to human error management offer the greatest potential from the perspective of safety management in high risk industries. The systems-based approaches to error management employ countermeasures that are based on the assumption that though we cannot change the human condition, we can change the conditions under which humans work. Expanding this perspective, error management has two components: 1) limiting the incidence of dangerous errors; and 2) creating systems that are better able to tolerate the occurrence of errors and contain their damaging effects (Reason, 2000).

While systemic defences are essential in the containment of inevitable error occurrences during normal flight operations, the systems-based approach must also be complemented by components of error management which focus explicitly on the management of error at the level of the individual operator and the specific team environment in which they operate. With respect to the normal flight operations in the commercial airline environment, this relates to the management of error by the operating crew within the flight deck environment.

Researchers at the University of Texas have developed a model of Threat and Error Management that provides a broad functional structure for error management processes during normal flight operations (Helmreich et al., 1999). This model provides a basic descriptive framework for the occurrence, management and outcome of errors during normal flight operations. As described in Figure Two, errors can occur spontaneously, or as a result of poor threat management. Within the model, "threat" can be defined as a situation or event that has the potential to impact negatively on the safety of a flight. In relation to the existing literature on error occurrence, these "threats" are typical error producing conditions.

In turn, errors are defined as crew action, or inaction, that leads to a deviation from crew, organisational or regulatory intentions or regulations. The full Threat and Error Management Model is described in Figure Three.

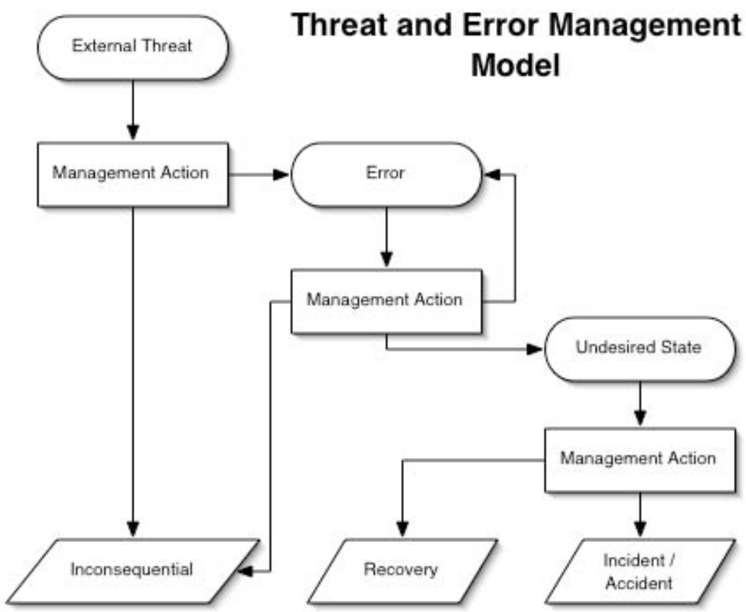


Figure Three: The University of Texas' Threat and Error Management Model.

According to the Threat and Error Management model, error management has two critical components: 1) error detection; and 2) error response. Error detection simply involves being aware that an error has occurred. Error response involves the actions crew-members take in order to rectify or mitigate the error once it has been detected. This model provides an intuitive framework for the analysis of unsafe events during normal system operation, and has been seen to possess high levels of explanatory value, utility and ecological validity through numerous real-world applications. However, while this model provides an effective descriptive framework for the observation of error in real-world environments, more detail is required in relation to the individual processes that give rise to effective error management.

Strategies for error management have been discussed in the literature, and typically a range of non-technical skills have been identified as essential error countermeasures (Helmreich & Merritt, 2000; Thomas, 2004). However, significantly more detail is required if we are to adequately understand the processes for error management during normal flight operations. This task is imperative if we are to produce error management training programs that are based upon a foundation of empirical research and as such are scientifically defensible.

2 METHOD

2.1 Participants

Participants were volunteer pilots and instructors from the single-isle jet fleet of an airline flying largely short-haul operations. A total of 40 simulator-based recurrent training sessions were observed for the purposes of this study. Each training session involved a currently qualified Captain and First-Officer acting as a crew for the session. A single instructor was responsible for briefing the crew on the content of the session, conducting the training session in the full-flight simulator, and debriefing the crew at the end of the training session. In each instance, these instructors were highly experienced operators within the commercial airline environment.

2.2 Design and Procedure

The study adopted an observational design, and utilised trained expert observers for the observation and analysis of the training sessions. The trained observers were experienced in the use of the structured performance evaluation methodology used in this study, and had attended a four-day training program in the use of the methodology for the analysis of normal line operations, and one additional day of training in use of the methodology in the training environment. Observer training focussed on the standardisation of observer's ratings, and the maintenance of acceptable levels of inter-rater reliability.

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.

2.3 Measures

The observational methodology provided both qualitative and quantitative data. Observers provided a written narrative of each threat and error event, which described the nature of the event itself, the crews' management of the event, and also the instructional response to the event.

A variety of quantitative measures relating to threat and error management were also coded by the observers during the training sessions. Each individual exercise that took place during the simulator-based training sessions was analysed as an operational threat as per the definitions used in the Threat and Error Management Model discussed in the introduction to this paper (Helmreich et al., 1999). Accordingly, the following variables relating to threat management were coded by the observers, with each variable providing categorical data.

Table One: Threat Management Variables

Variables relating to Threat Management	
Threat Detection	Instructional Aspects
Time to Threat Detection	Non-Technical Ratings – Threat Management
Threat Response	

Any errors that occurred during the training session were also coded by the observers using a similar approach. Accordingly, the following variables relating to error management were coded by the observers, with each variable providing categorical data.

Table Two: Error Management Variables

Variables relating to Error Management	
Error Origin	Error Producing Conditions
Error Genotype	Error Response
Error Phenotype	Instructional Aspects
Error Detection	Non-Technical Ratings – Error Production
Time to Error Detection	Non-Technical Ratings – Error Management

Of particular focus was the instructional response to threat and error events that occurred during the training sessions. Observers coded the frequency by which instructors discussed aspects of crew performance, highlighting times when instructors briefed or debriefed particular events, and in particular noting any instances when specific threat and error management strategies were discussed.

Furthermore, a range of non-technical skill behavioural markers were utilised in the analysis of threat and error management. These non-technical skills have been identified as core drivers of effective operational performance, and have been shown to influence directly the efficacy of threat and error management (Thomas, 2004).

A set of 16 non-technical behavioural markers, as listed in the following table, was coded on a seven-point scale. The anchors on the seven-point continuous scale were: 1) poor; 2) marginal; 3) needs improvement; 4) adequate; 5) good; 6) very good; and 7) outstanding. For each threat event (training exercise) observed, the set of non-technical markers were coded with respect to the overall management of that threat. For each error event observed, the set of non-technical markers were coded with respect to the production of the error, and then the overall management of the error event. Observers were instructed to code only behaviours that were deemed specifically relevant to the management of the specific threat or error event. This coding process thus allowed for determination of the important non-technical skills used by crews in the management of particular forms of threat and error.

