UNIVERSITY OF SOUTHAMPTON

FACULTY OF ENGINEERING AND THE ENVIRONMENT

Transportation Research Group

Individual Latent Error Detection (I-LED) in UK Naval Aircraft Maintenance

By

Justin R.E. Saward

Thesis for the degree of Doctor of Philosophy

September 2017

UNIVERSITY OF SOUTHAMPTON

<u>ABSTRACT</u>

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System-induced human error is the most significant factor in aircraft accidents; for which errors are both inevitable and a frequent occurrence. Human error is a by-product of performance variability caused by system failures, for which undetected error becomes a latent error that can impact system safety and therefore contribute to a future undesired outcome. The phenomenon of Individual Latent Error Detection (I-LED) is proposed. I-LED refers to the detection of workplace latent errors at some point post-task completion through the recollection of past activity by the individual who suffered the error. An extensive literature review shows the phenomenon to be a novel concept, indicating a clear gap in knowledge requiring research to explore the nature and extent of I-LED events. A multi-process theory is developed and combined with the systems perspective to provide a theoretical framework upon which to conduct real-world observations of I-LED events in cohorts of naval air engineers. Collected data indicate time, location and other system cues trigger I-LED events, for which the deliberate review of past activity within a time window of two hours of the error occurring and whilst remaining in the same sociotechnical environment to that which the error occurred appears most effective. Several practicable interventions are designed and tested, from which the overall benefit of integrating the I-LED phenomenon as an additional safety control within an organisation's safety system is assessed.

This thesis contributes to knowledge on workplace safety by applying systems thinking to understand the nature and extent of I-LED and its benefit to safety resilience in naval aircraft maintenance through enhanced operator competence to detect latent errors. I-LED research arguably offers a step-change in safety thinking by offering a level of resilience within the workplace that has not previously been accounted for in organisational safety strategies.

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Declaration of Authorship

I, **JUSTIN SAWARD**, declare that this thesis entitled

"Individual Latent Error Detection in UK Naval Aircraft Maintenance"

and the work presented in it are my own and has been generated by me as the result of my own original research. I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at this University;

2. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;

3. Where I have consulted the published work of others, this is always clearly attributed;

4. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;

5. I have acknowledged all main sources of help;

6. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;

7. Either none of this work has been published before submission, or parts of this work have been published as:

Journal Papers

Saward, J.R.E., Stanton, N.A., 2015a. Individual latent error detection and recovery in naval aircraft maintenance: introducing a proposal linking schema theory with a multi-process approach to human error research. *Theoretical Issues in Ergonomics Science*, 16(3), 255-272.

Saward, J.R.E., Stanton, N.A., 2015b. Individual latent error detection: Is there a time and a place for the recall of past errors? *Theoretical Issues in Ergonomics Science*, 16(5), 533-552.

Saward, J.R.E., and Stanton, N.A., 2017. Individual Latent Error Detection: A Golden Two Hours for Detection. *Applied Ergonomics,* 59, 104-113.

Saward, J.R.E., and Stanton, N.A., 2018. Individual Latent Error Detection: Simply stop, look and listen. *Safety Science*, 101, 305-312.

Awards

Honourable Company of Air Pilots (Saul) Prize for Aviation Safety Research: Awarded to an early-career researcher for research that has informed aviation Human Factors (2015)

Signed: ....

Date: ....

Acknowledgements

This research would not have been possible without the financial support provided as part of the Royal Navy's individual academic studies programme. Data could not have been collected without the open access provided by the aircraft squadrons and naval air engineers observed in the various studies, and I would like to offer my sincere thanks to squadron management and higher command for approving the studies.

I would also like to offer my thanks to my supervisor, Professor Neville Stanton. I have been immensely privileged and grateful to work under his expert supervision; his direction and guidance has brought real clarity and application to my research throughout the process.

To my wife and kids whose loving support, patience and quiet suffering have underpinned my ability to conduct this research over the years. Being absence from the family working on my PhD for long hours, invariably missing meal times and my almost total withdrawal from social gatherings with family and friends is in the past. This PhD is as much their achievement as it is mine – thank you Victoria, Alexander and Clara.

And to my folks whose unwavering support and inspiration throughout my academic and professional endeavours in life have given me great strength to achieve so much. Mum, I'm so sorry you didn't get to see this PhD finished before you ran out of time.

List of Abbreviations

AAIB	Air accident investigation branch
AEO	Air engineer officer
AET	Air engineer technician
AFS	After flight servicing
ASIMS	Air safety information management system
AMCO	Air maintenance coordination office
BU	Bottom-up
C	Control
CBA	Cost benefit analysis
CFQ	Cognitive failures questionnaire
CIT	Critical incident technique
CoI	Cost of investment
DASOR	Defence air safety occurrence report
EGR	Engaged ground run
FAA	Federal aviation authority
GEMS	Generis error modelling system
GB	Gearbox
H	Hazard
HEI	Human error identification
HFACS	Human factors analysis and classification system
HFE	Human factors and ergonomics
HFI	Human factors integration
HSE	Health and safety executive
I-LED	Individual latent error detection
IR	Intentional review
JSP	Joint service publication
LAET	Leading air engineer technician
LE	Latent error
LED	Latent error detection
LES	Latent error searching
MAP	Military airworthiness publication
MEDA	Maintenance error/event decision aid
MF700	Aircraft document
MoD	Ministry of Defence

MRGB	Main rotor gearbox
MTF	Maintenance test flight
MxMHr	Maintenance man-hour
PCM	Perceptual cycle model
PIS	Participant information sheet
PM	Prospective memory
PPE	Personal protective equipment
PSF	Performance shaping factor
PTF	Partial test flight
ROI	Return on investment
RN	Royal Navy
RtL	Risk to life
SA	Situational awareness
SF	System failure
SLL	Stop, look and listen
SRK	Skill, rule or knowledge
STS	Sociotechnical system
SQEP	Suitably qualified and experienced personnel
TD	Top-down
TRB	Tail rotor blade
TSM	Total safety management
UK	United Kingdom
UR	Unintentional review
VPF	Value of prevented fatality

Chapter 1: Introduction

1.1 Background

System-induced human error is recognised widely as the most significant factor in aircraft accidents; for which error is both inevitable and a frequent occurrence (Reason, 1990; Hollnagel, 1993; Maurino et al., 1995; Perrow, 1999; Wiegmann and Shappell, 2003; Flin et al., 2008; Woods et al., 2010; Amalberti, 2013). The potential consequences of system-induced error in safety critical contexts is universally understood, both in civilian and military environments where undetected error leads to a latent error that can contribute to a future system failure (Helmreich, 2000; Shorrock and Kirwan, 2002; Wiegmann and Shappell, 2003; Flin et al., 2008; Reason, 2008; Woods et al., 2010; Aini and Fakhru'l-Razi, 2013). This can occur when there is inadequate control of human performance variability due to deficiencies in the safety system caused by sociotechnical factors that influence safety behaviour (Leveson, 2004; Woods et al. 2010). Rarely is an organisational accident the result of a single cause (Perrow, 1999; Amalberti, 2013) thus it is often the confluence of more than one latent error that can create a causal path to an organisational accident (Reason, 1997; Perrow, 1999; Matsika, 2013).

The detection of latent errors has been observed amongst air engineers within UK naval aircraft maintenance, which does not appear to be wholly attributable to established safety management systems designed to defend against system deficiencies that can lead to human error. During the normal course of his employment as a serving Royal Navy Air Engineer Officer (AEO), the author observed occasions of workplace latent errors that were detected at some point post-task completion through the recollection of past activity by the individual who suffered the error. This Individual Latent Error Detection (I-LED) phenomenon appeared to be spontaneous since recall was unplanned and occurred without making a conscious decision to review past activity or cued from a formal process check or through an independent inspection by a third party. Examples include the later realisation that a tool wasn't removed from the aircraft engine bay, an oil filler cap wasn't replaced after replenishing the reservoir or the aircraft documentation wasn't completed correctly. More general everyday failures might be the spontaneous realisation that the gas hob had been left on or the door of their car or house wasn't locked. All examples could lead to unwanted consequences, if left undetected.

To understand the nature and extent of this phenomenon, an extensive literature review of wide-ranging publications shows system causes of human error effects have been researched widely, as has error avoidance and proximal detection, but no specific research appears to be available on I-LED. This confirms the phenomenon to be a novel concept and therefore a gap in knowledge exists that requires research.

System thinking transfers the emphasis from seeking individual human failings to understanding the network of sociotechnical factors that can cause system failures (Leveson, 2011). The systems view favours this macro-ergonomic approach to safety rather than the micro-ergonomic lens that can overly focus on individual human failings (Zink et al., 2002; Murphy et al., 2014). Thus macro-ergonomic analysis explores interactions across sociotechnical systems or networks between elements comprising humans, society, the environment and technical aspects of the system including, machines, technology and processes (Emery and Twist, 1960; Reason and Hobbs, 2003; Woo and Vincente, 2003; Walker et al., 2008; Amalberti, 2013; Wilson, 2014; Niskanen et al., 2016). These networks can be complex in terms of the number interactions between systemic factors such as tools, equipment, procedures, decision-making, operator training and experience and operating contexts (Edwards, 1972; Reason, 1990) and is where progressive safety strategies recognise that every element of the Sociotechnical System (STS) contributes to the organisation's safety goals through specific roles, responsibilities, relationships and safety behaviours (Flin et al., 2008; Woods et al., 2010; Plant and Stanton, 2016). Naval aircraft maintenance is typical of a complex sociotechnical network in a safety critical organisation and thus macro-ergonomic analysis of safety factors impacting the human performance of naval air engineers aligns to systems thinking but with a human-centred approach, as individual safety behaviour is of particular interest in the current research.

In the absence of specific research on the spontaneous recall of latent errors, a new multi-process theoretical framework is developed from existing theories on Prospective Memory (PM), Supervisory Attentional System (SAS) and schema theory. Schema theory is characterised through the Perceptual Cycle Model (PCM), which describes a cyclic relationship between schema selection and sensory cues in the external world that trigger human actions (Neisser, 1976). The PCM therefore helps with understanding cognitive safety behaviours in the natural workplace environment (Smith and Hancock, 1995; Stanton et al., 2009a; Plant and Stanton, 2013a). The multi-process framework is combined with the systems perspective to observe the I-LED experiences of cohorts of naval air engineers during normal aircraft maintenance activity, which is argued to offer a methodology that is congruent with progressive systems research in Human Factors and Ergonomics (HFE: Carayon, 2006). Using this methodology, naturalistic studies identify sociotechnical factors that facilitate I-LED events. The findings from these studies provide direction for the design and testing of several practicable I-LED interventions, which deliberately help air engineers engage with system cues such as workplace objects and written words.

Organisational accidents are the consequence of system hazards that can cause harm to people, equipment and the environment that have not been controlled adequately due to deficiencies in safety controls designed to mitigate for the inevitability of performance variability (Reason, 1997; Leveson, 2011). A resilient safety system is dependent on adequate safety controls (Reason, 2008; Woods et al., 2010; Amalberti, 2013; Hollnagel, 2014). The risk of uncontrolled hazards transitioning to latent errors is explored through an I-LED model derived from adapted bowtie analysis, which builds on Reason's (1997) barrier method to illustrate the use of system controls to restore safety equilibrium before an undetected casual path escalates to cause harm. Its ability to facilitate a better understanding of how hazards can be controlled through a simple diagram is widely recognised and has been embedded within safety systems associated with industries such as oil and gas, Defence, medical and aviation (Duijm, 2009; Khakzad et al., 2012; Matsika et al., 2013). The I-LED model is used in the current research to provide a simple pictorial representation of how I-LED interventions act as an additional safety control, and therefore contribute to safety resilience in an organisation. Here it is argued a total safety approach using I-LED interventions integrated within the overall safety system benefits resilience by providing further mitigation for human performance variability in the workplace. In support of this argument, new models for organisational resilience and operator competence are proposed to demonstrate how enhanced safety behaviours through I-LED interventions can help optimise safety in the workplace. To argue the costs versus benefits of integrating I-LED interventions within an existing safety system, financial costs and other resourcing implications are considered to complete knowledge on the nature and extent of the proposed I-LED phenomenon and its benefit to safety resilience in naval aircraft maintenance.

1.2 Aim and Objectives

The aim of this thesis is to address a gap in knowledge by understanding the nature and extent of I-LED and its benefit to safety resilience in UK naval aircraft maintenance. Thus the aim is not to explain why errors occur or offer new error avoidance strategies; it is to understand the I-LED phenomenon from a systems perspective so that safety-related interventions can be developed that help optimise organisational safety resilience. I-LED is the effect (dependent variable) to be observed with sociotechnical cues, present in the world, providing the triggers for recall.

To achieve this aim, research is framed around the following objectives:

- **Objective 1**: Using a human-centred systems approach, develop a theoretical framework to observe the I-LED phenomenon.

- **Objective 2**: Apply the theoretical framework to understand the nature and extent of I-LED events in naval air engineers working in their natural environment.

- **Objective 3**: Identify practicable interventions that enhance I-LED events in safety critical contexts.

- **Objective 4**: Understand the effectiveness of I-LED interventions in the workplace.

- **Objective 5**: Assess the benefit of integrating I-LED interventions within organisational safety strategies to enhance resilience.

1.3 Thesis Structure

This thesis comprises ten chapters to address the five objectives using three linked observational studies to investigate the I-LED phenomenon in cohorts of naval air engineers working in their normal operating environment.

Chapter 1 – Introduction

This chapter introduces the I-LED phenomenon observed in naval aircraft maintenance before stating the aim and objectives followed by a summary of each chapter and a description of the contribution to knowledge.

Chapter 2 – Application of multi-process theory to I-LED research

This chapter presents a review of human error detection literature and provides the context for research. Despite an extensive literature review, the nature and extent of this phenomenon is not understood fully and appears to be an under-researched area; causes of error and proximal error detection having been researched widely. To explore this phenomenon, a new theoretical framework is introduced based on a multi-process systems approach that combines theories on PM, SAS and schemata. Several examples from a UK military safety database are then analysed for existence of the phenomenon and evidence of the applicability of the multi-process approach. Thus the intent is not to explain why human error occurs; it is to develop a theoretical framework upon which to observe how an individual who suffered an error later detects their error without any apparent deliberate attempt to recall past activity.

Chapter 3 – Rationalising systems thinking with the term 'human error' for progressive safety research

During the review of human error detection in Chapter 2, it is noted that some concerns exist over the use of the term human error in contemporary systems thinking, as it can be misused at the micro-ergonomic level to blame individuals rather than signpost the opportunity to tackle deficiencies within the STS that caused the error. This chapter looks to authorise the use of the term by considering literature on this concern. The term human error is argued to remain meaningful when conducting HFE research from a systems perspective and therefore does not need to be excluded from progressive safety research such as I-LED. As with any lexicon terms must be used correctly, for which human error is simply a sub-set of macro-ergonomic systemic factors that flags the requirement for HFE analysis of systemic factors. As such, the term is used universally in the current I-LED research where naval air engineers create safety through their own I-LED events, triggered by system cues available in the surrounding sociotechnical environment.

Chapter 4 – Observing I-LED events in the workplace

To observe the nature and extent of I-LED, an I-LED model is derived from bowtie analysis to conceptualise the phenomenon and anticipate where I-LED events offer the greatest safety value as an additional safety control against the potential confluence of latent errors that risk an organisational accident. The application of appropriate theory and method selection to yield meaningful results from the population of naval air engineers is also reviewed. To help ensure quality data are captured, and to remain flexible to emergent findings, a series of linked studies using a mixture of methodologies are introduced. This strategy also accommodates changes to the research design if emergent findings materialise that require a different methodology or revision to the current research. This chapter also recognises that conducting real-world observations in the workplace is challenging when compared to observations made in a laboratory setting, where strict experimental control can be achieved. However advances in safety research come from exploring normative behaviours during normal operations and this advantage is argued to outweigh the challenges of real-world research.

Chapter 5 – A time and a place for the recall of past errors

This chapter describes an exploratory study involving the target population of naval air engineers using a questionnaire that was administered during group interviews. It was hypothesised that time, location and systems cues influence I-LED amongst air engineers who had experienced the phenomenon. The systems view of human error is combined with a multi-process theory to explore the I-LED phenomenon, for which the findings suggest that the effective cognition of cues distributed across the STS triggers post-task I-LED events. The exploratory study makes the link to safety resilience using a systems approach to minimise the consequences arising from latent error and provides direction for further research.