Table Three: Non-Technical Skill Markers

Category	Behavioural Marker
Communication	Communication Environment
	Leadership- Followership
	Inquiry
	Assertiveness
	Cooperation
	Statement of Plans and Changes
Situation Awareness	Vigilance
	Monitoring and Cross Check
Task Management	Briefing and Planning
	Workload Management
	Workload Prioritisation
	Automation Management
	Management of Fatigue and Stress
Decision-Making	Contingency Planning
	Problem Identification
	Evaluation of Plans

As an innovative element of the observational methodology, the coding of Error Producing Conditions was undertaken. According to our understanding of error occurrence, it has been suggested that various factors, both internal and environmental in nature, can increase the probability of error occurrence (Williams, 1988; Wreathall & Reason, 1992). A review of the current literature yielded a list of twelve common Error Producing Conditions which might increase the probability of error occurrence within the environment of both normal flight operations and training.

Table Four: Error Producing Conditions

Error Producing Condition	Error Producing Condition
Lack of Attention / Distraction	Poor / Unclear Procedures
Loss of Situation Awareness	Time Limitation
Fatigue	Aircraft System Design
High Workload	Unfamiliar/Novel Event
Lack of knowledge or skill	Environmental Conditions
Poor communication	Perceptual Illusion

For each error that occurred during training, each observer simply identified any factors they thought were present at the time and contributed to the occurrence of the specific error from the list of twelve possible Error Producing Conditions. Observers were instructed to rely as much as possible on observable behaviour in their identification of Error Producing Conditions. However, the difficulty of the observational analysis of such conditions as cognitive failure modes must be acknowledged. For instance, with respect to the Error Producing Condition of *fatigue*, observers would only code this as a potential Error Producing Condition when they observed the tell-tale behaviours associated with fatigue at the time of the error. This new coding framework with respect to the observation analysis of error events was seen to be a powerful tool in the subsequent analysis of error phenotype and error genotype.

2.4 Analysis

The data collected were subjected to a variety of statistical analyses. As the quantitative data was predominantly categorical in nature, statistical analyses were limited to techniques that were appropriate to such forms of data.

3 RESULTS

3.1 Threat Management During Training

The fundamental role of simulator-based training is to develop and maintain the knowledge and skills associated with the management of safe operations in the dynamic and complex environment of normal flight operations. Accordingly, a typical simulator-based training syllabus will embed a wide range of operational "threats" which the crews must effectively manage to ensure an adequate margin of safety is maintained.

Within the Threat and Error Management Model. "threats" are defined as situations or events that have the potential to impact negatively on the safety of a flight (Helmreich et al., 1999). Accordingly, each of the exercises contained within a simulator-based training syllabus can be interpreted as "threats" according to this definition, and subjected to the same analyses and coding techniques as used for the analysis of normal flight operations.

For instance, common exercises such as an engine failure after V1 or a traffic conflict resulting in a TCAS Resolution Advisory are typical examples of rare, high-risk operational threats. To this end, the term "threat" and "exercise" are used interchangeably in the following presentation of results.

3.1.1 Threat Occurrence

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 Line Oriented Flight Training (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. Indicative components of the program are outlined below:

Table Five: Indicative Syllabus Structure of Training Program

Day One	**Day Two**
Flight Planning and Preparation	Rejected Take-Off
Adverse Weather Operation	Engine Failure and Asymmetrical Flight
In-flight Systems Failures	Non-Precision Approaches
In-flight Diversion	Systems Failures
Non-Normal Manoeuvres	Passenger Evacuation
	Non-Normal Manoeuvres

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.

3.1.2 Threat Detection

The detection of a threat is the first stage in effective threat and error management. During normal line operations, it has been found that the vast majority of threats are detected by flight crew, with typically less than 10 percent of threats remaining undetected (Thomas, 2003c).

With respect to the training sessions observed in this study, less than one percent of threats were not detected by either crew-member. As illustrated in the table below, the majority of threats were detected by both crewmembers simultaneously.

Table Six: Threat Detection

Threat Detection		**Time to Threat Detection**	
Captain	16.5	Less than one minute	97.6
First Officer	14.5	Between one and five minutes	1.7
Both Crew	68.9	More than five minutes	.6
Nobody	.2	Not detected	.2

Frequency expressed as a percentage of all exercises observed (N=656)

The simulator-based training environment promotes high levels of expectation of operational threat for crews, especially when the crews' performance is being evaluated as part of a license renewal or proficiency check. The finding that less that one percent of threats remain undetected by crews is therefore not unexpected. Similarly, the finding that 97.6% of threats are detected within one minute of being introduced into the simulation also reinforces the suggestion that crews bring with them high levels of threat awareness and expectation into the training environment.

While the simulator-based training environment promotes high levels of threat awareness and therefore excellent performance by crews in relation to threat detection, the response by crews to the frequently high-risk and uncommon threats introduced in the training environment was found to be less consistent.

3.1.3 Threat Response and Outcome

The response to the "threat" posed by each exercise was coded in relation to the crews' overall management of the exercise. In general terms, if the exercised resulted in an error being made by a crew-member, the exercise was coded as mismanaged.

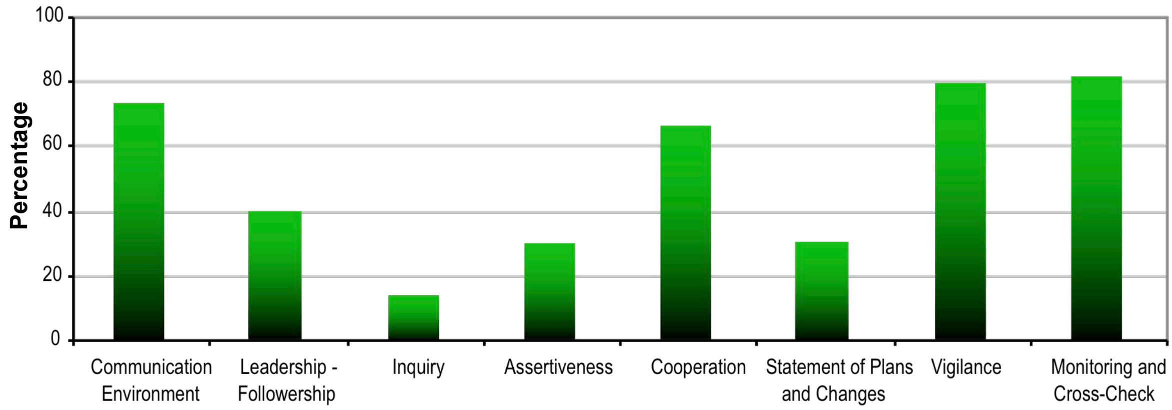
In total, 69.1% of all exercises were well managed by the crews, with no errors arising during the particular sequence. Subsequently, during only 30.9% of exercises were errors committed by the crews. The table below provides an indicative distribution of threat management according to the type of exercise observed.