Chapter 6 – A golden two hours for I-LED

The findings from Chapter 5 provide direction for a second study described in this chapter. The detection of latent errors post-task completion is observed in a further cohort of naval air engineers using a diary to record work-related I-LED events. The systems approach to error research is again combined with multi-process theory to explore sociotechnical factors associated with the I-LED phenomenon. Perception of cues in different environments facilitates successful I-LED where the deliberate review of past tasks within a time window of two hours of the error occurring, and whilst remaining in the same sociotechnical environment to that which the error occurred, appears most effective at triggering recall. Several practicable interventions offer potential mitigation for latent errors; particularly in simple everyday habitual tasks. The chapter concludes with the view that safety critical organisations should look to engineer further resilience through the application of I-LED interventions that deliberately engage with system cues across the entire sociotechnical environment to trigger recall, rather than relying on consistent human performance or chance detections.

Chapter 7 – I-LED interventions: Visual, verbal and a stop, look and listen

Human error is a by-product of performance variability caused by system failures, for which the accumulation latent errors that can lead to an undesired outcome. Knowledge of the nature and extent of the I-LED phenomenon gained from the two earlier studies are combined to design and test several practicable I-LED interventions aimed at defending against the networking of latent errors that can lead to an organisational accident or degradation in system performance. The I-LED interventions are tested on a further cohort of naval air engineers. Of those tested, a simple stop, look and listen intervention is found to be the most effective. The application of I-LED interventions are argued to offer a further step-change in safety thinking by helping to manage system induced human error effects through the deliberate engagement with cues that trigger recall; thereby facilitating Safety II events. Successful I-LED limits occasions for adverse outcomes to occur, despite the presence of existing control strategies, and thus should be of benefit to any safety critical organisation seeking to enhance resilience in their existing safety system.

Chapter 8 – Organisational resilience through a total safety management approach to system safety

To understand how I-LED interventions might benefit an organisation's safety system, literature on human-centred safety strategies is reviewed. It is argued resilience comes from a total safety approach that optimises sociotechnical controls at the organisational level through to the management of safety by individual operators in the workplace. A review of literature finds few models that describe an agreed safety strategy for managing organisational resilience thus a Total Safety Management (TSM) model is proposed that highlights the hierarchical relationship between safety 'as done' by competent operators through to the 'as designed' safety system. It is further argued resilience is dependent upon the system's ability to promote safe behaviours during interactions between humans and operating environments, which is predicated on the presence of competent operators in the safety network.

Chapter 9 – Assessing the benefits of I-LED interventions

This chapter considers the costs versus benefits of integrating I-LED interventions within an organisation's existing safety system. Cost Benefit Analysis (CBA) literature indicates that the main benefit of I-LED interventions comes from their integration with the organisation's safety system to form part of an enduring long-term safety strategy to engender and control safety behaviours in the workplace, which is discussed in the previous chapter. The integration of I-LED interventions as an additional safety control to help mitigate for system failures offers physical benefits in terms of reduced injuries or death, equipment damage and economics gains as well as intangible socio-political effects and non-technical attributes such as improved operator empowerment and job satisfaction. It is found that I-LED interventions are difficult to cost in financial terms due to often intangible cost data, although it is argued the typical interventions discussed in this chapter do not attract significant costs to introduce and maintain long-term. Analysis of safety failures recorded in a military database show several occasions where the perceived safety severity of a reportable event was high or medium. Here it is argued that use of an I-LED intervention might have prevented the safety failure, which suggests significant ROI is achievable for safety critical organisations aiming to maximise the heroic abilities of its operators.

Chapter 10 – Conclusions and Future Work

The aim of this thesis is to contribute to knowledge by understanding the nature and extent of the proposed I-LED concept and its benefit to safety resilience in UK naval aircraft maintenance. The final chapter concludes the thesis with a summary of findings against the five objectives, which support the aim. The novel contributions of this research are reviewed along with an evaluation of the approach to research and directions for future work. Concluding remarks offer a final statement of how I-LED interventions should be integrated within the safety system to offer safety benefits in naval aircraft maintenance but also wider populations comprising safety critical organisations.

1.4 Contribution to Knowledge

The research presented in this thesis contributes to knowledge on workplace safety by applying systems thinking to explore the I-LED phenomenon. This advances systems thinking and should benefit any safety critical organisation seeking gains in safety resilience. Multi-process theory combined with a macro-ergonomic perspective is argued to provide a suitable theoretical framework upon which to observe the I-LED experiences of cohorts of naval air engineers working in their natural environment. This approach confirms the presence of the I-LED phenomenon, for which I-LED events are likely to offer further mitigation for human error effects resulting from deficiencies in safety strategies designed to control hazards in the workplace. The deliberate review of past activity within a time window of two hours of the error occurring and whilst remaining in the same sociotechnical environment to that which the error occurred appears most effective. Time, location and other system cues facilitate these I-LED events. The detection of work-related latent errors is also found to occur when in non-work environments such as at home or driving a car; indicating distributed cognition extends across multiple sociotechnical networks. I-LED is found to be common in simple everyday habitual tasks carried out alone where perhaps individual performance variability is most likely to pass unchecked, with the potential for errors to pass undetected. Application of a Cognitive Failures Questionnaire (CFQ) confirms that the target population of naval air engineers exhibit normal cognitive behaviours associated with wider populations of skilled operators. The testing of several I-LED interventions, designed to focus operator attention on system cues such as equipment or written words, shows a stop, look and listen intervention to be most effective at detecting latent errors in the workplace. I-LED interventions can therefore act as an additional system control that helps defend against latent errors, which contributes to resilience within the safety system. The safety system needs to capture this new control strategy as part of integrated safety solution to control hazards where I-LED interventions can be included in a safety strategy managed locally by individual operators using system cues present in the world.

A new model depicting organisational safety resilience highlights the benefit of I-LED interventions if integrated within the overall safety system. An underpinning competence model also argues that there are four key components that need to be considered in the design of the safety system to help control performance variability in individual operators, i.e. be suitably qualified, experienced, possess personal readiness for work and be risk responsive. A further review of literature assesses the costs versus benefits of introducing new safety interventions. Any safety intervention, including I-LED, should be founded in theory and form part of an enduring long-term safety strategy to engender and control safety behaviours in the workplace. However, it is problematical to calculate the benefit of I-LED in financial terms due to a lack of tangible cost data, although the I-LED interventions discussed are not thought to require significant financial or organisational costs to integrate within the safety system and maintain long-term.

Arguably, I-LED interventions tackle latent errors that lie hidden and propagate through the entire sociotechnical network and can therefore offer wider benefits in terms of reduced injuries or death, avoiding equipment damage and economics gains as well as socio-political effects and non-technical attributes such as improved operator empowerment. Analysis of UK military safety data highlights several safety occurrences where the perceived severity was high or medium. It is argued that use of I-LED interventions might have prevented the occurrence and thus they are thought to offer significant return of investment (ROI) to safety critical organisations aiming to maximise the heroic abilities of its operators through I-LED interventions.

Overall, this thesis contributes to knowledge on workplace safety by advancing systems thinking through the exploration of the I-LED phenomenon. I-LED interventions derived from observations of naval air engineers are likely to enhance overall safety resilience by offering further mitigation for undetected errors that can lie hidden the safety system. The I-LED ability of naval air engineers is shown to be typical of skilled operators thus knowledge gained from the current research should generalise to any safety critical organisations employing similar cohorts of skilled workers.

Chapter 2: Application of multi-process theory to I-LED research

2.1 Introduction

An error detection phenomenon has been observed amongst naval air engineers within UK operational helicopter squadrons, which does not appear to be wholly attributable to established safety mechanisms designed to defend against human error. The observations by the author, who is a serving Royal Navy Air Engineer Officer (AEO), include examples such as the experienced air engineer that replenishes the aircraft engine oil during routine aircraft servicing but fails to replace the oil filler cap or who installs an aircraft component incorrectly during maintenance. Post the error event, and at some point later (minutes through to days) whilst resting in the crew room or continuing with other work say, the error was often detected through some seemingly spontaneous recollection of past activity by the individual who suffered the error; upon which the individual was compelled to instigate a recovery. Studies have shown errors that pass undetected become latent errors where the impact of the error may not be immediately obvious due to delayed effects (Reason, 1990; Graeber and Marx, 1993; Lind, 2008); the effect being a causal path to a future unwanted safety outcome such as harm to people or equipment (Reason, 1997; Wiegmann and Shappell, 2003; Aini and Fakhru'l-Razi, 2013). The actions of the observed air engineers resulted in the detection of latent errors before the system failure caused harm.

After an extensive literature, the nature and extent of the observed Individual Latent Error Detection (I-LED) phenomenon appears to be an under-researched area and is therefore not understood fully. The literature review is summarised in Table 2.1, which included wide-ranging publications describing human error and recovery in cognitive and systems terms as well as a review of the UK's Aviation Safety Information Management System (ASIMS) database. How individuals come to suffer error effects is well covered in literature, where human error is widely reported to be inevitable and a daily occurrence (Norman, 1981; Reason, 1990; Hollnagel, 1993; Perrow, 1999; Wiegmann and Shappell, 2003; Flin et al., 2008; Woods et al., 2010). If human error is common by-product of human performance, it is anticipated the proposed I-LED phenomenon is also prevalent.

Table 2.1. Syntax used in literature search.

Syntax	Search Engine	Count	Action	Cited Articles
In title: individual AND latent AND error(s) AND detection OR recovery	Scopus	18	All reviewed	0
	University of Southampton DelphiS	20	All reviewed	
	Google Scholar	6	All reviewed	
	Web of Knowledge	6	All reviewed	
In topic: human OR error detection OR recall NOT software NOT computer(s) NOT computing	Scopus	848	Top 500 citations	69
	DelphiS	220	All reviewed	
	Google Scholar	1760	Top 500 citations	
In topic: aviation OR aircraft AND maintenance AND error(s)	Scopus	395	All reviewed	15
	DelphiS	369	All reviewed	
	Google Scholar	596	All reviewed	

The first objective in the current research is to understand the proposed I-LED phenomenon through the development of a theoretical framework based on a multi-process systems approach to research, which combines theories on schemata, prospective memory and attentional monitoring. Thus the intent is not to explain why human error occurs; it is to develop a theoretical framework upon which to explain how I-LED events occur without any apparent deliberate attempt to recall past activity.

2.2 Context for Research

UK naval aviation is conducted in dynamic and complex environments, delivered around the globe; from land bases in the UK with full aircraft support facilities to deployed temporary airfields with very limited facilities, and from large multi-aircraft carriers to small single-aircraft ships. Typical examples of naval aircraft maintenance environments are provided in Appendix A. The naval air engineer operates within these operating contexts to deliver safe and effective aircraft maintenance and ground support to flying. Tasks vary significantly as the engineer transits between: the maintenance office where aircraft documentation is completed and tasks planned; the maintenance hangar; stores for parts; issue centre to collect tools; and the aircraft operating line (ramp) or ship's flight deck to launch, turn-around and also service aircraft. This sees the aircraft engineer (not just within the military) perform a great number of disparate activities during the working day, impacted by: time pressures; extremes of weather; changing maintenance requirements due to emergent work or changes to the flying programme; and resource constraints in terms of equipment, spares and people (Latorella and Prabhu, 2000; Reason and Hobbs, 2003; Patankar and Taylor, 2004; Flin et al., 2008; Woods et al., 2010; Rashid et al., 2010). For naval aviation maintenance specifically, the context is very similar to that of commercial aviation yet compounded further due to: operating aircraft from temporary airfields with very limited resources; operating from a moving platform whilst embarked in a warship; working on armed aircraft; and significant operational imperatives. Away from the aircraft, the naval air engineer will also be loaded further with extraneous duties, unrelated to aircraft maintenance, such as acting as force protection or assisting with ship general duties when deployed; all of which place additional demands on the engineer, which can lead to human performance variability that can influence error rates (Campbell and Bagshaw, 2002; Rashid et al., 2010). Additionally the total effects of man-machine interactions with advanced technologies, common in military contexts, may not be known (Kontogiannis, 1999). Thus resilience to all forms of human error is needed to avoid or mitigate for when error effects occur (Reason, 2008; Woods et al., 2010).

To construct a new theoretical framework to observe this phenomenon, the nature of human error is reviewed before describing a multi-process approach that combines theories on prospective memory, attentional monitoring and schemata with a recognised error categorisation format. Several examples from a UK military safety database are then used to facilitate initial exploration of theory as a pre-cursor to further research via later real-world studies aimed at developing system interventions to mitigate for latent error.

2.3 Nature of Error

2.3.1 *Human error*

Human error generally describes situations where either safety or the effectiveness of a task has been compromised due to human performance issues (Reason, 1990; Hollnagel, 1993; Amalberti, 2001; Wiegmann and Shappell, 2003). There are many definitions for human error. For example, Dhillion (2009, p. 4) defined error as ‘the failure to perform a specified task (or performance of forbidden action) that could result in disruption of scheduled operations of damage to equipment and property.’ UK defence aviation considers error to have occurred when ‘an aircraft or system with human interaction fails to perform in the manner expected’ (ASIMS, 2013b, p. 4) and in the maintenance context, Graeber and Marx (1993, p. 147) referred to 'an unexpected aircraft discrepancy (physical degradation or failure) attributed to the actions of the aircraft maintenance engineer.' Reason (1990, p. 9) defined error as 'a generic term to encompass all those occasions in which a planned sequence of mental or physical activities fails to achieve its intended outcome.' He also noted that people are not necessarily error prone, just more subject to error prone situations or conditions. Woods et al (2010, p. 239) proposed error to be simply the causal attribution of the psychology and sociology of an event.'

By citing just a few definitions it appears defining human error is challenging, where ambiguity and a sense of hindsight are often present. Indeed, there has been some concern that the term human error can lead to blaming individuals for system fallings as opposed to tackling wider macro-ergonomic causes, which is where organisational safety strategies should seek knowledge to make the greatest safety gains (Zink et al., 2002; Dekker, 2014). This concern is addressed in Chapter 3, which argues the term human error remains meaningful in safety analysis from a systems perspective provided it is simply used as the signpost to investigate system failures that cause error. Dhillion's (2009) definition doesn't refer to error impacting the safety of people and seems to suggest error is exclusively damage or delays to scheduled operations. The UK Defence definition links error to some unspecified performance expectation whilst Graeber and Marx (1993) suggest error to be specific to aircraft discrepancies only (rather than the totality of all aircraft maintenance activities). Hollnagel's (1993) analysis of human reliability in high-risk organisations also found human error difficult to define with most definitions having only little utility since they are often underspecified and contextually vague. In his later work on error, Reason (2008) agreed that there is no one universally agreed definition of error whilst Woods et al (2010) regard defining human error as remarkably complex with most error definitions being subjective. Thus for current research, error is argued simply to be a colloquial expression used to flag error effects or erroneous actions that must be contextualised and explained against system causes (i.e. situational error) to be a meaningful.

2.3.2 *Impact of human error in aircraft maintenance*

Human error effects are the most significant factor in aircraft accidents for both the military and civilian aviation organisations where errors occur regularly (Wiegmann and Shappell, 2003; Flin et al., 2008; Reason, 2008; Woods et al., 2010). System-induced human error is a normal by-product of human performance and a hazard to normal operating conditions that cannot be eradicated; deserving constant enquiry to identify and manage system failures causing error before an unwanted event permeates through the safety system (Reason, 1990: 2008; Amalberti and Barriquault, 1999; Helmreich et al., 1999; Dekker, 2006; Gilbert et al., 2007). Most estimates associate human error with 70-90% of accidents (Hawkins, 1987; Hollnagel, 1993; Helmreich, 2000; Adams, 2006). UK military aviation data indicate at least 70% of naval aviation safety occurrences are attributable to human errors (ASIMS, 2013a). For aircraft maintenance specifically, analysis of a major airline showed the distribution of 122 maintenance errors over a period of 3 years to be: omissions (56%); incorrect installations (30%); and wrong parts (8%) (Graeber and Marx, 1993). The Civil Aviation Authority (CAA, 2009) commissioned a study of UK civil aviation mandatory occurrence reports involving jet aircraft (years 1996-2006), which found incorrect maintenance actions and incomplete maintenance contributed 53.1% and 20.7%, respectively (total n=3284 mandatory reports). Physical examples include: loose objects left in the aircraft; fuel caps unsecured; missing components or incorrect installation; and cowlings or access panels unsecured (Latorella and Prabhu, 2000). Notably, the latter example occurred to an Airbus A320-231 where the engine cowl doors were left in the unlatched condition and resulted in the doors detaching in flight (AAIB, 2000). In the case of incorrect installation, the classic example is the accident that occurred to a British Airways BAC 1-11 that suffered an explosive decompression at cruising altitude (AAIB, 1990). Several of the attachment bolts securing the left-hand pilots window were sized incorrectly during overnight maintenance on the aircraft. Once the aircraft was in flight and therefore pressurised at its cruising altitude, the window suffered a catastrophic failure and near loss of life occurred. Thus the effects of human error are present in aircraft maintenance and potentially a significant factor impacting the safety success and effectiveness of maintenance tasks if errors pass undetected.

2.4 Existing Error Detection Research

Aircrew error has traditionally received much attention (Latorella and Prabhu, 2000), as the benefits are clear, although there is now global recognition that maintenance error also poses a serious hazard to safety that drives the need for system barriers or defences (Hobbs and Williamson, 2003; Reason and Hobbs, 2003). Here, research has moved to systemic factors as opposed to individual factors to avoid or mitigate for error since the human condition of error is inevitable and it is seen as incumbent upon the organisation to 'protect' itself from human error effects (Dekker, 2006; Reason, 2008; Woods et al., 2010). However, it is argued that the systems perspective needs to maintain a human-centred approach to safety research. For example, understanding how individuals self-detect and recover from latent error reveals a path to error protection in systemic contexts that can only come from knowledge of how individual safety behaviours integrate with the physical environment and overall safety system.

Woods (1984) studied operator performance during simulated emergency events for a nuclear power plant and found that: two-thirds of errors across emergency scenarios went undetected; half the execution errors (slips and lapses) were detected by the operators; and no mistakes (planning errors) were detected without intervention from an external agent. Error types are discussed in Section 2.5.2, where the link to schema theory is explored. Here, a slip refers to a task carried out in error (such as dropping a tool) and a lapse involves a task where the required action is omitted (such as forgetting to close a servicing panel). Mistakes occur when the action is carried out incorrectly due to flawed knowledge about the task or an incorrect rule is selected (Reason 1990). Further, Kontogiannis and Malakis (2009) examined error detection rates in various aviation studies (by: Wioland and Amalberti, 1996; Doireau et al., 1997; Sarter and Alexander, 2000) and found that error detection rates appeared lower for mistakes (planning errors) yet higher for slips and lapses (execution errors). Sellen (1994) argued that slips are more often detected proximal to the error through the action itself and mistakes through an outcome that requires external intervention (through a procedure or third party).

A Maintenance Environment Survey Scale (MESS) was applied to Australian Army aircraft maintenance (Fogerty et al., 1999) and found 79% (n=448) of respondents admitted to making errors that they self-detected and 50% to making errors that were detected by supervisors. Patel et al (2011) studied error detection and recovery in the critical care domain using both experimental and real-world approaches. They showed that error detection and correction (recovery) are dependent on expertise and on the nature of the everyday task of the clinicians concerned, where the majority of their errors were detected and recovered whilst remaining at work. Similarly, Wilkinson et al (2011) study on error detection and recovery in dialysis nursing also found that expert nurses develop a special ability to detect and recover from their errors and the nature of the error was dependent upon the nature of the task. An observational study of aircrew error by Thomas (2004) showed that around half of the errors went undetected by experienced crew, although few of these errors led to undesired aircraft state (unwanted outcome). Amalberti and Wioland (1997) showed errors made by highly trained operators (such as aircrew) can be frequent, yet most are either inconsequential or detected and corrected before leading to an undesired outcome. Blavier et al (2005) also found the number of execution errors increases significantly with task complexity but so does their detection whilst the number of planning errors and their detection are unaffected by complexity. These findings relate to proximal error detection, yet an operator can experience spontaneous belief that an error has occurred but be unsure of the nature of the error (Zapf and Reason, 1994) and search for information about the past activity. Here, Zapf and Reason considered that there are three ways errors are detected: conscious self-monitoring (planned detection); external environmental cue (unplanned); or a third party such as a supervisor when checking a safety critical task (again, planned detection). What is of interest in the current research is the seemingly spontaneous detection discussed earlier due to some unexplained unconscious self-monitoring (unplanned detection).

The literature review in Table 2.1 found no research on individual detection and recovery of latent errors was found and thus it appears to be an under researched area. Causes of human error have been researched widely, as has error avoidance (Kontogiannis, 1999), for which formal error identification tools or Human Error Identification (HEI) techniques exist to predict the likelihood of error in safety critical organisations (Stanton and Baber, 1996). Such techniques calculate the likelihood of error with associated risk indices but, by design, these techniques are concerned largely with the design of safe systems and not the analysis of latent error. Additionally, HEI techniques do not account for attentional mechanisms (self-monitoring) in observable behaviours or take adequate account of error contexts (Stanton and Baber, 1996; Hollnagel, 1993). For error that has occurred, research has considered proximal error detection and found weaknesses in the effective detection of these errors, without which, recovery is not possible (Blavier et al., 2005). Such research captures planned detection and correction of error as opposed to the unplanned latent detection of errors that ‘come to mind’ later (Kontogiannis, 1999; Sellen et al., 1996). Detection of execution errors is higher (albeit proximal to the error event) than planning errors whilst the ability to self-detect errors appears to be linked to expertise (although the expert is not immune to error) and when experiencing spontaneous belief that something is in error, the individual will search for information about the past task (i.e. instigate latent error searching in memory). Since error detection appears to be influenced by multiple sociotechnical factors, the following section will argue for a multi-process approach to observe the phenomenon.

2.5 Role of Schema in Error

2.5.1 *Schema theory*

Bartlett (1932) introduced schema as information represented in memory about our external world of objects, events, motor actions and situations. Norman (1981, p. 3) defined this information as 'organised memory units' for knowledge and skills that are constructed from our past experiences, which we use to respond to (interact with) external sensory data. In this respect, schema theory is arguably aligned with Human Factors and Ergonomics (HFE) as a broad science that considers all aspects of the human interaction with the external environment (Carayon, 2006). Specifically, the application of schema theory has been influential and effective for military applications, including aviation (Plant and Stanton, 2013a) and thus provides theory for application to the naval aviation maintenance context.

What we encode and commit to memory is determined by pre-existing schema and is an iterative process, which develops residual memory structures or genotype schema based on our general understanding of the physical environment (Reason, 1990; Stanton et al., 2009b; Plant and Stanton, 2012). Schema consists of 'slots' of data (Rumelhart and Norman, 1983) for fixed compulsory values or variable optional values, which are specified when planning intention (see prospective memory). Data slots are dependent on the interaction with external sensory information in the physical environment and are part of the process to select required schema. Where the sensory information is not available or not attended to by the conscious, the data slot will be represented by a default value (Cohen et al., 1986). For example, when refuelling an aircraft: fixed data are fuelling equipment and procedures; variable data are aircraft and amount of fuel; and default data could be use of the incorrect fuel as the air engineer did not know the aircrew needed a different fuel for the next flight (for military operations, there are several fuel options). A properly encoded schema is therefore essential for planned intent to be carried out correctly and, as will be discussed later, it will be predicted that the nature of the schema data slots influences error detection.

Schemata are also hierarchical and interrelated where only the highest-level schema (parent) needs conscious activation for subordinate (child) schema to trigger autonomously; child schema being needed for particular skills (i.e. motor response) or knowledge of particular properties of objects and location (Norman, 1981; Mandler, 1985; Cohen et al., 1986; Reason, 1990; Baddeley, 1997). For example, when the air engineer conducts aircraft flight servicing the high level schema for this activity is activated consciously with subordinate schemata to open and close panels, operate equipment (motor skills) and navigate around the aircraft triggering automatically (and in sequence). This is an important hierarchical feature of schema theory as it provides an explanation as to how finite capacity is made available to attend to other unrelated functions such as talking to a colleague whilst working or thinking about the next maintenance task. Execution of this activity requires the bottom-up (BU) processing of external data from sensory inputs with top-down (TD) prior knowledge (schemata) to project a response (Neisser, 1976; Cohen et al., 1986; Plant and Stanton, 2013a). This processing of the external environment with internal pre-existing schema to achieve the required response captures elements needed for situational awareness (SA) and is essential for the execution of tasks without error (Plant and Stanton, 2013a); situation awareness being 'the cognitive processes for building and maintaining awareness of a workplace situation' (Flin et al., 2008, p. 17). Here, reality needs to match the mental template (activated schemata) for correct SA (Rafferty et al., 2013), for which on-going monitoring by the operator is needed.

Endsley and Robertson (2000) hypothesised that schemata are influential in the possession of correct SA, where the perception of external data and application of the correct schemata delivers correctly executed responses. For the example above, schema theory indicates that the BU/TD processing of well-practiced tasks can lead to confusion as the memory trace for the real activity (fuel required by the aircrew) has been derived from a past experience (schema for the fuel type most commonly used). Amalgamation of a different reality to the genotype schema held in memory can lead to error (Cohen et al., 1986) and is also the view of Reason (1990) who considered cognitive under specification between external data and schemata can manifest as errors. Thus the important link between error and schema theory needs to be made before constructing a theoretical framework upon which to approach I-LED research; facilitating the opportunity for SA re-gains.

2.5.2 *Linking schema theory to error*

Norman's (1981) research on execution errors described the use of incorrect schema applied to a planned task, which can lead to unintentional slip of action (error effect). It is argued that this finding can be applied to Reason's error types from which specific error behaviour or phenotype schemata can be observed in the physical environment to assess human performance 'in the moment' of activity (Stanton et al., 2009b; Plant and Stanton, 2012). Rasmussen (1982) categorised human performance behaviours as skill, rule or knowledge based (SRK). Skill based performance is characterised by a routine, well-practiced and expected task that requires little cognition as the operator is largely pre-programmed (motor response) to carry out the task. Rule based performance is typified by familiar situations (but not as routine as for skill based) where the task has been trained for such that a semi-conscious processing is needed to achieve the task. Knowledge based performance relates to novel of difficult situations that require greater cognition for analysis and planning to achieve a task, for which previous experience or training supports task success; characterising the experienced operator (Maurino et al., 1995; Reason, 1997). Here, it is argued Rasmussen's SRK-based performance behaviours can be linked directly to the nature of the activated schema (Stanton and Salmon, 2009).

Reason (1990) expanded on Norman's (1981) seminal work to produce the Generic Error Modelling System (GEMS) where slips categorise execution failures during routine situations; a well-practiced skill based task, requiring little cognition, is carried out incorrectly. Lapses are similarly well-practiced skill based tasks, requiring little cognition, yet not carried out (omission). Erroneous actions (error), associated with conscious task planning, are categorised as mistakes where deficiencies in judgement or inferential processes cause the failing to formulate the correct plan based on flawed knowledge and/or incorrect comprehension of recognised rules (Reason, 1990; Sellen, 1994). Reason (1990, p. 11) argued the categorisation of error helps focus attention on the interdependencies between 'local triggering factors and error behaviours' (phenotype), and of particular interest is behaviour leading to latent error. Blavier et al (2005) suggested that using Reason's GEMS has utility when describing error detection mechanisms as it can be related to attention and memory. For current research, the link can be made to schema theory to develop a theoretical perspective for the observed phenomenon:

- Skill based slips are a consequence of a correct schema(s) selected in memory but executed incorrectly (Norman, 1981; Rasmussen, 1982). For example, inadvertent operation of aircraft floatation bags during servicing;
- Skill based lapses occur when the required schema(s) is not enacted (Rasmussen, 1982; Reason, 1990). For example, forgetting to sign aircraft maintenance documentation;
- Knowledge or rule based mistakes occur due to a data slot(s) that is populated incorrectly, wrong schema selected based on incorrect perception of external sensory data or correct high-level schema is selected but the data slot(s) defaults incorrectly as external sensory information not available (Rasmussen, 1982; Rumelhart and Norman, 1983; Reason, 1990). For example, carrying out

a component replacement on the wrong aircraft. Additionally, a specific schema may not be available as the operator is faced with a novel situation. Here, the operator may look for a 'best fit' to achieve the task (Cohen et al., 1986) – for example, where a maintenance technique learnt for one aircraft type is used on a different type. Of note, this could be termed a violation when using the GEMS lexicon (Reason, 1990).

The above proposes an important link between error types (Reason, 1990) and schema theory, which can be applied to error detection. Additionally, storage of planned actions (selected schema) can be explained through prospective memory (see next section).

2.6 Multi-process Approach to I-LED

2.6.1 *The need for a multi-process approach*

Schema theory applies to the human responses needed to achieve a task (Norman 1981), for which an attentional mechanism is needed to 'prepare' the schema(s) in memory to be enacted later and determine hierarchical interactions and trigger criteria. Here, it is argued that schema theory does not currently account for this activity and thus there must be other cognitive processes involved. The correct application of a particular schema at the correct time and to the correct task requires the preparation, activation, monitoring and feedback for task success. Multi-process theory provides a theoretical approach that may account for the total interaction with the external world where it is hypothesised that Prospective Memory (PM) is responsible for the preparation of schema (schema selection and trigger criteria) and a Supervisory Attentional System (SAS) for activation, monitoring and feedback (Norman and Shallice, 1986).

2.6.2 *Multi-process theory*

A multi process approach, termed by Einstein and McDaniel (2005), argues task success is dependent on several mechanisms that include memory, monitoring mechanisms, task encoding, trigger cues and contextual factors (Brewer et al., 2010). Dismukes (2012) supported the multi process concept but indicated that this does not necessarily account for everyday tasks that are habitual in nature and less likely to need a formal plan of action to be made such as for the air engineer carrying out routine flight servicing. But this is a key feature of schema theory where well practiced execution tasks are largely automatic responses characterised by schemata for motor responses that may not require conscious control, although a level of monitoring is required (Green et al., 1996). Thus task intent (prospective memory) and attentional mechanisms need to be considered, along with schema theory, to make multi-process predictions for the latent detection of situational error.

2.6.3 *Prospective memory*

Forming a plan of action enables intent to be stored in working memory until its execution (Palmer and McDonald, 2000; Dockree and Ellis, 2001). Originally recognised by Ebbinghaus (1885:1964) as a discrete type of memory it is only in later years that working memory has been studied closely, from which recent literature has emerged that reports the concept of PM. This refers to occasions when intent has been formed and stored in working memory for later recall (Reason, 1990; Baddeley, 1997; Sellen, 1994; Ellis, 1996; Kvavilashvili and Ellis, 1996; Blavier et al., 2005; Dismukes 2012), for which it is argued that schema selection, hierarchy and trigger criteria are the responsibility of PM. Reason (1990) reported that there could be a delay between intention forming in PM and taking action, which is particularly vulnerable to failure such as forgetting to carry out a planned action. Preparing cognitive information in memory from external cues in the world then assessing task success requires some form of monitoring of the physical environment is then needed to activate the schema as intended.

2.6.4 *Monitoring theory*

The SAS is responsible for matching of external sensory data (from the physical environment) with the selected schema, for which several schemata may be selected in a hierarchical pattern determined by the strength (importance) of the target activity (Plant and Stanton, 2013a). Studies on PM indicate that formed intentions (selected schema) are ‘loaded’ into memory to act upon later, which generates a ‘to do list’ or internal marker (Sellen et al., 1996; Marsh et al., 1998; Van den Berg et al., 2004). Dockree and Ellis (2001) found subsequent cancelling of the internal marker (deletion of a schema on the to-do list) may be regulated by the SAS described by Norman and Shallice (1986), which is influenced by abstract cues for thoughts & linguistics, sensory & perceptual cues and psychological (emotional) state cues (Bargh and Chartrand, 1999; Guynn et al., 1998; Mace et al., 2011; Einstein and McDaniel, 2005).

Plant and Stanton (2013a) similarly argued that schema theory also predicts triggering in response to external sensory inputs (interaction with the physical environment) but the activation of a particular schema may also come from another schema; both of which are subject to interference from competing schemata that are similar or the selection of a new schema that has been deemed more important than the immediate activity. Since it has been argued that schemata operate largely autonomously this provides an explanation for why some errors pass undetected but it does not explain why such errors come back in mind later. For example, going upstairs to fetch a jumper but seeing the bed needs making, which you attend to before proceeding back downstairs without the jumper you planned to fetch. In the example of the oil filler cap not being replaced, it may be that a competing schema was considered more important such as attending to leak that has been spotted on the aircraft. Here the competing schema responding to the leak has been seen as more important and enacted in preference to the schema for replacing the oil filler cap. Should this be true, it is not understood fully why the schema for the oil filler cap comes back to mind later such that the missing cap is realised by the individual. So for this to occur, it is argued that some later review or inner feedback (Kontogiannis, 1999) of a selected schema(s) takes place that results in an involuntary memory, and this unplanned detection can be explained through SAS monitoring theory. Here, it is proposed that SAS monitoring leads to a review of completed tasks to confirm they have been executed correctly and, where necessary, updates established genotype schema and/or constructs new schema if the task was novel. This is a key feature of schema theory (Reason, 1990; Plant and Stanton, 2012) and could be seen as a 'housekeeping' function; essential for learning and acquiring experience. Further, it is argued that outcomes of this monitoring also explain the seemingly spontaneous recall of latent error (unplanned detection) as a consequence of post-task housekeeping or a conscious and deliberate search for potential latent errors where self-doubt comes to mind, and for which the latter is offered as Latent Error Searching (LES).