Table Seven: Threat Response

Exercise	Managed without Error	Error Occurred
Rejected Take-Off	88.5	11.5
Engine Failure on Take-Off	66.7	33.3
Adverse Weather Operation	54.9	45.1
In-flight Systems Failures	81.7	18.3
Non-Normal Manoeuvres	81.8	18.2
Asymmetrical Approach	65.8	34.2
Non-Precision (NDB) Approaches	84.2	15.8
Passenger Evacuation	96.2	3.8

Frequency expressed as a percentage of exercises observed in each category (N=656)

A range of non-technical skills is known to underpin effective threat management during normal flight operations. The figure below illustrates the distribution of non-technical ratings of "adequate" or above for those threats events where no errors occurred in the management of the threat.



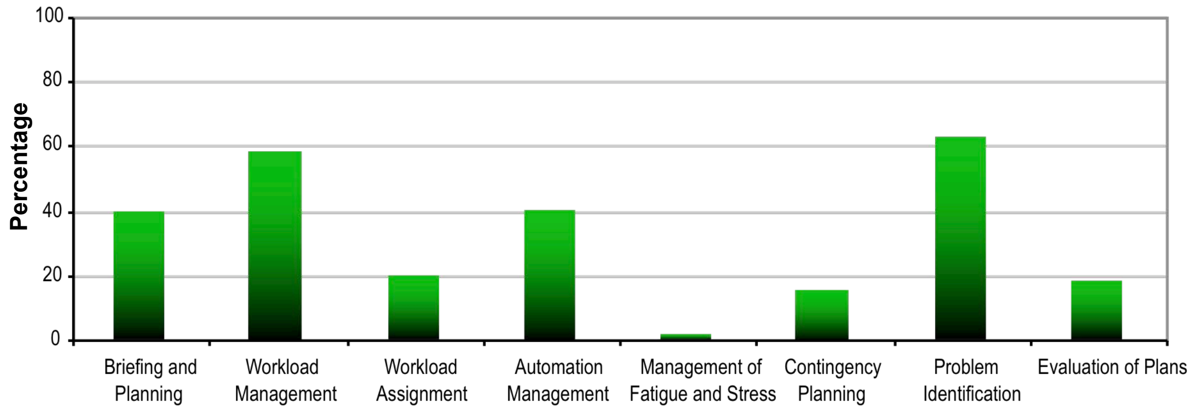


Figure Four: Indicators of Effective Threat Management (percentage of ratings "adequate" or above for effectively managed threat events N=453).

As evident in Figure Four, the five most frequently observed non-technical skills associated with effective threat management were: 1) Monitoring and Cross-Check (81.7%); 2) Vigilance (79.5%); 3) Communication Environment (73.9%); 4) Cooperation (66.0%); and 5) Problem Identification (62.9%). These markers therefore form the key indicators for effective threat management.

Similarly, deficiencies in non-technical performance can also be seen as drivers of poor threat management. The figure below illustrates the distribution of non-technical ratings below "adequate" ratings for those threat events where one or more errors occurred in the management of the threat.

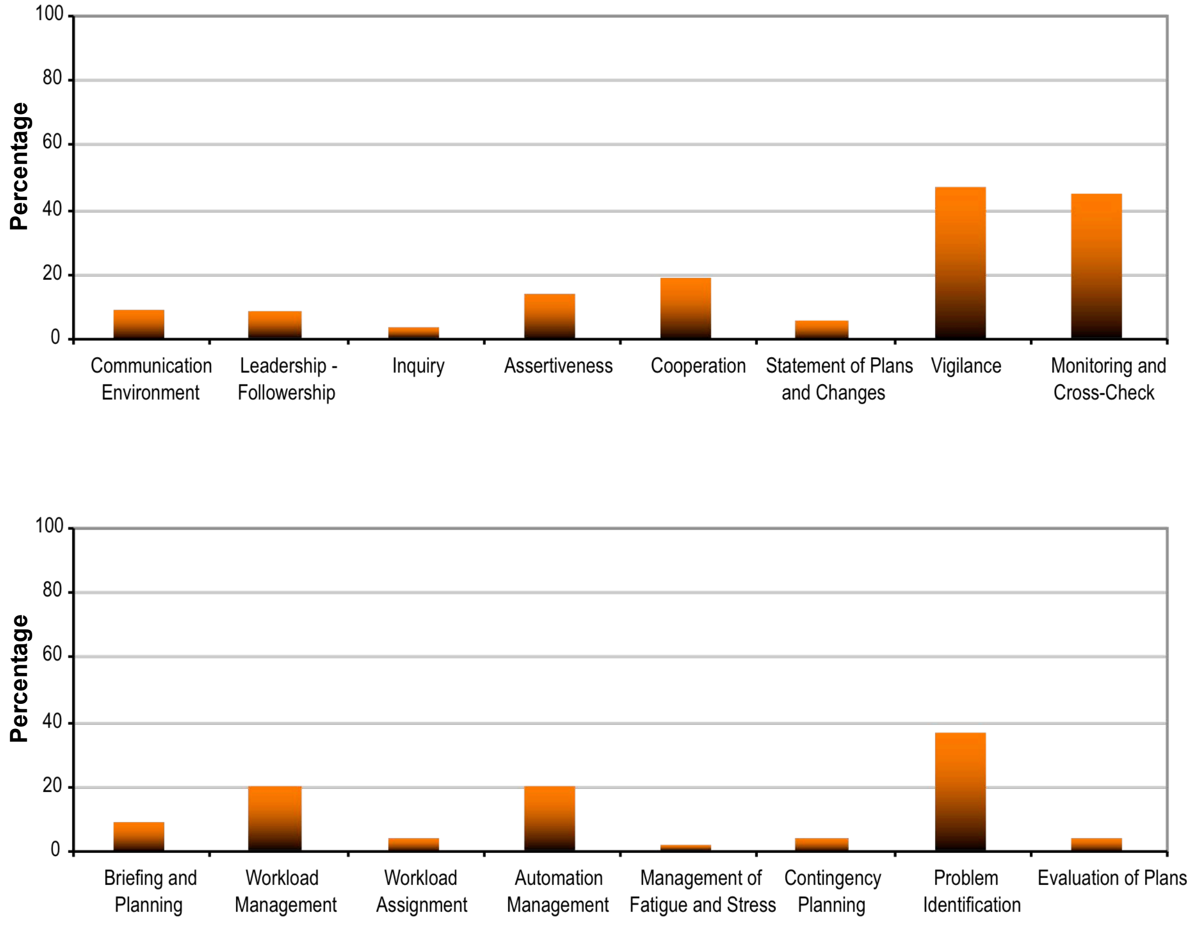


Figure Five: Indicators of Poor Threat Management (percentage of ratings below "adequate" for threat events in which one or more errors occurred, N=203).

As evident in Figure Five, the five most frequently observed non-technical skills associated with threat events where one or more errors occurred were: 1) Vigilance (46.8%); 2) Monitoring and Cross-Check (44.8%); 3) Problem Identification (36.4%); 4) Workload Management (20.2%); and 5) Automation Management (19.7%). Accordingly, poor performance by crews on these markers form a key indicator of mismanaged threats.

3.1.4 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 table below provides a summary of the frequency with which instructors undertook a range of specific instructional processes with respect to each individual threat contained in the simulator-based training syllabus for the airline involved in this study. For consistency, only those exercises that were formal elements of the training syllabus are included in this summary.

Table Eight: Instructional Aspects of Threat Management

Instructional Aspects	Day One	Day Two
Exercise was briefed	69.5	80.3
Exercise was discussed in simulator	62.9	46.6
Exercise was discussed in debrief	51.0	59.7
Timely detection of event was discussed	21.2	8.6
Strategies for error prevention were discussed	40.4	39.3
General threat and error management was discussed	14.6	4.5

Frequency expressed as a percentage of all exercises from the syllabus observed (N=441)

During day one of the airline's training program, which consisted of a LOFT exercise followed by a series of instructional exercises, 69.5% of the exercises were briefed by the instructor. During day two, which had a greater focus on the evaluation of crew proficiency, a total of 80.3% of exercises were briefed by the instructor. This is a significantly higher proportion of exercises briefed than on day one, and suggests that more comprehensive briefings are given prior to the proficiency check, $\chi^2(1, N=441) = 6.480, p <.05$.

Conversely, on day one, 62.9% of exercises were discussed in the simulator during the progress of the training session. When compared to a total of only 46.6% of exercises discussed in the simulator on day two, it is evident that there is a significant difference, and that the instructional focus on day one provides greater opportunity for interaction between the instructor and the crew, $\chi^2(1, N=441) = 10.653, p <.01$.

Observers also coded a number of variables relating to the informal threat and error management training processes undertaken by the expert instructors. In general, while it was found that more than one third of exercises included some discussion of *error prevention*, 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. For instance, in relation to an exercise such as an engine failure at lift-off, the instructional brief and debrief would typically focus on the requirements for aircraft configuration and performance, and the procedural sequence of drills associated with the effective management of the "threat". 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 number of noteworthy briefing sessions where instructors focussed on error prevention. 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 instructors debrief of crew performance. Indeed, a significant difference was found between the frequency with which instructors debriefed exercises, with exercises in which one or more errors occurred being debriefed significantly more frequently that exercises in which no errors occurred, $\chi^2(1, N=441) = 10.015$, $p < .01$.

This finding suggests an inherent bias towards the analysis of poor performance in the instructional practices within airline training programs. Observers noted that instructors rarely debriefed in any detail exercises that were particularly well managed by crews. Frequently, the discussion of good performance was limited to a brief compliment from the instructor. This intuitive finding highlights the focus of current airline training programs on the identification and rectification of deficiencies in operator performance. However, this approach to the orientation of instructor intervention in training may pose difficulties for the development of specific error management training programs. It is possible that specific threat and error management training might require a greater emphasis on the detailed analysis of effective performance, alongside analysis of areas of operator deficiency.

The detailed analysis of good crew performance would appear to be necessary in the process of unpacking the non-technical aspects of performance that are often implicit or tacit in nature. Similarly, the process of detailed analysis of good crew performance enables the reinforcement of specific strategies of effective threat and error management. Accordingly, an area of improvement from current practice in the development of threat and error management training programs would be a greater focus on the analysis and reinforcement of good crew performance.

3.2 Error Management During Training

The occurrence of error is a natural part of everyday human performance, and the field of Human Factors has reinforced the adage that "to err is human". To this end, error has recently become an accepted facet of normal flight operations, and the development of generic error management skills has emerged as an important new focus for aviation training programs.

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.

3.2.1 Error Occurrence

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 relitavely low overall rate of error production.

There was little practical difference between the error rates of Captains and First-Officers. Captains were found to be responsible for 50.2% of all errors, slightly more errors than First-Officers who were responsible for 40.1% of errors, with the remaining 9.7% of errors being attributed to "both" crew members actions during training. It is likely that the higher rate of is at least partially related to the fact that Captains were assigned "Pilot Flying" for proportionately more of the exercises during the training sessions. The table below summarises the occurrence of error during training with respect to the variables of Error Origin and Error Type.

Table Nine: Distribution of Error Genotype

Error Genotype	**Error Origin - CAPT** (N=139)	**Error Origin - F/O** (N=111)	**Error Origin – Both** (N=27)
Slip	38.1	44.1	3.7
Lapse	20.9	24.3	40.7
Mistake	41.0	31.5	55.6

Frequency expressed as a percentage of errors observed according to error origin.

With respect to error genotype, there was a relatively equal distribution of slips, lapses and mistakes between Captain and First-Officer. There was a statistically significant difference in the distribution of error genotype, largely associated with the higher proportion of lapses and mistakes committed by both crewmembers in concert, $\chi^2(4, N=277) = 16.967, p <.01$.

While lapses have been found to be the most frequently occurring error type during normal line operations, the relatively equal distribution of errors in the training environment is most likely to be a product of the high frequency and multiplicity of challenging threat events presented to crews during the four-hour simulator sessions.

Each error observed during training was subsequently coded against 11 distinct categories of error phenotype. Error phenotype provides a categorisation of error with respect to the type of operational task in which the error was manifested. The distribution of error phenotype is provided in the table below.

Table Ten: Error Phenotype

Error Phenotype Category	Frequency
Aircraft Handling	37.5
Flight Management Computer Errors	6.9
Flight Controls and Configuration	8.7
Mode Control Panel Errors	6.5
Aircraft Systems	10.5
Communications	4.0
Checklist	7.2
Callouts	9.4
Briefing and Planning	3.6
Cross-Check	1.1
Workload Assignment and Management	4.7

Frequency expressed as a percentage of all errors observed (N=277)

For each error, observers identified what, if any error producing conditions, were seen to be present and contribute to the occurrence of error. As evident in the table below, *Unfamiliar Event* was the most frequently coded error producing condition, contributing to 70.4% of all errors observed. Similarly, *Lack of Attention or Distraction* was seen to contribute to 52.7% of errors and *High Workload* was seen to contribute to 50.2% of all errors observed. These three error producing conditions appear to be substantial drivers for error occurrence in the simulator-based training environment.

Table Eleven: Error Production

Error Producing Conditions			
Lack of Attention / Distraction	52.7	Poor / Unclear Procedures	1.8
Loss of Situation Awareness	18.1	Time Limitation	5.8
Fatigue	5.1	Aircraft System Design	1.4
High Workload	50.2	Unfamiliar Novel Event	70.4
Lack of Knowledge or Skill	36.1	Environmental Conditions	8.3
Poor Communication	13.4	Perceptual Illusion	2.5
Stress	14.1	Organisational Expectations	0.4

Frequency expressed as a percentage of all errors observed (N=277)

Poor performance in a range of non-technical skills is known to promote the occurrence of error during normal flight operations. The figure below illustrates the distribution of non-technical ratings of below "adequate" for each occurrence of error.