Bartlett's (1932) research found the accurate recall of past events was attributable to the ability to reconstruct schemata applied at the time a given task was executed. For the detection of slip errors Norman (1981, p. 11) proposed a feedback mechanism exists 'with some monitoring function that compares what is expected with what has occurred' (arguably SAS monitoring). For successful error detection this monitoring function detects any discrepancy between the selected schema and task execution for incorrect execution (genotype/phenotype schema mismatch) and/or genotype assimilation. Thus it is this monitoring function that is of interest and thought to extend to lapses and mistakes, and beyond the proximal to I-LED events; where past tasks comes to mind, upon which task success is questioned (Zapf and Reason, 1994; Sellen et al., 1996). Thus, SAS and schema theories combined may indicate that error detection is more successful when post-task housekeeping takes place in a physical environment that is the same as or similar to the physical environment in which the actual error occurred (or simply when there is a genotype/phenotype mismatch). Additionally, triggering conditions have been cited as critical for correct human performance (Norman, 1981) and are dependent upon the physical environment, for which current research will determine if the physical environment also influences SAS monitoring to lead to successful I-LED.

2.7 Error Detection and Recovery Examples

2.7.1 *ASIMS data*

This chapter introduces a multi-process theoretical framework to explore I-LED events from the perspective of the air engineer's interaction with the physical working environment. To facilitate initial exploration of the proposed theoretical framework prior to further research, ASIMS (2013a) was interrogated for examples of latent error. This UK MoD restricted database contains approximately 30,000 air safety reports recorded using the Defence Air Safety Occurrence Report (DASOR) template (noting that ASIMS contains around a further 130,000 reports dating back to 1970 but prior to the introduction of DASORs in 1990). The template was constructed from two established HF templates in aviation: the Maintenance Error Decision Aid (MEDA) designed by Rankin and Allen (1996); and Human Factors Analysis and Classification System (HFACS) designed by Wiegmann and Shappell (2003). Each DASOR captures real-world error events and so offers a potentially rich secondary data source for re-analysis. Only RN aircraft maintenance reports were sampled to align with the chapter. This yielded 1,933 reports that were sifted to just three, as the majority of reports did not cite latent errors. This was not unexpected, since an individual may not see the need to report an error that has been recovered successfully; being potentially analogous to the pyramid heuristic (Heinrich, 1931) that suggested the vast majority of errors go unreported. Despite the scarcity of relevant DASORs, narratives from each report were individually analysed thematically before 'horizontal' comparison (Robson, 2011). This comparative technique (Cassell and Symon, 2004; Polit and Beck, 2004) highlighted common themes and optimised data extraction from the very limited number of reports (Schluter et al., 2008). Table 2.2 shows themes associated with latent error detection and recovery that were determined from the narratives of each of the three DASORs. Identifying information has been removed and the bracketed text explains technical terms.

Table 2.2. Thematic analysis of DASORs.

DASOR Examples	Multi-Process Error Detection Themes: PM Encoding	Multi-Process Error Detection Themes: Trigger (Cueing) Condition	Multi-Process Error Detection Themes: SAS Monitoring	Error Recovery Themes
Example 1 "During Flight Servicing, the AET [engineer] inadvertently selected Aeroshell 555 [oil] juniper rig [delivery system] to replenish the ECU [aircraft engine] oil system on all engines. Post replenishment, he realised his mistake and reported it immediately. The AET selected the correct equipment; unfortunately, he selected the rig with the wrong fluid. There is no evidence of distraction. He was not consciously fatigued, having returned home the night before. A contributory factor is the lack of visual cues to assist correct rig identification. Oil systems were drained and replenished."	'Flight Servicing'	'Lack of visual cues'	'Realised mistake'	'Reported it' 'Systems drained and replenished'
Example 2 "AET conducted an aircraft refuel. On completion and once the fuel bowser had left the dispersal, it became apparent to the AET that he had left his night flying wands [torches] adjacent to the fuelling hose on the fuel bowser. AET recalls that when he placed the wands down that they were still illuminated. On completion of refuelling, the bowser driver pulled the cover down over the hose reel point, which would have obscured the wands that were inside it from view. As soon as the AET realised the items were missing he reported it and items retrieved from the bowser."	'Aircraft refuel'	'Obscured from view'	'Became apparent'	'Reported it' 'Items retrieved'
Example 3 "Following a tail rotor flying control cable change, the maintainer that carried out the task realised he had negated to remove the cable identification tags on completion. He immediately notified the watch controller who instigated an inspection, which revealed that the identity tags were still attached to the tail rotor cables. This incident was caused by poor communication between the supervisor and independent inspector."	'Control cable change'	'Poor communication'	'Realised'	'Notified controller' 'Instigated an inspection'

2.7.2 *DASOR examples*

Subjectivity in reported narratives meant that it was difficult to determine themes with confidence, as textual data were underspecified. Additionally, to maintain the quality of deductive analysis care was taken to ensure the researcher did not influence how textual data was interpreted although this was also an advantage as the experience of the author was essential to exploit the maximum information from the technical lexicon used in the narratives (Schluter et al., 2008). For each, the importance of the text was questioned by interrogating each line with a 'so what' approach to allow themes to emerge (Robson, 2011 p. 479) although the extremely small number of reports means no statistical significance or strong evidence to assure the proposed theoretical framework can be claimed since there is likely to be significant error in the findings and variance against the population. For each DASOR, the analysis served only to demonstrate the existence of the phenomenon and provide initial evidence that multi-process theory proposed in this paper is applicable to the context being researched.

2.7.3 *Link to theoretical framework*

Themes highlighted in Table 2.2 were used to explore the applicability of the link between multi-process theory and the naval air-engineering context. Each DASOR describes well-practiced maintenance tasks carried out by trained engineers, which included aircraft flight servicing, refuelling and changing a control cable. For these habitual tasks, it is offered that the PM element of the theoretical framework was established at task inception and each reported error event was a sub-set (child schema) of the main maintenance activity (parent schema) and therefore overall schema activation needed to be hierarchical and interrelated as each main task necessitated the sequencing and activation of sub-tasks. In Example 1, it is argued the engineer tasked with carrying out flight servicing (parent schema) selected a replenishment rig containing the wrong oil, which had required activation of the child schema with particular knowledge of the equipment being used. The engineer tasked with an aircraft refuel in Example 2 activated a child schema that manifest as a motor response to place his torches on the fuel bowser during the refuelling sequence. For Example 3, the main task to replace tail rotor cables may have led to latent error due to a failure to trigger the child schema with the knowledge that cable tags are to be removed upon completion of the cable replacement. The engineers who suffered these errors also detected the error later (post task completion) whilst physically present in the hangar or outside on the line/dispersal (ramp); in each example, the engineer detected the latent error in the same or similar physical environment to that which the error occurred. Here, correct schema behaviour (phenotype schema) did not occur proximal to the maintenance task, as each engineer appears to have not detected important cues or sensory information in the physical environment such as: the incorrect oil replenishment rig in the first example; location of the night flying torches in the second example; and communication between supervisor and independent inspector in the third example.

The themes 'realised mistake' and 'became apparent' may support the claim that the SAS monitoring element of the proposed theoretical framework is also present for the I-LED phenomenon to occur; where the schema mismatch (genotype/phenotype) is detected via a housekeeping function that occurs post-task completion (potentially giving rise to LES). Upon detection each latent error was recovered successfully, which also minimised the consequences and avoided any potential 'bad' outcomes (Woods et al., 2010): the oil system was drained and replenished in Example 1; torches recovered in Example 2; and the tail rotor cable tags were removed in Example 3.

The limited DASOR data indicate the observed phenomenon has been experienced by naval air engineers in the workplace whilst the themes described at Table 2.2 suggest early evidence exists to link the proposed multi-process theoretical framework to the naval aircraft maintenance context. Within this framework, external cues (or triggers) across the sociotechnical system or network are argued to be of paramount importance; where both the nature of physical environment and potential for vigilance decrement through missed cues (Reason and Hobbs, 2003) highlight the dependence on cue recognition for correct schema behaviour, and which continues to be essential for successful I-LED.

2.8 Summary

System-induced human error effects have been shown to the most significant factor impacting the safety success of an organisation yet the term human error is defined variously and is difficult to qualify or even measure objectively and thus a working definition for further research has been given. In reviewing literature to support the observed phenomenon, it is evident that much research has identified the vagaries of human error within an organisation; representing multiple occasions of system failures since error effects are inevitable and occur daily (Norman, 1993; Reason, 1990; Hollnagel, 1993; Maurino et al., 1995; Perrow, 1999; Weigmann and Shappell, 2003; Wood et al., 2010). When there is a delay or absence in feedback, latency in the safety system exists

(Rasmussen and Pedersen, 1984). Insufficient SA and latent errors have been discussed, which can contribute to an unwanted network of events or causal path and thus there is a need for systems knowledge of how past errors are later detected by the air engineer who suffered the error to design system defences or controls.

The nature and extent of multi-process influences on I-LED is an under researched area. As far as could be determined from the vast corpus of existing literature, no clear research was found for I-LED associated with the unplanned and seemingly spontaneous recall of past activity. Studies have focused on error avoidance or proximal detection rather than the detection of latent errors post task completion. This could impact the organisation's safety goals (Rasmussen and Pedersen, 1984; Latorel and Prabhu, 2000). In the absence of specific research, a multi-process approach has been introduced that indicates I-LED is dependent on three distinct areas: the quality of PM encoding; triggering conditions in the physical environment; and SAS monitoring. This introduces a novel theoretical framework to contribute to systems thinking, which is argued to account for the total human interaction with the physical environment. Here, it is hypothesised that PM is responsible for the preparation of schema (schema selection and trigger criteria) and is linked to SAS theory for the execution, monitoring and feedback (housekeeping activity). This housekeeping function may be dependent on sensory data within the physical environment for I-LED events to occur or, at least, give rise to self-doubt that something has been missed such that the operator may be compelled to check their work (Sunderland et al., 1983; Baddeley, 1997). This appears analogous to the observed phenomenon where an air engineer becomes suspicious that a completed task may be in error, from which he or she suffers the overwhelming desire to return to check their work.

Thematic analysis of DASORs facilitated the initial exploration of I-LED events by providing evidence for the observed phenomenon and applicability of the proposed multi-process theoretical framework, for which schema mismatch appears to be dependent on system cues in the physical environment for successful I-LED to occur. Yet the exact nature, extent and observable effects remain a mystery and thus further research is needed. Here, the theoretical framework needs to be tested through naturalistic real-world studies to gain understanding of this under researched area from a sociotechnical stance. Dekker (2003, p. 100) suggested that understanding the mind comes from analysis of the 'world in which the mind found itself instead of trying to pry open the mind' (i.e. understanding the role of the physical environment) and is an important statement as the need for 'operational' understanding of error behaviours is recognised (Flin et al., 2008) and drives an argument for schema research to be conducted in real-world contexts. Deliberately, this positions current research within the realm of HFE research rather than cognitive psychology, as it is the influence of the external environment on safety behaviour that, arguably, presents the greatest safety value (Plant and Stanton, 2013b). Thus future studies will first thematically analyse narrative data from air engineers who have experienced an I-LED event before moving to empirical research within the physical working environment to observe system interventions based upon multi-process findings. Ecological experiment also brings benefit with observational studies since schema are internal representations of the world for which measurement can only come from observed behaviour in the real-world contexts (Plant and Stanton, 2013b).

I-LED research also needs to consider the experience of the air engineer. Since trainees are naturally at an early stage of learning (Fitts and Posner, 1967), expectantly, there is likely to be greater variability in performance behaviours due to schema development. It is therefore difficult to assure stability or meaning from studying this trainees and thus research should focus on trained naval air engineers. Although the trained operator is not immune to error their ability to spontaneously self-detect situational errors is a notable characteristic and needs to take account of safety behaviours and attentional mechanisms leading to I-LED.

I-LED research may also enhance existing safety systems that already mitigate for the inevitability of error, thereby supporting the concept of resilience introduced earlier (Reason, 2008; Woods et al., 2010) although it is accepted that zero error is an unlikely safety goal (Kontogiannis, 1999; Woods and Hollnagel, 2006). Woods et al. (2010, p. 6) suggested 'people create safety in the real-world under resource and performance pressures at all levels of the socio-technical system'; a view supporting both systemic and individual error contexts, and which drives the need for HFE research in truly naturalistic real-world settings. This provides the opportunity to understand the nature and extent of situational error from a systems stance, for which I-LED is the effect to be observed. Without this knowledge, humans do not evolve their capabilities (Reason, 1990). Specifically, this chapter has offered a new theoretical framework upon which to conduct further research leading to the identification of interventions to enhance I-LED events amongst naval air engineers (and wider) using a human-focused systems perspective. However, it is accepted that achieving meaningful real-world research is challenging since strict experimental control is not possible although the potential ecological benefit should outweigh such concerns to deliver meaningful contributions. Chapter 4 explores this challenge by illustrating the role of I-LED as an additional safety control and introduces a research strategy upon which to observe I-LED events in the normal workplace environment. Prior to this, Chapter 3 reviews the concern highlighted in this chapter with regards the use of the term human error in systems research.

Chapter 3: Rationalising systems thinking with the term 'human error' for progressive safety research

3.1 Introduction

Chapter 2 introduced the I-LED phenomenon, for which I-LED events are likely to offer further mitigation for human error effects or erroneous acts caused by system failures. The recall of past error events by the individual operator who suffered the error appears to be triggered by system cues. The aim of the current research is to advance knowledge of systems safety by researching the nature and extent of I-LED events. Thus it is necessary to authorise a theoretical position that rationalises systems thinking with the term human error, as both are central themes in the exploration of the phenomenon. Use of the term human error has been cited as out-dated and should be retired in favour of a new emergent systems lexicon, since reference to human error in causation modelling can be used to infer individual blame and therefore wider sociotechnical causes are ignored (Dekker, 2014). It is argued in the following chapter that Human Factors and Ergonomics (HFE) research from a systems perspective requires a human-centred approach where human error effects are simply the catalyst for wider HFE analysis (Carayon, 2006) and is therefore congruent with progressive safety research. HFE analysis yields real-world application in terms of mitigating system failures through organisational control measures impacting safety behaviour at the local level thus the term human error should be employed, and not retired.

3.2 Human Error

Traditional human error research often referred to situations where either the safety or the effectiveness of a task is compromised due to human failings (Reason, 1990; Hollnagel, 1993; Amalberti, 2001; Wiegmann and Shappell, 2003). There are many definitions for human error, which Chapter 2 provided a review of some of the most frequently used. Generally though, human error describes occasions where human performance was not enacted as expected due to system-induced influences (Reason and Hobbs, 2003; Leveson, 2004; Reiman, 2011). However, the term human error has been cited as a misunderstood term that causes a focus on individual failings rather than seeking to understand the macro-ergonomic view of system failures that cause human error effects (Dekker, 2014). Applied academic research has long recognised the influence of wider sociotechnical issues that can lead to performance variability (Hutchins, 1995; Stanton and Baber, 1996; Dekker, 2014; Reason, 2008; Woods et al., 2010; Cornelissen et al., 2013; Hollnagel, 2014; Chiu and Hsieh, 2016) but it is perhaps understandable that society has favoured the focus on individual failings since they are most often the easily identifiable and explainable effect at the sharp-end of safety operations rather than trying to analyse and mitigate for the system causes complicit in complex sociotechnical networks (Flin et al., 2008; Carayon, 2006; Salmon et al., 2016).

Human error is a normal by-product of performance variability, which encapsulates a range of human interactions within a given sociotechnical environment that includes non-normative and normative behaviours in the workplace (Reason, 1990; Woods et al., 2010; Cornelissen et al., 2013; Saward and Stanton, 2017). Error is the observable effect of system failures due to deficiencies in organisational safety strategies where the real causes of human error are deep-rooted in system factors such as organisational decisions, equipment design, management oversight and procedures (Woods et al., 2010; Dekker, 2014; Stanton and Harvey, 2017). To avoid the temptation to blame individuals, some safety thinking has moved to retire the term human error in favour of terms such as erroneous acts, human performance variability or system failures (Dekker, 2014). Arguably, this move is not likely to remove the temptation to conclude individual failings thus it risks being seen as semantics unless greater emphasis on the systems perspective is shown to benefit the organisation through reduced harm and/or increased productivity, which is covered in Chapter 9. In moving away from explaining error to understanding how system design caused a deviation from normative and expected procedures, there is a need to understand the factors that shape individual safety behaviour. HFE research requires knowledge human performance shaping factors or error promoting conditions so that the wider societal factors and technical environment can be matched and controlled reliably to mitigate for human performance variability (Rasmussen, 1997; Reason, 1990; Leveson, 2004; Hollnagel, 2014; Carayon et al., 2015). This is an area that characterises operator competence, which is an essential element of a resilient system, and is discussed further in Chapter 8.