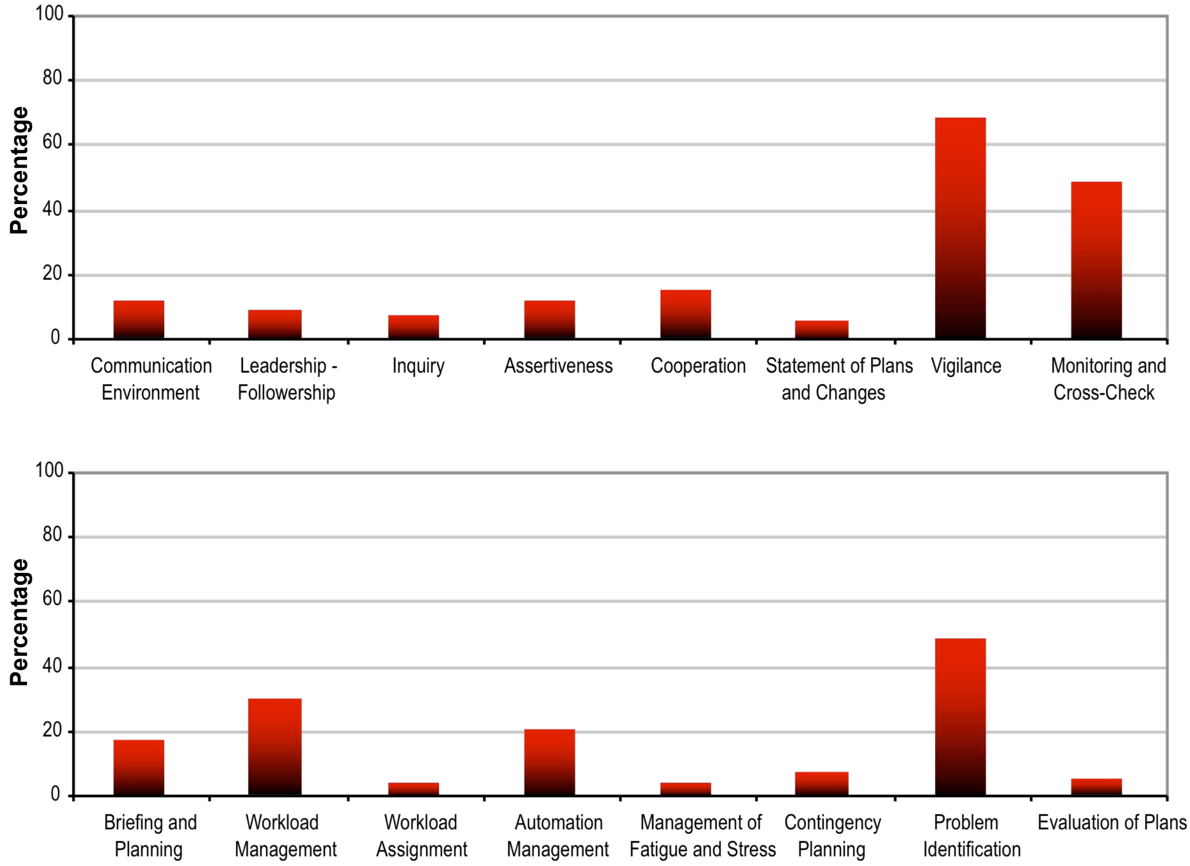


Figure Six: Indicators of Error Production (percentage of ratings below "adequate" for error production, N=277).

As evident from the figure above, observers coded, as important aspects of error generation, poor performance in several key non-technical skills. The five non-technical skills most frequently associated with error generation were: 1) *Vigilance* (68.2%) of all errors; 2) *Problem Identification* (48.8%); 3) *Monitoring and Cross-Check* (48.4%); 4) *Workload Management* (29.6%); and 5) *Automation Management* (20.9%). Accordingly, these five non-technical skills appear to be important aspects of error generation.

3.2.2 Error Detection

The first stage of effective error management involves the timely detection of error. Recent research examining error management during normal flight operations has identified error detection as a weakness in error management practice (Thomas, 2004; Thomas et al., 2004). As summarised in the table below, the crew detected less than half the errors they committed during training, with 31.4% of all errors remaining undetected by the crew.

Table Twelve: Error Detection

Error Detection		Error Detection Time	
Captain	18.8	Less than one minute	59.2
First Officer	17.0	Between one and five minutes	7.6
Both Crew	13.7	More than five minutes	1.8
Instructor	19.1	Not detected	31.4
Nobody	31.4		

Frequency expressed as a percentage of all errors observed (N=277)

The instructor was responsible for bringing 19.1% of errors to the attention of the crew during the simulator-based training session. Overall, there was a significant difference in the distribution of error detection between day one and day two, $\chi^2(4, N=277) = 29.564, p < .001$. During day one of the program, instructors brought to the attention of the crew a total of 30.5% of errors, compared to 9.4% on day two.

Observers noted that instructors would frequently point out to the crew an error they had committed during the LOFT scenario, such that a brief discussion point could take place, and that the instructional benefit of the error could be maximised. Similarly, an instructor might freeze the simulator, and debrief the crew on a specific error they had committed, before repositioning the simulator for a repeat of the exercise.

These findings and observations clearly highlight the different instructional foci of the training-oriented day one program, and the proficiency evaluation orientation of day two, and indicate how error management training might best be integrated within the traditional simulator-based training curriculum of commercial airlines.

From the perspective of effective instruction, the need for timely analysis and feedback on performance is suggested as a critical component of any error management training program. Observers noted the frequency with which crew had difficulty recalling details of the training session during any analysis of performance in the post-session debrief. It was apparent that due to the four-hour length of the simulator-based training sessions, and the fatiguing aspects of the training itself, the instructional benefits of the post-session debrief might be limited at best. Similarly, the results of this study support the role of non-jeopardy forms of training as the foundation of simulator-based threat and error management training programs. The freedom non-jeopardy forms of training offer instructors and crew with respect to the detailed instructional analysis of performance are important elements to be formally embedded within any error management training program.

3.2.3 Error Response and Outcome

The second stage of error management involves the effective response to the error event, and the mitigation of any negative consequences that might arise from the error. This stage of error management is predicated on error detection, as quite simply, if a crew are not aware of the error, or of the problem-state that arises from the error, they are unable to positively take any action to mitigate the consequences of the error. The table below provides a summary of the distribution of error response according to the eleven broad categories of error observed during the study.

Table Thirteen: Error Response

Error Type	Managed	Mismanaged	Undetected
Aircraft Handling	53.8	29.8	17.3
Flight Management Computer Errors	73.7	0.0	26.3
Flight Controls and Configuration	70.8	4.2	25.0
Mode Control Panel Errors	66.7	0.0	33.3
Aircraft Systems	58.6	6.9	34.5
Communications	54.5	0.0	45.5
Checklist	70.0	0.0	25.5
Callouts	19.2	3.8	76.9
Briefing and Planning	60.0	10.0	30.0
Cross-Check	0.0	0.0	100.0
Workload Assignment and Management	46.2	7.7	46.2

Frequency expressed as a percentage of errors observed in each category (N=277)

As evident in the table above, there appears to be considerable practical differences in the distribution of error response with respect to the type of error that occurred. For instance, while only 17.3% of *Aircraft Handling* errors were not detected, this error phenotype was the most frequently mismanaged by the crews with a total of 29.8% of these errors resulting in an additional error or undesired aircraft state. Conversely, 100% of all *Cross-Check* errors and 76.9% of all *Callout* errors were not detected.

As with other aspects of threat and error management, a range of non-technical skills have been found to be essential determinants of effective crew performance. With respect to effective error management, the key indicators were: 1) *Vigilance* (47.7%); 2) *Problem Identification* (45.7%); 3) *Monitoring and Cross-Check* (43.1%); *Communication Environment* (27.5%); and 5) *Cooperation* (24.2%). Accordingly, these five non-technical skills appear to be important aspects of effective error management. These findings are summarised in Figure Seven below.

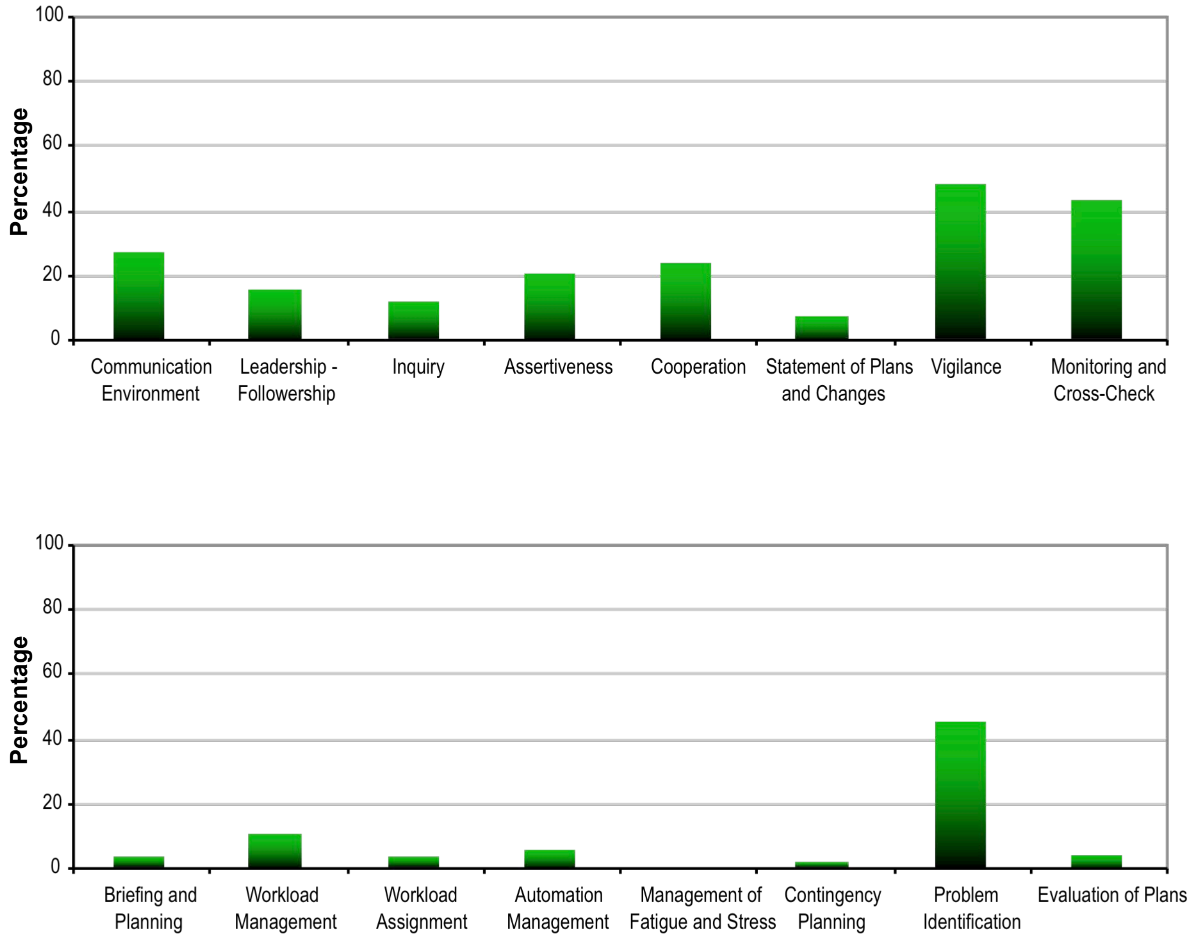


Figure Seven: Indicators of Effective Error Management (percentage of ratings "adequate" or above for effectively managed error events N=153).

Considerable practical differences were also evident in relation to the outcome of errors that occurred during training. As summarised in Table Fourteen below, the majority of error phenotypes had very low levels of negative consequence in the form of additional errors or undesired aircraft states. However, error phenotypes such as *Aircraft Handling* errors, *Callout* errors, *Mode Control Panel* errors and *Workload Assignment and Management* errors were all associated with elevated levels of consequential outcome.

Table Fourteen: Error Outcome

Error Type	**Inconsequential**	**Undesired State**	**Additional Error**
Aircraft Handling	62.5	31.7	5.8
Flight Management Computer Errors	100	0.0	0.0
Flight Controls and Configuration	91.7	8.3	0.0
Mode Control Panel Errors	88.9	11.1	0.0
Aircraft Systems	89.7	3.4	6.9
Communications	54.5	0.0	45.5
Checklist	100	0.0	0.0
Callouts	61.5	34.6	3.8
Briefing and Planning	100	0.0	0.0
Cross-Check	100	0.0	0.0
Workload Assignment and Management	78.7	17.7	3.6

Frequency expressed as a percentage of errors observed in each category (N=277)

With respect to errors that were not effectively managed by crews, the five key non-technical markers were: 1) *Monitoring and Cross-Check* (46.8%); 2) *Vigilance* (46.0%); 3) *Problem-Identification* (37.9%); 4) *Assertiveness* (21.8%) and; 5) *Workload Assignment* (16.9%). Accordingly, these five non-technical skills appear to be important indicators of poor error management. These findings are summarised in Figure Eight below.