HFE is concerned with human interactions within systems thus Fedota and Parasuraman (2009) also rightly challenged this new paradigm shift away from human error as overly focussing on the organisational factors, which risks ignoring important factors associated with human behaviour within a specific context. This is a concern held by Plant and Stanton (2016), for which they highlighted the capability of the schema-based perceptual cycle in linking human elements of cognitive behaviour with the operating environment. When human error is discovered in the workplace, it is catalyst for HFE analysis of the system deficiencies that generate error-promoting conditions causing failures in the system, which can lead to undesirable risks such as an accident or reduced performance. This is the starting point for HFE analysis, not the time to blame individuals (Stanton and Baber, 1996; Reason and Hobbs, 2003; Reiman, 2011; Saward and Stanton, 2015a). The term latent error refers to safety failures that become embedded in the system, which can impact future safety performance, i.e. system-induced conditions that promote errors that pass undetected and then lie hidden in the STS (Reason, 1990). The detection of latent errors is an essential element of achieving system safety (Rasmussen and Pedersen, 1984; Reason, 1997; Shorrock and Kirwan, 2002; Wiegmann and Shappell, 2003; Flin et al., 2008; Aini and Fakhru'l-Razi, 2013). Thus it is argued that human factors experts analysing error events should not avoid using the term human error, provided it is used to signpost residual error effects caused by system influences that require attention; it is an effective term to trigger HFE analysis of the wider causes in complex STSs, both in design of safe systems and implementation of control measures for the restoration of safety when a system failure occurs. Indeed, few go to work to deliberately cause an accident, thus any attribution of individual blame is a failure to understand systemic causal factors where accountability needs to be balanced against learning from system failures (Reason, 1990; Dekker, 2014).

To be assured of where the term human error sits in progressive safety research, the role of systems thinking and the function of HFE in preventing the escalation of causal paths to an accident need further consideration.

3.3 Systems Thinking

Systems thinking transfers the emphasis from individual human failings to understanding the living network of all sociotechnical factors that can cause system failures (Leveson, 2011). The systems view favours this macro-ergonomic approach to safety rather than the micro-ergonomic lens to avoid focusing on individual human failings (Zink et al., 2002; Murphy et al., 2014). Thus macro-ergonomic analysis explores the sociotechnical interaction between elements comprising humans, society, the environment and technical aspects of the system including, machines, technology and processes (Reason and Hobbs, 2003; Woo and Vincente , 2003; Walker et al., 2008; Amalberti, 2013; Wilson, 2014; Niskanen et al., 2016). These networks can be complex in terms of the number interactions between systemic factors such as tools, equipment, procedures, decision-making, operator training and experience and operating contexts (Edwards, 1972; Reason, 1990) and is where progressive safety strategies recognise that every element of the STS contributes to the organisation's safety goals through specific roles, responsibilities, relationships and safety behaviours (Leveson, 2011; Dekker, 2014; Plant and Stanton, 2016). A safety failure occurs when there is inadequate control of the sociotechnical factors (across networks), which impacts human performance (Woods et al., 2010). Each has dependencies on the other in the network so when things go wrong, it should be recognised as a failure of the system as a whole that has resulted in a hazardous condition due to design-induced factors and not individual errors (Stanton et al., 2009a). The naval air engineer is one element in a complex sociotechnical system of aircraft maintenance where system deficiencies can cause failures, borne out in an observable error effects. Chapter 2 described the complex sociotechnical environment of naval aircraft maintenance but complexity is not a stranger to other contexts such as commercial aviation, transportation, logistics and healthcare where complexity comes not only from the human-machine networks but wider geographical, temporal, cultural, socio-political, regulatory, technological and economic dimensions that place extreme demands on human performance in these ever-changing workplace networks (Blavier et al., 2005; Carayon, 2006; Leveson, 2011; Hollnagel 2014). Arguably, over reliance on the macro-ergonomic approach can mask the detection of all human factors impacting safety success within these networks by the very nature of the complexity involved. No universal method exists for the macro analysis of sociotechnical systems (Kleiner et al., 2015), which generates scope for significant variance in safety-related control strategies.

Organisational or system accidents occur when there is insufficient awareness of the risks of safety failures and/or there is ineffective control of the interacting component hazards within the STS (Leveson, 2004). Critically, it has been highlighted that an organisational accident is rarely the result of one error event since it is more usually the networking of more than one error event or system failure that creates a causal path to the system accident (Perrow, 1999; Amalberti, 2013). But despite a systems approach to the design and implementation of a safe system of work, the accident can still come as a surprise to safe or ultra-safe organisations (Hollnagel, 2014). Arguably, the macro-ergonomic approach risks missing important human factors for the delivery safe systems, which is a void that is often bridged through the heroic abilities of operators in the system. Here, Reason (2008) views humans as 'heroes' where safe behaviour exists that adapts to system failures to enact a successful recovery, which supports safety resilience. Similarly, Hollnagel's (2014) modelling of accident causation highlighted Safety II events where the adaptive capability of human operators can locally overcome or avoid system failures in the workplace (heroic recoveries), whilst his Safety I analogy refers to error avoidance and capture through the planning and delivery of effective safety controls aimed at defending against identified hazards.

Shappell and Wiegmann (2009) found recommendations from NTSB aviation accident reports often focused on organisational changes or design improvements rather than taking a more balanced sociotechnical approach that includes recommendations to improve the safety behaviour of operators during normal operations. Their point being that accident rates in aviation have largely stabilised over recent years thus if the adage is true that there are now new accident, just new operators ready to suffer a system failure, then more needs to be done to design system interventions that account for the inevitability of performance variability by capitalising upon heroic recoveries. Changing or enhancing safety behaviour needs to form part of an enduring system solution, as the control measures to affect the change need to be integrated within the overall safety design. Arguably, I-LED events offer the potential to enhance safety behaviour by maximising the use of system cues to mitigate for inevitability of human performance variability, and therefore I-LED is a system solution to counter the risk of a causal path to an organisational accident.

Not all examples of normal operations can be bounded by a procedure as complex operating environments can be highly dynamic, which generates novel and unexpected safety issues. I-LED events can perhaps mitigate for error effects caused by unexpected safety challenges. Indeed, safety is itself the effect from successful system interactions (Leveson, 2004), which is likely to be routed in effective management of system hazards; from planned safety through to the reality of everyday normal operations. If humans can exhibit heroic recoveries, and this truly mitigates for exceptional circumstances, then progressive safety research should re-balance the systems view by ensuring more is understood about individual (and team) safety behaviours. I-LED is believed to contribute to this more complete view of safety if integrated with existing system controls and thus research in this area is believed to be progressive and underwrites to the macro-ergonomics view. The systems view is progressive thinking but it must also pay due consideration to how individual failings can be avoided through local responses to everyday safety challenges not accommodated in the safety design. This is analogous to the holes in Reason's (1997) Swiss cheese that have not all been 'plugged' by a safety control such as training or a procedure yet operators can often locally detect persistent and erroneous holes affecting safety performance, and respond effectively (Amalberti, 2013). Expectantly, the system must define and achieve a level of operator competence to support successful I-LED events, which is discussed in Chapter 8.

Effective safety strategies therefore need to plug holes to offer sufficient control over hazards that pose a risk to system safety and offer effective 'as done' safety at the sharp-end of normal operations (Flin et al, 2008; Morel et al., 2008; Amalberti, 2013; Hollnagel, 2014). The studies in the following chapters show that I-LED interventions support 'as done' safety activity in the workplace and are practicable and sufficiently flexible to accommodate exceptional occasions caused by system failures (Reason, 1990). This contributes to workplace safety strategies provided I-LED interventions are integrated within the organisation's safety system to ensure training, time to conduct the intervention, and the availability of context dependent cues are available in the workplace. This is argued to offer a progressive application of real-world safety, which is discussed further in Chapter 8. Notably, I-LED research can perhaps help counter other potential consequences of latent errors, which are not safety-related, such as overall system performance, social-economic gains and political and reputational value (Kleiner et al., 2015) that may form part of wider resilience against organisational decision that create potential opportunities for system failures.

3.4 Summary

Progressive safety research requires a systems view but equally must not forget that the individual human is at the fore of the safety solution (Flin et al., 2008), which drives the need to assure operators are competent to meet the safety expectations of the safety system ('as designed': Hollnagel, 2014). A competent operator enhances safety resilience through their heroic recoveries by detecting and recovering from human error caused by system failures. The importance of human performance factors and safety behaviour in the workplace drives the argument that the system needs to ensure the competence of its operators can achieve the safety expectation of the safety system. Effectively human capabilities must be matched to the operating environment such as a trained and experienced aircraft engineer or pilot. Both are specially selected for certain performance attributes that are needed to bound performance variability within the environment of aircraft maintenance or the flight deck. A pilot may not make a successful engineer and vice versa. Thus matching human performance is essential. Understanding safety behaviours and how they can be managed at the sharp-end to counter human error effects by plugging holes in the safety system is one of the main elements of the STS that should contribute to an organisation's safety goals (Flin et al., 2008; Leveson, 2011; Hollnagel, 2014).

The term human error has been argued to remain meaningful when conducting

HFE research from a systems perspective and therefore does not need to be excluded from progressive safety research such as I-LED. As with any lexicon terms must be used correctly, for which human error is simply a sub-set of macro-ergonomic systemic factors that flags the requirement for HFE analysis of systemic factors. As such, the term is used universally in the current I-LED research where the ability for individual operators to create safety through their own I-LED behaviour is as much a system safety solution as the wider HFE design and implementation of systemic defences or controls such as procedures, training, equipment, the operating environment and management of safety at the organisational level. I-LED is therefore argued to be congruent with the systems thinking where HFE analysis of human error is argued to remain relevant and meaningful in progressive safety research provided the term is used from a systems perspective to describe performance variability effects caused by system failures and not overly focus on individual failures. This theoretical position is returned to throughout the current research. The notion of competence and resilience is discussed in Chapter 8 when addressing the role of I-LED interventions in optimising resilience whilst the following chapter explores a conceptual framework upon which to observe I-LED events based upon the theoretical perspectives discussed in this chapter.

Chapter 4: Observing I-LED events in the workplace

4.1 Introduction

The previous chapter described the potential risk of harm to people and/or equipment posed by a system failure when maintenance error is not detected proximal to the task. An undetected system failure leads to a latent error that can later give rise to an unwanted outcome; such as degraded system performance or, at worst, an accident. Rarely is an organisational accident the result of a single cause (Perrow, 1999; Amalberti, 2013) thus in terms of undetected errors, latent errors can network with other safety failures to create a causal path or chain of events within the Sociotechnical System (STS) that can cause harm. An effective strategy to counter or defend against hazards becoming a system failure or transitioning to a latent error is to design Human Factors and Ergonomics (HFE) safety controls to target system hazards so that they are properly managed without risking a safety disturbance or safety failure (Carayon, 2006; Leveson, 2011; Johnson and Avers, 2012). Application of safety controls throughout the STS to avoid harm, as opposed to aspiring to zero system failures, is characteristic of a resilient system. This requires a systems approach that comprises HFE designed safety controls targeting the network of hazards, system failures and potential error promoting conditions that occur within complex operating environments (Reason, 2008; Woods et al., 2010; Leveson, 2011; Amalberti, 2013; Hollnagel, 2014). The I-LED phenomenon introduced in Chapter 2 is thought to act as an additional system control that aids an individual's detection of their latent error by exploiting system cues to trigger the recollection of past activity. Thus I-LED is arguably representative of an additional safety control that helps defend against networks of safety failures and error promoting conditions that form a causal path to an accident; thereby contributing to resilience within the safety system.

The aim of the current research is to understand the nature and extent of the I-LED phenomenon and its benefit to safety resilience in UK naval aircraft maintenance through the targeted application of I-LED interventions as safety controls. This chapter first explores the function of safety controls from the systems perspective before making the link to an adapted bowtie model as a method to help conceptualise the contribution of the I-LED phenomenon to resilience. To explore I-LED and the extent naval air engineers create safety from the recall of past errors, the strategy to research the phenomenon is also presented, which reviews the methodologies and studies designed to observe I-LED events in real-world workplace environments.

4.2 Conceptualising I-LED as a safety control

4.2.1 *Safety controls*

An organisational accident is the consequence of hazards that have not been controlled, which can lead to various safety failures (Leveson, 2011). If not detected proximal to the error event associated with the failure, the resulting latent error can network with other safety failures throughout the STS to form a causal path harming people, equipment or the environment (Reason, 1997; Flin et al., 2008; Leveson, 2011). Large safety critical organisations consist of a complex network of systems in systems that give rise to multiple hazards, which need to be controlled for safety and productivity (Hollnagel, 2014; Stanton and Harvey, 2017). HFE considers the network of sociotechnical interactions between elements comprising humans, society, the environmental and technical aspects of the system including, machines, technology and processes (Carayon, 2006; Walker et al., 2008; Amalberti, 2013; Wilson, 2014). A resilient safety system is therefore dependent on adequate HFE designed safety controls such as procedures, training, suitable equipment, competent operators and effective safety management oversight embedded strategically throughout the workplace or STS (Reason, 2008; Woods et al., 2010; Amalberti, 2013; Hollnagel, 2014).

Where there is a risk the organisation's safety system cannot control its operating hazards, Reason and Hobbs (2003) proposed a strategy to improve safety resilience involving targeted controls or barriers to help prevent the complex network of hazards becoming safety failures. Their strategy comprises three control methods: design the safety system to remove all probability of the error event occurring; capture the hazard before it can cause a safety failure; or design the system to tolerate safety failures. Chapter 2 highlighted an example maintenance error event where the aircraft engine oil filler cap was not replaced after replenishing its oil system. This uncontrolled hazard becomes a system failure that can transition to a latent error, as it was not detected proximal to the error event. The criticality or outcome of this latent error is that oil is now potentially free to escape the engine oil reservoir during flight, which presents an undesirable safety disturbance that needs to be detected and recovered to restore system safety. Using Reason and Hobbs (2003) safety strategy, additional controls could include: a self-sealing oil reservoir that removes the need for a filler cap, which effectively removes all probably of the error event occurring; use of a checklist or independent check might capture the missing oil filler cap (Sklet, 2006; Duijm, 2009); or escaping oil tolerated within the STS through a cockpit oil pressure low indicator to alert the crew in sufficient time to respond and/or redundancy through a second or third aircraft engine. The number of controls needed is a function of: system complexity; the number of hazards in the STS; and the level of safety required as part of the organisation's overall safety goal, which largely depends on the criticality or outcome of safety failures (Matsika et al., 2013).

The following section describes a widely recognised visual representation of the path of hazards through a STS, where uncontrolled hazards transition through the safety system as undetected system failures that lie hidden as latent errors. Here, Leveson's (2011) general control theory and Reason and Hobbs (2003) methodology can be applied to reduce risk or defend against risk escalation. The role of I-LED in helping to detect latent errors can also be conceptualised, which is the focus of the current research.

4.2.2 *Bowtie model*

Uncontrolled hazards that become a safety failure can present an immediate effect or lie undetected within the STS as a latent error that can network with other error promoting conditions to create a causal path (Reason, 2008; Leveson, 2011; Hollnagel, 2014). It has been argued the detection of latent errors forms part of a resilient safety system that can recover from a safety disturbance to restore safety equilibrium before an undetected casual path risks escalation to cause harm. Resilience is dependent upon effective system controls represented in the I-LED model represented in Figure 4.1, which is derived from Reason's (1997) barrier method (Swiss cheese) for controlling hazards as well as Reason and Hobbs (2003) later control methodology for additional hazard mitigation. Figure 4.1 is depicted as a 'bowtie' to represent risk reduction activity on the left-hand side and the potential for risk escalation on the right-hand side borne from safety disturbances transitioning through the STS (i.e. the 'knot' of the bowtie). Of note, this is a distinctly different use of bowtie analysis seen in safety critical organisations such as oil and gas, Defence, medical and aviation where it is used to identify and mitigate hazards (Duijm, 2009; Khakzad et al., 2012; Matsika et al., 2013). For the current research, the bowtie in Figure 4.1 provides a model to highlight the network of safety hazards that need to be controlled by the system and to highlight where the I-LED phenomenon is thought to benefit safety resilience. The following sections describe the bowtie model in more detail.

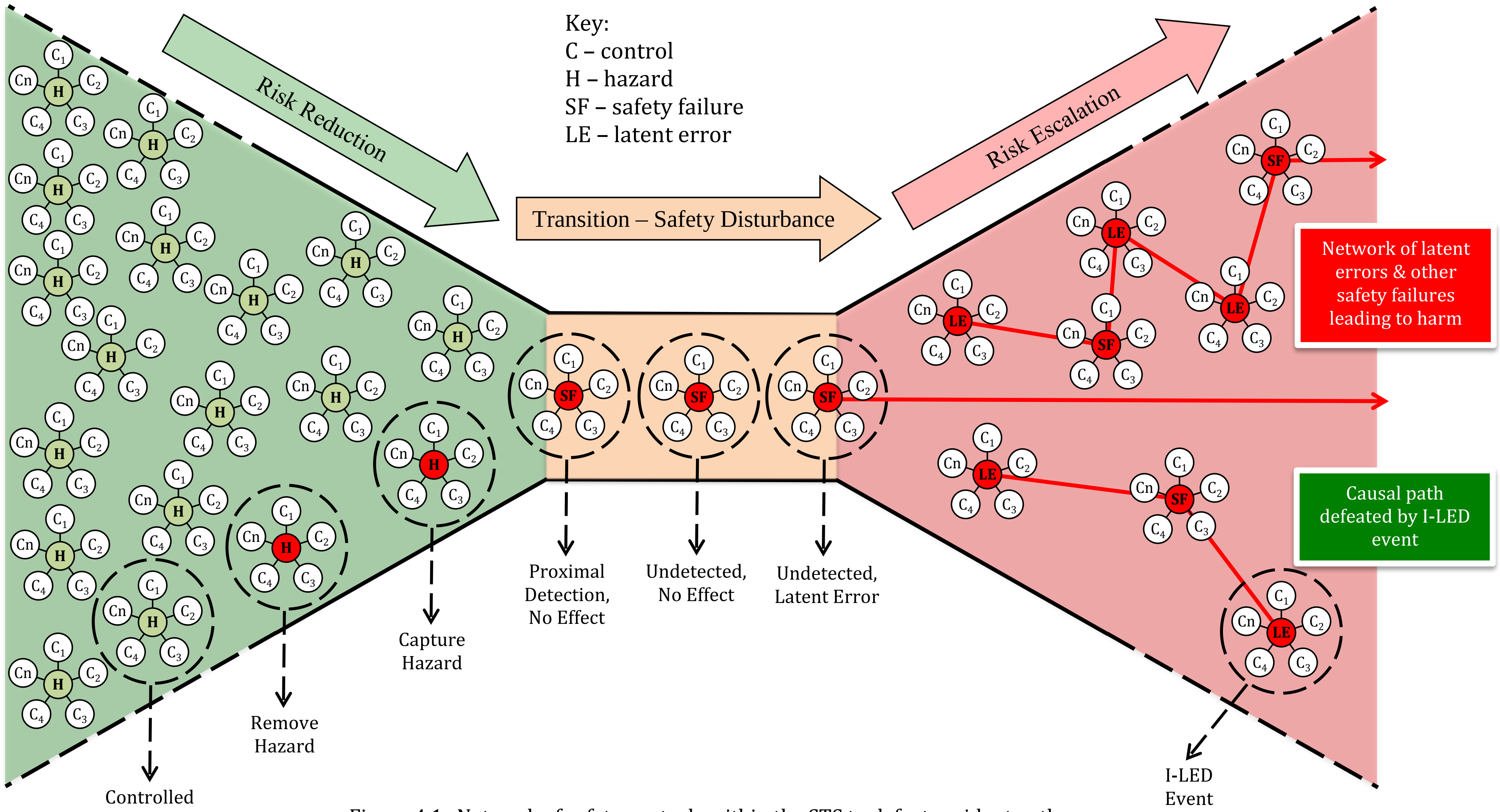


Figure 4.1. Network of safety controls within the STS to defeat accident path.

The I-LED model offers an end-to-end pictorial representation of system hazards that can cause a safety disturbance by transitioning to a system failure then latent condition if not detected. The boundary of the bowtie depicts the limit of the organisation's STS, for which the real-world is a three-dimensional network of operating hazards as opposed to the model as drawn, which suggests a simple linear transitional path from hazard to accident. This linear view of accident causation belies the complexity of system hazards and their associated risk networks that can generate path to an accident (Carayon, 2006; Niskanen et al., 2016; Stanton and Harvey, 2017) and thus the model is drawn purposefully to provide clarity to the concept of controlling system hazards throughout the lifecycle of an safety critical organisation. Thus the bowtie represents the network of system controls needed before, during and after a safety failure to provide total safety or resilience, which gives rise to a symmetrical bowtie indicating a balanced systems approach to safety. Resilience is described further in Chapter 8 where arguably progressive safety strategies should attempt to trace and control safety risks associated with operating hazards through a Networked Risk Management (NRM) strategy, i.e. NRM is a proposal that links potential accident causation paths as suggested in Figure 4.1 so that controlled interventions can also be networked to create resilience using a systems approach to risk (hazard) management as opposed to a linear view of causation (Hollnagel, 2014; Niskanen et al., 2016; Stanton and Harvey, 2017). However, the mapping of causation networks using a NRM approach is outside the scope of the current research.

To explore how the I-LED model represents system safety, the following refers to a maintenance error event recorded in ASIMS (2013a), which resulted in an aircraft accident. The real event has been heavily anonymised with only the salient points kept from the original ASIMS narrative:

> *The Tail Rotor Blade (TRB) of a helicopter was replaced during overnight routine maintenance, which was conducted in an aircraft hangar at a UK base. The maintenance procedure required the removal of several nuts securing the TRB. The operative (junior engineer) that replaced the TRB was also responsible for replacing the nuts. The nuts were replaced but not secured correctly in accordance with the maintenance procedure. A mandatory check of the maintenance work by a supervisor also missed the TRB nuts were not secured correctly.*

4.2.2.1 *Risk reduction*

The left side of the bowtie represents all the multiple hazards in a complex safety critical organisation that need to be controlled to reduce the risk of an undesirable outcome (Safety I: Hollnagel, 2014). Referring to Figure 4.1, hazards ('H' in Figure 4.1) are enveloped by HFE designed safety controls ('C' in Figure 4.1), for which it is argued there is likely to be various controls needed for each hazard, denoted by C_1-C_n. For example, training, presence of competent operators, procedures, user friendly equipment, management oversight, limitations on Performance Shaping Factors (PSF), etc. The latter generally refers to sociotechnical factors that can increase the occurrence of human error or erroneous acts (Kirwan, 1998). The analogy is that effective hazard controls reduce risk in the safety system. These hazards remain 'contained' in the left of the model and only transition to a safety disturbance if the hazard cannot be controlled adequately. Before this, Reason and Hobbs (2003) control methods can be applied to design-out uncontrollable hazards (shown as a red coloured 'H') or mechanisms put in place to capture the hazard. For the example maintenance error event, the hazard is the ability to not fit the TRB nuts correctly. In addition to the standard controls highlighted (C_1-C_n), the hazard could be removed through the re-design of the TRB securing system or captured through a targeted independent check.

4.2.2.2 *Transition to safety disturbance*

The targeted independent check by the supervisor was ineffective though and therefore the hazard transitioned to a system failure ('SF' in Figure 4.1); creating a disturbance in the safety system. As Figure 4.1 suggests, the proximal detection provides an opportunity to capture the error. Here, Chapter 2 noted Amalberti and Wioland (1997) research that showed errors made by highly trained operators can be frequent, yet most are either inconsequential or detected and corrected before leading to an undesired outcome. Zapf and Reason (1994) highlighted several controls that can be applied to proximal error detection: conscious self-monitoring (planned detection); external environmental cue (unplanned); or a third party such as a supervisor when checking a safety critical task (again, planned detection). The transition also highlights Amalberti and Wioland's (1997) view that some undetected safety failures might become latent errors that do not affect safety and are therefore be inconsequential. A systems perspective though suggests it can be hard to identify hazards that do not affect system safety by contributing to a network of hazards that creates a chain of events, as by definition it is an unsafe condition that requires control. It is argued then that few undetected system failures can be considered inconsequential; they just lie undetected where their influence as an unsafe latent error is unknown.

4.2.2.3 *Risk escalation*

Undetected error or a system failure transitions to a latent error ('LE' in Figure 4.1) with the potential to cause harm, as single event or by networking with other safety failures to form a causal path. The right side of the bowtie has been adapted to represent this as a potential risk escalation pathway that can lead to an accident if further controls or interventions are not applied. For the example maintenance error event, the risk of the safety failure might be realised immediately if the securing nuts were to loosen on start causing serious vibration or the TRB comes off the hub injuring ground personnel. Otherwise the TRB nuts might lose torque in flight and fail, which would normally result in the loss of the aircraft. In a different scenario, if the TRB nuts were to loose torque gradually in flight then the aircrew would be alerted through excessive vibrations and perhaps have time to execute a successful emergency landing. However, when combined with a poor response to the emergency due to ineffective training and compounded by poor weather or unforeseen operating hazards such as operating over the sea at night then the outcome could again be very different (which arguably highlights the complexity and dynamic nature of normal operations).

Arguably, it is in the right side of the bowtie model that LED events, including I-LED, can act as additional controls to limit or prevent harm. Example LED events might include detection as a result of: before flight aircraft servicing; aircrew inspection of the TRB during their pre-flight inspection; or vibration monitoring on aircraft start. The engineer suffered a lapse when the schema to secure the TRB nuts was not enacted

(Rasmussen, 1982; Reason, 1990) resulting in the omission to torque the nuts later. Should the engineer later recall the error, without cueing from a formal process, then this is offered to be an example of an I-LED event in the bowtie as shown. The detection of the latent error defeats the causal path and therefore counters risk escalation to restore safety equilibrium. Thus it is argued Figure 4.1 provides a systems representation of the transition of undetected hazards through to latent errors, and the role of other LED interventions such as process checks and independent inspections as well as the additional control measure of I-LED to restore safety as part of a resilient safety system. The I-LED model is therefore thought to offer a suitable conceptual model by which to observe the proposed I-LED phenomenon as an additional control, from which the following sections review the methods by which to observe I-LED events in real-world workplace environments.

4.3 Research Strategy

4.3.1 *Target population*

The target population exists within the operating context of UK naval aircraft maintenance where around 1,700 naval air engineers are employed, which includes junior operatives through to senior supervisors; being male and female of ages 18 to 50 years. As the Royal Navy is an equal opportunities employer, military personnel are all British Commonwealth citizens of broad ethnicity. Participants in each study have been sampled from this population; taking care to ensure samples do not overlap such that data from adjacent studies risked contamination. Sample groups were selected and sized to be meaningful and statistically valid as required by each study. Sampling by operator group (operative or supervisor) provided a broad range of experience levels. This population was chosen since the author is a serving Royal Navy Air Engineer Officer (AEO) and therefore provided a deep knowledge of the operating context, free access to the target population and safety databases where needed; resulting in a data rich environment to explore. Whilst knowledge and expertise in a subject area is needed to exploit the maximum information from the available data, it was recognised that the researcher needed to ensure this deep knowledge did not inadvertently bias the research and thus various strategies are used in each study to counter any effects. This included testing for inter-rater agreement, review of electronic recordings where used and studies designed based upon theory and evidence from other studies to derive question sets and analyse data (Cassell and Symon, 2004; Schluter et al., 2008).

4.3.2 *Importance and challenge of naturalistic real-world observations*

To explore the nature and extent of I-LED in the workplace and therefore its contribution to safety resilience, everyday routine safety behaviour needs to be observed since naturalistic research allows successful error detection and recovery to be observed in response to real-world scenarios (Saward and Jarvis, 2007). Unlike highly procedural environments found on a flight deck or in process control, it is arguably more difficult to observe everyday error behaviours of the aircraft engineer due, in part, to the complex, dynamic and multiple operating environments experienced by the aircraft engineer when carrying out day-to-day maintenance tasks (Prabhu and Drury, 1992; Latorella & Prabhu, 2000; Rashid et al., 2010). For example, the live flight deck environment benefits from flight data and cockpit voice recordings, which provide a rich source of real-world data (Flin et al., 2008). This facilitates an accurate account of error detections. Conversely, nothing comparable exists within the aircraft maintenance environment so errors are not always apparent when observing the naturalistic environment and can therefore pass undetected leaving it very challenging to observe I-LED events. Notably, Flin et al (2008) argued that understanding of error behaviour could only come from the assessment of operational behaviours in context whilst Woods et al. (2010, p. 236) believed *research on how individuals and groups cope with complexity and conflict in real-world settings produces the necessary insight on how to approach error*. Dekker (2003, p. 100) suggested that understanding the mind comes from analysis of the *world in which the mind found itself instead of trying to pry open the mind* (i.e. understanding the role of the physical environment) and is an important statement as the need for 'operational' understanding of error behaviours is widely recognised and drives an argument for schema research to be conducted in real-world contexts. Deliberately, this positions current research within the realm of HFE research rather than cognitive psychology, as it is the influence of the external environment on error behaviour that, arguably, presents the greatest safety value (Plant and Stanton, 2013b). Thus future studies will first thematically analyse narrative data from air engineers who have experienced latent error detection before moving to empirical research within the physical working environment to observe I-LED interventions designed using multi-process findings. Ecological experiment also brings benefit with observational studies since schema are internal representations of the world for which measurement can only come from observed behaviour in the real-world contexts (Plant and Stanton, 2013b).

Much enquiry has been made of error avoidance and proximal error detection (and recovery) where mostly empirical analysis involving carefully controlled laboratory experiments has been conducted (Allwood, 1984; Kanse, 2004; Thomas, 2004; Flin et al., 2008; Wilkinson et al., 2011; Patel et al., 2011; Kontogiannis, 2011). Understanding safe behaviour through local safety practices can only come from assessing operational behaviours in context. However it is recognised that strict experimental control is not possible in naturalistic studies, although the advantage of naturalistic studies is that it avoids the bias of artificial controlled experiments that can erode the ecology of findings. Studies have also shown the nature of the operating context is not easily replicated in simulated experiments due to the complexity of sociotechnical interactions (Prabhu and Drury, 1992; Latorella and Prabhu, 2000). Sellen et al (1997) found conducting their experiments in a work environment provided a level of ecology that yielded important sociotechnical factors such as the influence of competing activities/tasks, time and physical locations although they highlighted the challenge of tracking performance in dynamic real-world environments. Thus it might not possible to faithfully emulate realistic system contexts or cues in a laboratory setting but the potential ecological benefits are widely recognised to outweigh any potential concerns to deliver a meaningful contribution to safety knowledge (Norman and Shallice, 1986; Dekker, 2003; Kvavilashvili and Mandler, 2004; Reason, 2008; Flin et al., 2008; Finomore et al., 2009; Woods et al., 2010). As this may enhance resilience to the inevitability of human error, the researchers were confident that a real-world study in the natural workplace was needed to investigate the phenomenon but two areas needed to be addressed: use of appropriate theory against which to assess I-LED performance; and selection of research methodologies that facilitate effective data gathering from the workplace.

4.3.3 *Theory upon which to observe I-LED events*

The extensive review of literature in Chapter 2 found little research on I-LED events occurring post-task completion. In the absence of current theories, the case was argued for a multi-process approach to systems research that combines theories on PM, SAS and schema theory to observe I-LED events. Combining several theories to achieve a multi-process research strategy suggests it is unlikely that a single factor (independent variable) would be observed and therefore multiple sociotechnical factors with interrelated determinants would need to be considered in each study.

When reviewing theory upon which to research I-LED events, it was noted that the schema theory element of the theoretical multi-process framework has been challenged as to whether it is appropriate theory for HFE research. Bartlett (1932) introduced schema as information represented in memory about our external world comprising objects, events, motor actions and situations. Norman (1981) defined this information as 'organised memory units' for knowledge and skills that are constructed from our past experiences, which we use to respond to information from the world. This human interaction with the world is characterised by the Perceptual Cycle Model (PCM), which represents human actions based on the cyclic interaction of schemata with perceptions of the world. The model can be largely automatic for skilled operators using well learnt skills (Norman and Shallice, 1986), which includes the ability to spontaneously detect past errors as discussed in Chapter 2. Here it is the lack of definition and understanding of the internal workings of the mind plus absence of a unitary value to measure schema performance that has been criticised (Mandler, 1985; Smith and Hancock, 1995; Endsley and Robertson, 2000). Plant and Stanton (2016) also recognised the inherent difficulties in measuring schema performance in the external environment but argued the use of schema theory in HFE research is more concerned with how we interact with the world rather than specific knowledge of genotype and phenotype schema, which are themes described in Chapter 5. Dekker (2003) supports this position with his argument that safety gains come from understanding the world around the mind as opposed to its internal workings. It is argued that knowing internal memory units exists and that they possess a hierarchy for correct sequencing is sufficient, rather than trying to unlock detailed knowledge of exactly how the mind works. Thus applying schema theory in the knowledge that an operator matches tasks (PM element) with actions by monitoring (SAS) cues in the world (PCM) is believed sufficient for I-LED research. Plant and Stanton (2016) continue to highlight much research in SA is based upon schema theory, which has resulted in significant gains in safety research. Stanton and Walker (2011) argued schema theory has been tested over time and shown to provide sufficient account of how operators interact with the sociotechnical environment and it can also help identity where system failures can occur. The latter is an important element for the I-LED model shown in Figure 4.3 as it helps with the design and management of safety barriers that control our interaction with the world to remove or capture errors due to system failures or for an I-LED event to trap the latent error before risk escalation. Thus schema theory, as part of multi-process approach to I-LED research, is argued to be appropriate theory.