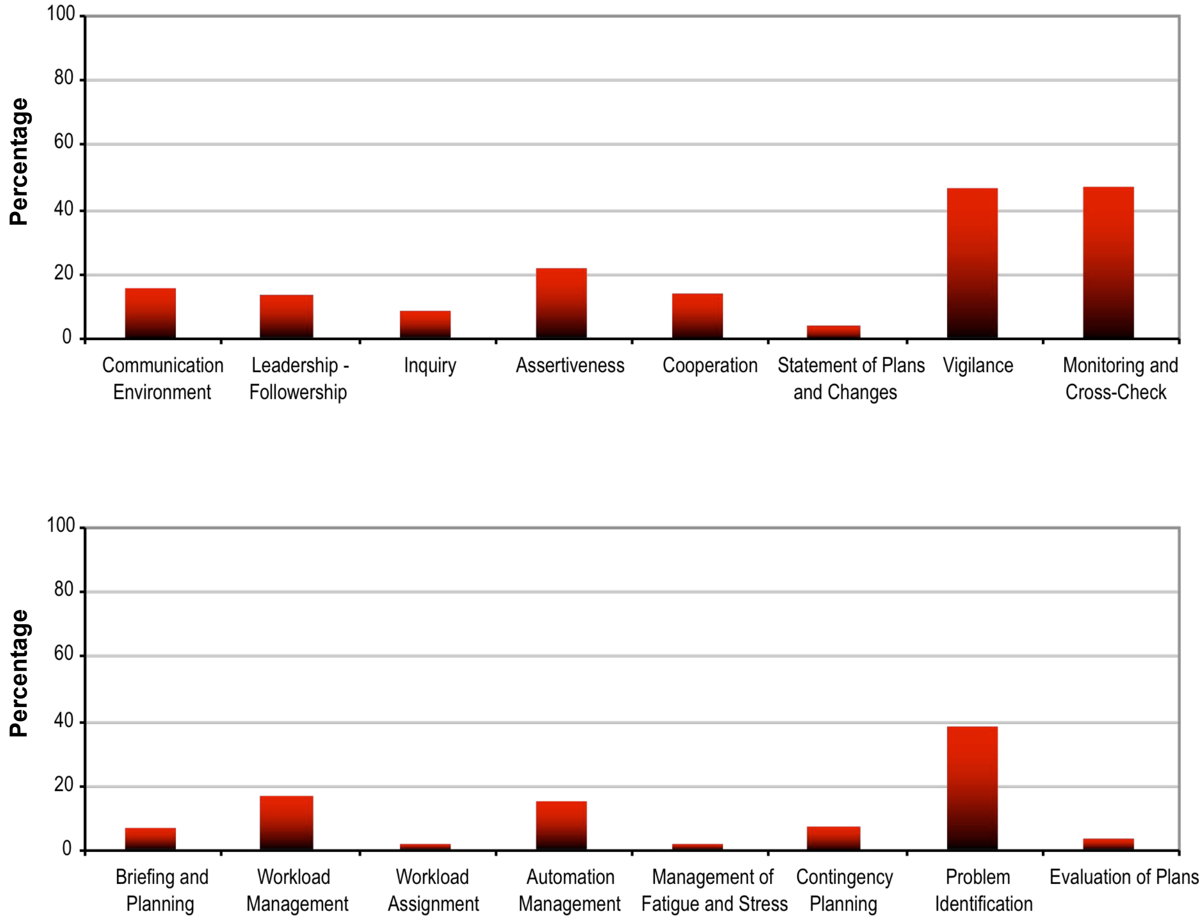


Figure Eight: Indicators of Poor Error Management (percentage of ratings below "adequate" for mismanaged error events N=124).

3.2.4 Instructional Aspects of Error Occurrence and Management

The manner in which error events were utilised as an element of the overall training process provides important information that can inform the development of a formal error management training curriculum.

Table Fifteen: Instructional Aspects of Error Management

Instructional Aspects	Day One	Day Two
Instructor acknowledged the error	76.6	64.4
Error was discussed in simulator	56.3	48.3
Error was discussed in debrief	39.8	59.1
Timely detection of error was discussed	3.1	6.0
Strategies for error prevention were discussed	34.4	39.6
General threat and error management was discussed	6.3	8.7

Frequency expressed as a percentage of all errors observed (N=277)

As summarised in the table above, it was found that the instructor acknowledged the majority of errors committed by crews. In general terms, the instructor discussed in detail 52.0% of errors in the simulator, and 50.2% of errors during the post-session debrief. 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 were led to undesired aircraft states were debriefed by the instructor in the simulator significantly more frequently that any errors that were inconsequential, $\chi^2(2, N=277) = 11.236$, $p < .01$. 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.

4 DISCUSSION AND CONCLUSIONS

4.1 Instructional Use of Threat and Error

While the Threat and Error Management model is a relatively new addition to our understanding of safety in commercial airline operations, the concepts contained in the model have been developed from our knowledge with respect to the everyday occurrence of operational complexities. These operational complexities in turn are known to act as error producing conditions, increasing the likelihood of error occurrence, above the baseline rate of spontaneous error occurrence. Accordingly, the use of the Threat and Error Management model in the simulator-based training environment offers a number of benefits towards the enhancement of current training programs, and aviation safety in general.

4.1.1 Operational Fidelity

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. This form realism has been termed *operational fidelity* when applied to the simulator-based training curriculum (Thomas, 2003b).

High levels of operational fidelity in simulator-based training can be utilised to assist in the development of a wide range of both technical and non-technical skills. In particular, threat and error management data collected from the airline's normal flight operations can be utilised to shape the actual simulator-based training curriculum. In this manner, the overall training systems design of the airline can be seen to be *responsive* to actual operational requirements of the airline, building on identified strengths, and addressing any thematic weaknesses observed within fleets.

4.1.2 Embedding Error Avoidance, Detection and Response Strategies

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. Each unique type of threat is matched with a broad set of common error phenotypes and error genotypes. 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 that 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. This approach to error management training can specify the application of threat and error management competencies to predefined operational events, and develop real applied skills in threat and error management.

4.1.3 Operation Towards the Edge of the Safety Envelope

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. This approach to threat and error management has recently been emphasised in the military aviation environment as crucial in the development of skills in the recovery of safety critical situations, and the development of confidence in the mitigation of consequential errors (Naikar & Saunders, 2003).

As the results from the first study of the current research project clearly identified, the creation of clear "fences" with respect to the acceptable boundaries of safe operation is a critical component of both error avoidance and error detection (Thomas & Petrilli, 2004). To this end, error-management training within the simulator-based training environment should provide adequate opportunity for crew to explore the margins of safe operation, and experience transgression of the safety envelope, as an important component of developing skills in key error management strategies.

4.2 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.

4.2.1 Opportunities for Instructional Interaction

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 of a commercial airline. The study has reinforced the intuitive suggestion that less opportunities exist for detailed development of skill and exploration of generic non-technical competencies within the context of the ongoing evaluation of pilot proficiency. This study demonstrated that more detailed exploration of threat and error management principles was infrequent in general, yet better opportunities existed for such an instructional focus during LOFT scenarios and during exercises which emphasised a training, rather than checking, focus.

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.

Simulator-based training that adopts a LOFT format enables the application of critical multi-crew processes that underpin effective threat and error management. Furthermore, 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.

4.2.2 The Use of "Gotchas"

One important focus for error management training, that was evident in the survey of current practice, involved considerable attention being paid to 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 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 airline's simulator-based training program.

4.2.3 Integrating Technical and Non-Technical Skill Development

While this study has provided a number of insights from current practice, the results of this study have also emphasised an overall lack of attention being paid to generic threat and error management strategies 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 skills 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 use of advanced technology in training (Hörmann, 2001).