4.3.4 *Linked studies approach to research*

The second challenge to real-world research is selecting research methodologies that facilitate effective gathering and analysis of data from the natural workplace. To help ensure quality data were captured, and to remain flexible to emergent findings, a staged approach to research using a mixture of methodologies is employed in a series of linked studies (Trafford and Leshem, 2008). Strategically, this flexible approach facilitates the application of various research paradigms and data collection instruments that can be applied when observing the target population over a protracted period. This strategy also safeguarded against any study that failed. Emergent findings from each study were used to guide research in terms of direction for subsequent studies. This required continued engagement with current literature for the iterative development of hypothesis and theories; expectantly, this has matured thinking on the phenomenon as each study reported its findings.

To provide direction for each I-LED study, research was framed around the aim and objectives 2, 3 and 4 stated in Chapter 1 to construct three linked observational studies to investigate the I-LED phenomenon:

- Objective 2: *Study 1 (Exploratory group interviews).* To 'baseline' research and facilitate analysis of emergent themes relating to the proposed phenomenon exploratory group interviews were conducted, which included the administration of a questionnaire designed according to multi-process theories. Group interviews allowed an explanation of the research to be given and to address any questions with the questionnaire in a non-directive manner to ensure completeness of individual responses (Oppenheim, 1992). This approach was also selected to collect a large amount of data efficiently whilst fully inducting the researchers in the concept. Data were analysed thematically (Robson, 2011) to highlight significant findings and to further conceptualise and contextualise the proposed phenomenon before identifying themes / hypothesis to test in subsequent studies.

- Objective 3: *Study 2 (Workplace self-report diaries).* A self-report diary was used to data on every day I-LED events occurring in the workplace. Whilst capturing individual perceptions, the advantage of self-report diaries as a research instrument is that it can be used ecologically to observe the subjective phenomenon by reporting on specific events or tasks present in everyday activity without intrusion but with adjacency and detail (Reason, 1990; Cassell and Symon, 2004; Robson, 2011). The diary recorded I-LED observations over two months and was constructed using Critical Incident Technique (CIT), which is the general term that describes the process of capturing important incidents recorded by the participant in a diary (Flanagan, 1954); an incident being *any observable human activity that is sufficiently complete in itself to permit inferences and predictions to be made about the person performing the act.* The term critical simply refers to a significant I-LED event reported by the participant. To help determine whether the target population for the diary study exhibited normal cognitive behaviours, literature was reviewed for an appropriate instrument to employ. The Cognitive Failures Questionnaire (CFQ) scores an individual's propensity for everyday cognitive failures using 25 questions scored 0-100 against a 5-item Likert coding, where a high mean score (>51) indicates a propensity for cognitive failures (Broadbent et al., 1982). The CFQ was used to confirm normal cognitive behaviours in the previously unstudied cohort of naval air engineers but not to judge individual cognitive performance whilst also providing a benchmark upon which to authorise research findings against wider populations. Data from the self-report diaries were analysed thematically to highlight significant findings; thereby providing direction for Study 3.

- Objective 4: *Study 3 (I-LED interventions).* Study 2 indicated the application of targeted I-LED intervention techniques that draw upon system cues, are likely to enhance the effective detection of latent errors. The study also argued that targeted interventions are especially important for simple everyday habitual tasks carried out alone where perhaps individual performance variability is most likely to pass unchecked if there are organisational deficiencies in system defences. Thus appropriate I-LED interventions (for a specific safety context) are likely to offer further resilience against human performance variability. Study 2 reported any intervention needed to be deployed within a real-world context to operationalize and assess its benefit. Thus Study 3 has been designed to advance knowledge on I-LED by observing the utility of I-LED interventions within the workplace determined from Study 2. To help provide direction on the practicable interventions to be observed in the study, additional qualitative data collected during Study One was accessed. This analysis guided the selection of appropriate I-LED intervention techniques to be used in the study. The findings from Study 3 are used to answer Question 3 and therefore complete the component parts needed to address the main research question.

4.4 Ethical considerations

Each study required careful consideration of ethical issues such as the purpose of research, data collection and storage, privacy assurance and protection against any negative effects that individuals may experience as a consequence of the research (Trafford and Leshem, 2008). Therefore, ethical statements and associated risk assessments have been tailored to meet the needs of each study; with approval gained from University of Southampton Ethics Committee. Since research involves military personnel, the Ministry of Defence Research Ethics Committee (MoDREC) was consulted, which confirmed no additional ethics approval was required whilst local engineering management where approached in advance of each study for consent to conduct specific research.

4.5 Summary

To observe the nature and extent of the I-LED phenomenon, the I-LED model based upon an adapted bowtie representation shown in Figure 4.3 has been introduced to provide a conceptual representation upon which to anticipate where I-LED events offer the greatest benefit as additional safety control against the potential networking of latent errors that risk an organisational accident. Arguably I-LED events act as an additional control measure (Safety II) that can be integrated within an existing safety system that is applied locally by operators. To conduct real-world observation in the natural working environment is challenging when compared to observations made in a laboratory setting, where strict experimental control can be achieved. However advances in safety research come from observing real-world behaviours during normal operations and this advantage has been argued to outweigh the challenges of naturalistic research. Part of this challenge is the application of appropriate theory and method selection to yield meaningful results from the population of naval air engineers. Thus the design of the current study allows sufficient flexibility via series of linked studies using mixed-methods. This strategy also accommodates changes to the research design if emergent findings materialise that require a different methodology or revision to the observed phenomenon based on real world findings. The next chapter introduces the first study, which uses group interviews to determine the presence and nature of the proposed I-LED phenomenon in the target population.

Chapter 5: A time and a place for the recall of past errors

5.1 Introduction

System-induced human error is recognised widely as the most significant factor in aircraft accidents; for which error is both inevitable and a frequent occurrence (Reason, 1990; Hollnagel, 1993; Maurino et al., 1995; Perrow, 1999; Wiegmann and Shappell, 2003; Flin et al., 2008; Woods et al., 2010; Amalberti, 2013). The potential consequences of system-induced error in safety critical contexts is universally understood, both in civilian and military environments where human error describes situations when either safety or the effective completion of a task has been compromised as a result of human action (Helmreich, 2000; Shorrock and Kirwan, 2002; Wiegmann and Shappell, 2003; Flin et al., 2008; Reason, 2008; Woods et al., 2010; Aini and Fakhru'l-Razi, 2013). Error that passes undetected becomes a latent error, which can result in a future undesirable outcome (Graeber and Marx, 1993; Reason, 1997; Lind, 2008; Aini and Fakhru'l-Razi, 2013). Chapter 2 introduced a phenomenon where latent errors appeared to be detected spontaneously at some point post-task completion. Despite an extensive literature review on human error detection occurring post task completion, no legacy research was found for the phenomenon and thus the need to explore the nature and extent of Individual Latent Error Detection (I-LED) was proposed, which is distinct from other LED safety strategies such as process checks, supervisor inspections and pre-flight checks. Historically, causes of error and error avoidance research has targeted: the human-machine interface; human error identification and classification systems; and organisational error management strategies aimed at reducing the likelihood of error (Reason, 1990; Hollnagel, 1993; Kontogiannis, 1999; Shorrock and Kirwan, 2002). Human error was defined in Chapter 2 as simply a colloquial expression used to simply flag error effects or erroneous actions that must be contextualised against the system context (i.e. situational error) to be meaningful. Thus to understand human error as a consequence of the operating environment or sociotechnical context, a systems approach is needed as this is where system influences cause human error effects (Hutchins, 1995; Dekker, 2002; Reason, 2008; Woods et al., 2010).

To observe the I-LED phenomenon using a systems approach, Chapter 2 proposed a multi-process theoretical framework; combining theories on Prospective Memory (PM), Supervisory Attentional System (SAS) and schema theory. The multi-process framework argues the PM element forms intent for a task to be carried out in the future (Baddeley and Wilkins, 1984; Kvavilashvili and Ellis, 1996; Blavier et al., 2005; Dismukes, 2012), which creates a ‘to do’ list or markers in the mind (Sellen et al., 1997; Marsh et al., 1998; Van den Berg et al., 2004). The schema theory element describes information represented in memory about our knowledge of the world we interact with (Bartlett, 1932). Schemata are developed over time through past experiences and account for the knowledge and skills that we apply to everyday situations in response to external sensory cues (Norman, 1981). This is an iterative process where repeated exposure to similar situations leads to highly developed schemata that are associated with an experienced operator who becomes well-practiced at particular tasks (Bartlett, 1932). Developed schemata that form internal memory structures, which can be accessed to respond to a particular task, are known as genotype schemata whilst phenotype schemata refer to the actual response when executing a task (Neisser, 1976; Reason, 1990). This is an important distinction in schema theory as it is the phenotype schema that manifests as the observable effect when assessing human activity and therefore it this phenotype schema behaviour that is of particular relevance when exploring I-LED. Chapter 4 highlighted some of the criticisms of schema theory due to its under specification as a theorem that lacks unitary value to conduct measurements. However, a review of literature in Chapter 4 found schema theory to be a useful theoretical approach to observing human interactions with the world, which can be used to help understand sociotechnical factors influencing safety behaviour.

Schema theory is further characterised by the Perceptual Cycle Model (PCM). The model describes a cyclic relationship between schema selection and sensory cues in the external world that trigger human actions (Neisser, 1976). Thus the PCM is argued to sit within the multi-process framework to account for human interactions with the world. The PCM and schema theory indicate that only the highest-level schema needs conscious control for subordinate schema to trigger autonomously (Norman, 1981; Mandler, 1985; Cohen et al., 1986; Reason, 1990; Baddeley, 1997). For example, an engineer may be tasked to flight service an aircraft. This requires the conscious selection and triggering of the high-level schema for aircraft servicing, which in turn, necessitates the triggering of subordinate schemata that are automatically associated with the high-level task such as opening a panel, using tools, checking levels, replenishing fluids etc. It is argued the engineer is more likely to detect the high-level schema being in error due to forgetting to carry out the entire flight servicing task, as opposed to one of the many largely autonomous and discrete subordinate schemata. A latent error is generated when the internally selected genotype schema is either not triggered or triggered but the phenotype schema, which manifests as the actual human action, does not match the action required for the task. In effect, the failed trigger or genotype/phenotype mismatch has not been detected by the PCM proximal to the error event (for comprehensive coverage of PCM theory refer to: Bartlett, 1932; Neisser, 1976; Norman, 1981; Mandler, 1985; Stanton et al., 2009a; Plant and Stanton, 2013a).

The SAS element of the multi-process framework, proposed by Norman and Shallice (1986), is attributed the attentional mechanism that continuously monitors the external world for sensory cues that trigger schemata and which provides task feedback within the PCM schema-action-world cycle (Smith, 2003; Einstein et al., 2005). Thus, it is this SAS element that regulates the cancelling of completed tasks on the 'to do' list. This task feedback also updates established genotype schema and enables the development of new schema if the task was novel (Reason, 1990; Plant and Stanton, 2012). Multi-process theory constructed in Chapter 2 coined this activity as the schema housekeeping function within the PCM where intended actions are monitored for completion and feedback from the action also facilitates learning and the acquiring of experience.

Chapter 3 discussed the need to approach human errors effects as the catalyst for understanding system failures that caused the error. The system perspective therefore considers the world in which people are immersed in and which drives safety behaviours from a human-centred approach. The PCM accounts for human error from the systems perspective as shown in Figure 5.1, which has been adapted from Neisser (1976) and Smith and Hancock (1995) to highlight the elements of multi-process theory introduced in Chapter 2. Here, the sociotechnical world provides the system cues that trigger actions, from which the PM element was argued to be responsible for the creation of a 'to do list' of tasks, described in Chapter 2. The PM selects required schemata (cognitive information) to carry out the action as part of this activity. Task execution occurs when the PM directs behaviour based on samples of the world by the SAS (Plant and Stanton, 2012). Execution of this activity requires the bottom-up (BU) processing of external data from sensory inputs with top-down (TD) prior knowledge (schemata) to project a response (Neisser, 1976; Cohen et al., 1986; Plant and Stanton, 2013a). This processing of the external environment with internal pre-existing schema to achieve the required response captures elements needed for Situational Awareness (SA) and is essential for the execution of tasks without error (Plant and Stanton, 2013a). When errors occur, the continual monitoring by the SAS to assess task performance and schema reinforcement / learning through schema housekeeping (Saward and Stanton, 2015a) also provides the opportunity for I-LED events.

The combination of multi-process theory and the PCM shown on Figure 5.1 is argued to encapsulate cue dependency for the triggering of schemata, which is dependent on the effective cognition of sensory cues distributed throughout the external environment (Hutchins, 1995). Thus the relationship between the mind and the external world is important, for which distributed cognition theory argues cognitive cues are distributed throughout all sociotechnical environments in which the mind finds itself (Hutchins, 2001). This helps to understand that human actions are dependent on cues distributed throughout the external environment and leads to the concept of Distributed Situational Awareness (DSA), which is needed for effective human performance (Stanton et al., 2014). This dependency on external cues to trigger schema action has been investigated in PM studies of human error proximal to task activity, which have reported that error avoidance relies on the successful cognition of system cues (Grundgeiger et al., 2014). Thus it is hypothesised I-LED is dependent on sensory cues distributed throughout the external environment. Further, since PCM theory describes a schema-action-world cycle (Plant and Stanton, 2013a), time must be associated with the frequency of the cycle thus it is hypothesised time is also a factor in I-LED.

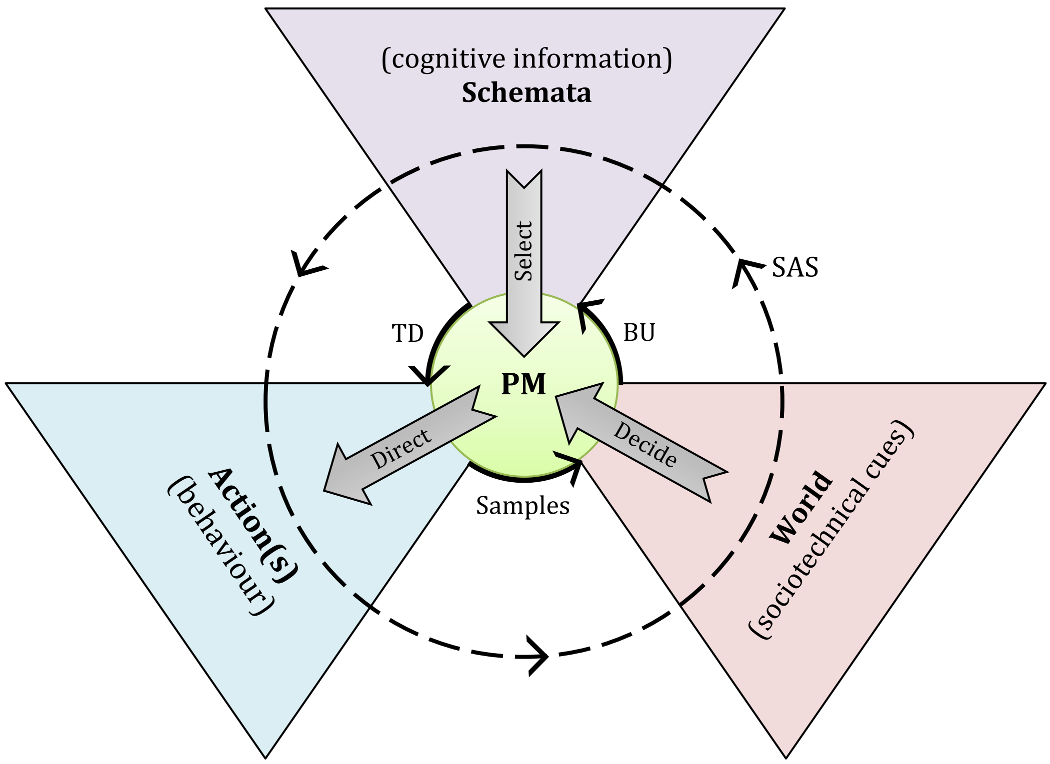


Figure 5.1. Multi-process PCM (Derived from Neisser, 1976; Smith and Hancock, 1995).