The non-technical skills associated with both effective and poor threat and error management were seen to include a set of core skills that were coded consistently as the most frequent mediators of crew performance. The three most frequently identified skills were: 1) *monitoring and cross check*; 2) *vigilance*; and 3) *problem identification*. These findings add further support to the findings of the first study of the current research project that highlighted the role of situation awareness and accurate mental model creation in the overall process of error management (Thomas and Petrilli, 2004).

Accordingly, error management training programs must embed strategies to effectively integrate technical and non-technical skill development. For instance, with an exercise such as a non-precision approach, integrated error management training would simultaneously focus on the procedural processes and aircraft handling techniques involved, alongside the non-technical skills involved in planning, monitoring, decision-making and communication. By unpacking the specific non-technical skills used in the avoidance, detection, and response to errors that occur during each operational event, an error management training program is able to embed tangible development of non-technical competencies that form the foundation of error management.

4.2.4 Curriculum Development

This study has demonstrated the need for considerable ongoing development of the content, structure and instructional processes involved in error management training within the context of commercial aviation. 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 2) the instructional approaches adopted in the implementation of the training.

The results of this study, while providing considerable insight into the informal processes used by experienced instructors with respect to threat and error management in simulator-based training, cannot alone inform the development of an error management training curriculum without reference to the results of study one, which explored in detail the error management strategies used by pilots in normal flight operations (Thomas and Petrilli, 2004).

The next steps in the development of error management training programs involve an integrated synthesis and amplification of the results of the current two studies towards the development of a broad curriculum specification for error management training. Once this task is completed, further work will involve the development of detailed competency specifications using the knowledge and skill dimensions provided in this initial curriculum framework. Finally, 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 within commercial aviation.

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REFERENCES

Dekker, S. W. A. (2003). Illusions of Explaination: A Critical Essay on Error Classification. *International Journal of Aviation Psychology, 13*(2), 95-106.

Helmreich, R. L. (2000). On error management: lessons from aviation. *British Medical Journal, 320*, 781-785.

Helmreich, R. L., Klinect, J. R., & Wilhelm, J. A. (1999). Models of threat, error and CRM in flight operations. In R. S. Jensen (Ed.), *Proceedings of the Tenth International Symposium on Aviation Psychology* (pp. 677-682). Columbus, OH: Ohio State University.

Helmreich, R. L., & Merritt, A. C. (2000). Safety and error management: The role of Crew Resource Management. In B. J. Hayward & A. R. Lowe (Eds.), *Aviation Resource Management* (pp. 107-119). Aldershot, UK: Ashgate.

Hörmann, H.-J. (2001). Cultural variation of perceptions of crew behaviour in multi-pilot aircraft. *Le Travail Humain, 64*(3), 247-268.

ICAO. (2002). *Line Operations Safety Audit (LOSA)*. Montreal, Canada: International Civil Aviation Organisation.

Johnston, N. (1997). Teaching human factors for airline operations. In G. J. F. Hunt (Ed.), *Designing instruction for human factors training in aviation* (pp. 127-160). Aldershot, UK: Ashgate.

Klinect, J. R. (2002). LOSA searches for operational weaknesses while highlighting systemic strengths. *International Civil Aviation Organisation (ICAO) Journal, 57*(4), 8-9, 25.

Klinect, J. R., Wilhelm, J. A., & Helmreich, R. L. (1999). Threat and Error Management: Data from Line Operations Safety Audits. In R. S. Jensen (Ed.), *Proceedings of the Tenth International Symposium on Aviation Psychology* (pp. 683-688). Columbus, OH: Ohio State University.

Naikar, N., & Saunders, A. (2003). Crossing the Boundaries of Safe Operation: An approach for training technical skills in error management. *Cognition, Technology and Work, 5*, 171-180.

Norman, D. A. (1981). Categorization of action slips. *Psychological Review, 88*, 1-15.

Phillips, E. H. (2000). Managing Error at Centre of Pilot Training Program. *Aviation Week & Space Technology, 153*(3), 61-62.

Rasmussen, J. (1986). *Information Processing and Human-machine Interaction: An Approach to Cognitive Engineering*. New York, NY.: Elsevier Science.

Reason, J. (1990). *Human Error*. Cambridge, UK: Cambridge University Press.

Reason, J. (1997). *Managing the Risks of Organizational Accidents*. Aldershot, UK: Ashgate.

Reason, J. (2000). Human error: models and management. *British Medical Journal, 320*, 768-770.

Rizzo, A., Ferrante, D., & Bagnara, S. (1995). Handling Human Error. In J.-M. Hoc, P. C. Cacciabue & E. Hollnagel (Eds.), *Expertise and Technology: Cognition &*

Human-Computer Cooperation (pp. 195-212). Hillsdale, NJ: Lawrence Erlbaum Associates.

Thomas, M. J. W. (2003a). Improving organisational safety through the integrated evaluation of operational and training performance: An adaptation of the Line Operations Safety Audit (LOSA) methodology. *Human Factors and Aerospace Safety, 3*(1), 25-45.

Thomas, M. J. W. (2003b). Operational Fidelity in Simulation-Based Training: The Use of Data from Threat and Error Management Analysis in Instructional Systems Design. In *Proceedings of SimTecT2003: Simulation Conference* (pp. 91-95). Adelaide, Australia: Simulation Industry Association of Australia.

Thomas, M. J. W. (2003c). Uncovering the origins of latent failures: the evaluation of an organisation's training systems design in relation to operational performance. In *Proceedings of the Sixth International Aviation Psychology Symposium*. Sydney, Australia: Australian Aviation Psychology Association.

Thomas, M. J. W. (2004). Predictors of Threat and Error Management: Identification of core non-technical skills and implications for training systems design. *International Journal of Aviation Psychology, 14*(2), 207-231.

Thomas, M. J. W., & Petrilli, R. M. (2004). *Error Management Training: An Investigation of Expert Pilots' Error Management Strategies During Normal Line Operations and Training - Study One Report* (No. 2004/0050 - ATSB Aviation Safety Research Grant Scheme Project). Adelaide, SA: University of South Australia.

Thomas, M. J. W., Petrilli, R. M., & Dawson, D. (2004). An Exploratory Study of Error Detection Mechanisms in Normal Line Operations. In *Proceedings of the 26th Conference of the European Association for Aviation Psychology*. Lisbon, Portugal: European Association for Aviation Psychology.

Williams, J. C. (1988). A Data-based Method for Assessing and Reducing Human Error to Improve Operational Performance. In E. W. Hagen (Ed.), *IEEE Fourth Conference on Human Factors and Power Plants*. New York, NY.: Institute of Electrical and Electronics Engineers.

Wreathall, J., & Reason, J. (1992). Human errors and disasters. In *Proceedings of the 1992 IEEE Fifth Conference on Human Factors and Power Plants, Monterey, California* (pp. 448-452). New York: IEEE.