To observe the phenomenon of I-LED, a robust method is needed to categorise the actions of the naval air engineer, for which Reason's (1990) Generic Error Modelling System (GEMS) offers an established and widely accepted method. His model describes skill-based action errors in terms of slips and lapses with rule/knowledge based action errors described as mistakes. The GEMS also describes violations but these human actions are not included in the current study due to their deliberate nature (Reason, 1990). A slip is a well-practiced task that is carried out in error unintentionally such as dropping a screwdriver (motor skill) whilst a lapse also involves a well-practiced or familiar task but where the required action is omitted such as forgetting to close a servicing panel on an aircraft. Mistakes occur when the action was carried out as intended but the wrong plan of action was formulated based on flawed knowledge or an incorrect rule was selected for the specific sociotechnical context. Thus, the GEMS categorisation system is argued to have utility when exploring the relationship between external triggers and error behaviour, which offers a theory-driven approach I-LED research.

The aim of the current study is to apply systems thinking to the multi-process framework introduced in Chapter 2 to explore the nature and extent of I-LED amongst a population of naval air engineers that operate in the aircraft maintenance context. The aim progresses Objective 2, which is to apply the theoretical framework to understand the nature and extent of I-LED events in naval air engineers working in their natural environment. I-LED events are examples of safety behaviour that helps mitigate for system failures in the workplace. Arguably, this approach supports the paradigm shift in addressing error from a systems perspective and offers the opportunity to enhance organisational safety strategies through development of practicable interventions to enhance I-LED.

5.2 Methodology

5.2.1 *Questionnaire design*

The questions in Table 5.1 were constructed according to the multi-process approach to I-LED constructed in Chapter 2 and are therefore based upon theories for PM, attentional monitoring and schemata. Quantitative and qualitative data were collected for the hypothesis by structuring the questionnaire around three main areas: the maintenance task; error event; and detection of post-task latent error. The measurement ability of each question was assessed against multi-process theories, through participant feedback and analysis of questionnaire responses during piloting. Since questions reflected the proposed phenomenon and were structured to explore the hypothesis, this also offered a degree of construct validity and a theory-driven questionnaire that was believed to be sufficiently comprehensive to capture evidence for the exploratory nature of the current study (Oppenheim, 1992).

To protect questionnaire responses from contamination due to participants conferring or from individuals biasing other participant's views, the researchers carefully controlled group dynamics. For example, the researchers were ready to interject if any strong views where raised in the group or specific details of a personal error event were put forward during the group interview. Conversely, to help ensure researcher immersion did not influence participants the group interviews were recorded digitally and reviewed to check the integrity of the process and that the researchers had not I-LED the participants (Cassell and Symon, 2004). This was achieved by reviewing the recordings with an Air Engineer Officer (AEO) who was not involved with the study. An engineer was used so that technical terms and the context would be understood. All recordings were found to be consistent and did not contain any strong views or leading comments that could potentially bias a group. Thus these recordings were used for quality control only and were not subject to further analysis.

Table 5.1. Group interview questions.

Category	Question
Maintenance Task	1. What was the task to be carried out? 2. Was this your only task to be carried out? (Yes/No) 3. How was the task identified? (i.e. were you asked, was it part of a process, self-identified, etc) 4. Where were you when tasked? (i.e. in AMCO, hangar, working on an aircraft, etc) 5. Did you carry out the task immediately or was it carried out at some point later? 6. What was the time of day when tasked?
Error Event	7. Please describe your error. 8. What was the time lapse between when you were tasked & the error?
Latent Error Detection	9. Please describe how you became aware of your error. 10. Where were you at the time you became aware of your error? 11. What was the time lapse between the error & your detection? 12. Have you ever been concerned that a past task was in error but found it not in error when checking (please give example)? 13. How do you think the self-detection of latent errors could be improved?

5.2.2 *Sampling strategy*

To achieve a representative sample, within the resources available for the current research, Royal Navy units consisting of naval air engineers at helicopter squadrons and those on various maintenance courses were identified to give a sample stratified across the target population according to geographic location, type of work and experience. Within the resources available for the current study, a total of 68 engineers were identified for the study from a target population of approximately 1700 (4%): eight engineers for piloting; 48 for data collection; and a further 12 to help assure thematic saturation and ameliorate participant error (Robson, 2011). This strategy required 17 group interviews to be conducted with four participants in each group (including two groups for piloting); organised by groups of four operatives and four supervisors to give a broad range of aircraft experience and ages. Groups of four were chosen to generate sufficient discussion but not so large that some individuals did not have a chance to offer a contribution or ask a question. The size of the groups also minimized the impact of the research on the aircraft maintenance unit whilst the overall samples size provided a manageable amount of data for analysis. To identify individual participants within each unit, local management were asked to conduct a simple random sample to identify eight air engineers from their available manpower. As the sample from each squadron was very small, local management were asked to conduct a simple 'raffle' approach by selecting names 'out of a hat' (Rowntree, 1981). An additional two engineers were also requested to allow for any individuals that chose not to take part in the research or were not available on the actual day of the group interview.

5.2.3 *Piloting*

The administrative process and a draft questionnaire were piloted using two group interviews (operatives, n=4 and supervisors, n=4) that were representative of the population. Each group was asked to provide feedback based on Wiegmann and Shappell's (2001) guide for an effective taxonomy, commenting on: the comprehensiveness of the written participant information and questionnaire; diagnostic capability of the questionnaire to determine if questions were sufficiently wide-ranging and appropriate to capture everything they wanted to say about their example of latent error; and how usable they perceived the questionnaire to be. This resulted in several revisions to the questionnaire and changes to the administrative process such as removing ambiguity in some questions and simplifying sentences. General readability of a Participant Information Sheet (PIS) was also assessed against the Flesch reading ease score. The PIS shown at Appendix B was given to participants, which included written information to explain the research and benefit of their contribution, scored 42.7 and thus slightly difficult to read. Feedback from piloting helped achieve a final score of 60.1; indicating plain English for adult reading.

5.2.4 *Data collection procedure*

Group interviews were conducted to introduce the concept of I-LED to participants and administer the questionnaire. This allowed the researchers to explain the overall aim of the research and clarify any queries with the questionnaire in a non-directive manner to ensure completeness of individual responses (Oppenheim, 1992). Local engineering management were approached in advance for consent to conduct the research and selected individuals were notified one week prior to each group interview to explain the purpose of the research and how their data would be used. This was achieved via a participant information sheet (Appendix B) that was provided in advance of the group interview. After reading the information, individuals were free to opt out and another engineer from the manpower list was selected. Participants were asked to come prepared with an example of everyday post-task latent error that happened to them at work that, to reduce the potential impact from memory decay, needed to be a recent example (within the last 12 months). Each group interview was conducted within the normal workplace. Each session consisted of an initial brief followed by a short period of group discussion to help understand the concept of I-LED and to provide an opportunity to ask questions before completing the questionnaire. All participants signed a consent form, which also highlighted the study had received ethical approval from Southampton University Ethics Committee (Approval No. 13496). Participants could continue to raise queries as they completed the questionnaire. Each group interview lasted around 40mins. On completion, questionnaires were checked for completeness and participants reminded of how their contribution would be used. Overall, the data collection process took three weeks, after which collected data were cleaned for errors and anonymity before analysis (Oppenheim, 1992).

5.2.5 Data analysis

Descriptive statistics were produce for the responses to the questions shown in Table 5.1. To test for the strength of association between category variables, several contingency tables were constructed. Pearson's Chi-square test was applied to each contingency table unless the frequencies were lower than five, in which case Fisher's exact test was used. Timing data were correlated using Spearman's Rho non-parametric test as data were ranked according to reported mean times. The analysis of participant narratives from Questions 9 & 13 shown in Table 5.1 was conducted using thematic analysis (Robson, 2011). Themes were generated from the participant responses shown at Appendices C and D, then compared 'horizontally' with all participants to identify any global themes (Cassell and Symon, 2004; Polit and Beck, 2004). An iterative constant comparison approach was used to review narrative data to exhaust emergent themes until thematic (theoretical) saturation was achieved (Glasser and Strauss, 1967). This required comparison with a further 12 questionnaires completed by additional group interviews to help assure thematic saturation. To test for inter-rater agreement, an independent assessor was used who conducted a 100% review of the data. Cohen's Kappa was calculated on the frequencies shown as opposed to percentage agreement to correct for any chance agreement (Robson, 2011). This found k=0.86, indicating very good agreement.

5.3 Results

5.3.1 *Description of sample*

Participants were all fully qualified naval air engineers and experienced at their specific employment. The engineers were grouped operatives and supervisors, according to the two main employment levels within a squadron as opposed to the experience they have of a particular task. For example, operatives possess limited authorisations for aircraft maintenance that involves routine maintenance tasks such as aircraft flight servicing. A supervisor will have been an operative before promotion and is afforded wider authorisations for more demanding maintenance tasks such as in-depth aircraft fault diagnosis and additional functions such as planning aircraft maintenance and leading maintenance teams. The current study views each participant as equally experienced for their particular employment and thus the grouping of operative and supervisor simply reflects the general differences in how they are employed in a squadron.

The sample included both males (n=45) and females (n=3) from the target population, for which the low count of females in the sample is representative of the population. The sample consisted of 24 junior engineers (mean age=27.6 years, SD=4.3, Range 21-39) and 24 senior engineers (mean age=36.6 years, SD=6.9, Range 23-57). Trainees were not included as they are at an earlier stage of learning and thus still developing their maintenance skills (Fitts and Posner, 1967). As such, trainees are not authorised to conduct aircraft maintenance without 100% supervision and additional safety checks are put in place to carefully monitor their work. Only one candidate chose not to participate based upon the belief that he had not experienced the phenomenon and eight questionnaires were discarded after an initial read-through due to illegible handwriting or because the responses were not examples of post-task I-LED.

5.3.2 *Analysis of responses*

5.3.2.1 *Maintenance task and error event*

Questions 1-6 in Table 5.1 captured contextual data preceding the error event to identify potential LED influences. Responses to Question 1 all described familiar maintenance tasks that were routine and well practiced. For example: aircraft servicing; component changes; completion of aircraft documentation; logistics; and refuelling. Question 1 also showed 79.2% (n=38) of maintenance tasks to be complex tasks; complex tasks being an aircraft engine change or flight servicing an aircraft (defined by naval aircraft maintenance policy). The remainder 20.8% (n=10) were simple tasks such as checking a toolbox, securing an aircraft panel or signing for completed work in an aircraft maintenance document. Question 2 reported most engineers 60.4% (n=29) were tasked with more than one maintenance activity at the time the error event occurred, having identified the maintenance task mostly through a process followed by a verbal brief then self identified: 56.3% (n=27); 41.7% (n=20); 2%(n=1) respectively. Question 5 reported there was a delay starting 52% (n=25) of the maintenance tasks that were later found in error with 48% (n=23) started immediately. The data from Question 5 did not provide sufficient detail to calculate the length of the delays.

Combined responses from Questions 2 & 7 are shown in Table 5.2, which highlights the location where a maintenance task was identified and where the actual error event occurred. For 42% (n=20) of maintenance tasks, the maintenance requirement was identified whilst in the Aircraft Maintenance Coordination Office (AMCO), 37% (n=18) in the hangar and 21% (n=10) in other environments, including: maintenance offices; crew room; or whilst physically on an aircraft. Participants reported 52% (n=25) of error events occurred in the aircraft hangar, followed by 21% (n=10) on the line, 12% (n=6) in the AMCO and 15% (n=7) were other work locations such as a tool store or workshop. Responses to Question 7 also allowed Table 5.3 to be constructed, which shows each error event categorised according to Reason’s (1990) GEMS error categorisation. 69% (n=33) of maintenance error events were categorised as a lapse with mistakes accounting for 27% (n=13) and slips 4% (n=2). Latent detection of execution errors (slips and lapses) represented 73% (n=35) of the sample with planning errors (mistakes) accounting for 27% (n=13). The results gave an equal overall count of error categories between junior and senior engineers although senior engineers did not suffer any slips.

Table 5.2. Locations associated with task identified and the error event.

Physical Location	Task Identified	Error Event
AMCO	20 (42%)	6 (12%)
Hangar	18 (37%)	25 (52%)
Line (Ramp)	4 (8%)	10 (21%)
Other	6 (13%)	7 (15%)

Table 5.3. Error events categorised according to GEMS (Reason 1990).

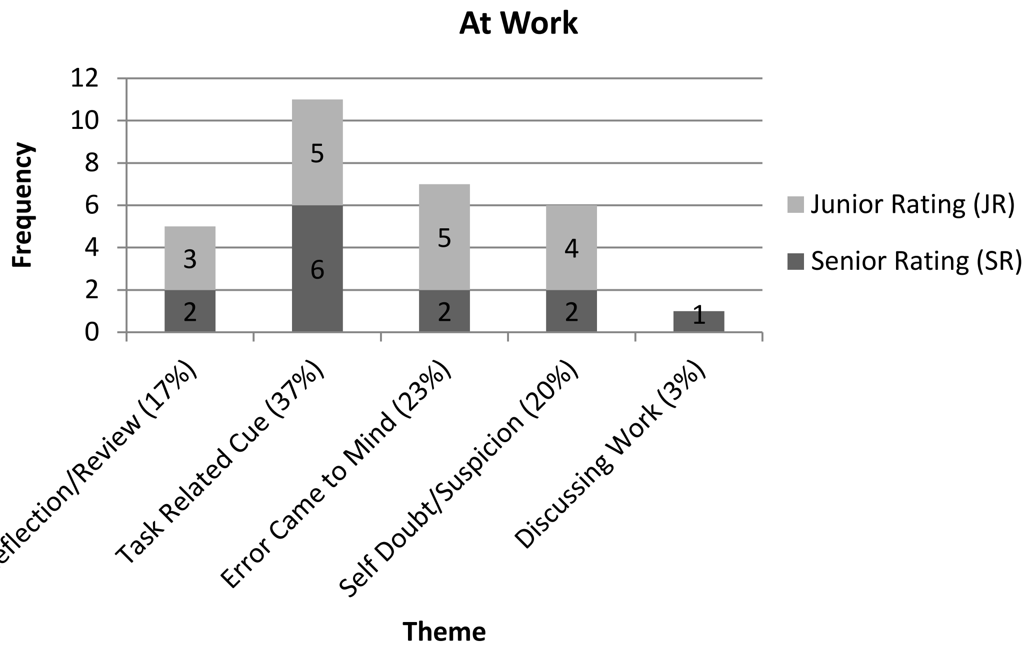
Error Category	Error Type	Count	Example
Execution Error (n=35)	Lapse	33 (69%)	Forgot to ensure wiring loom secured
	Slip	2 (4%)	Engine oil dipstick not seated correctly
Planning Error (n=13)	Mistake	13 (27%)	Wrong component fitted

5.3.2.2 *Error detection themes*

Error detection themes that emerged from the responses to Question 9 are recorded in Appendix C and summarised in Table 5.4. Thematic analysis revealed five main themes associated with different environments, along with a count of reported occasions. Themes for 'self-doubt/suspicion' and 'task-related cue' each account for 25% (n=12) of the sample followed by 'error came to mind' 23% (n=11), 'reflection/review' 21% (n=10) and 'discussing work' 6% (n=3). Table 5.4 also provides example narratives for each theme based upon whether the I-LED occurred At Work or Not At Work. At Work is argued to mean the same or similar working environment to that which the error occurred and Not At Work being other physical environments unrelated to the workplace, i.e. at home or driving a car. Thus reading from Table 5.4, 62.5% (n=30) of I-LED events occurred when At Work and 37.5% (n=18) when Not At Work. To illustrate this delineation further, Figure 5.2 shows themes against physical environment and experience.

Table 5.4. Detection themes associated with environment.

Detection Theme	At Work (n=30)		Not At Work (n=18)		Totals
	Frequency	Example Narrative	Frequency	Example Narrative	
Reflection / review	5	*"As I walk back to hangar…..I visualised previous job and remembered seeing leads in breach position."*	5	*"Driving home thinking about the day's work."*	10 (21%)
Task-related cue	11	*"I went to return the tools and saw the spanner I used…..then I realised I'd forgotten to tighten the bolts."*	1	*"On return home that night I was watching TV…..news showed Sea King* [helicopter]. *This made me think……"*	12 (25%)
Error came to mind	7	*"In the line office prior to next task….looking out of window and remembered that I hadn't removed blanks."*	4	*"At lunch remembered putting a rag at the back of the engine."*	11 (23%)
Self-doubt / suspicion	6	*"Disbelief in my work so went to check."*	6	*"At home watching TV at night I felt uneasy about something."*	12 (25%)
Discussing work	1	*"Talking over paperwork, it occurred to me that I may not have tightened the screws."*	2	*"In bar….was chatting with colleague….realised I had omitted check on cannon* [gun]."	3 (6%)



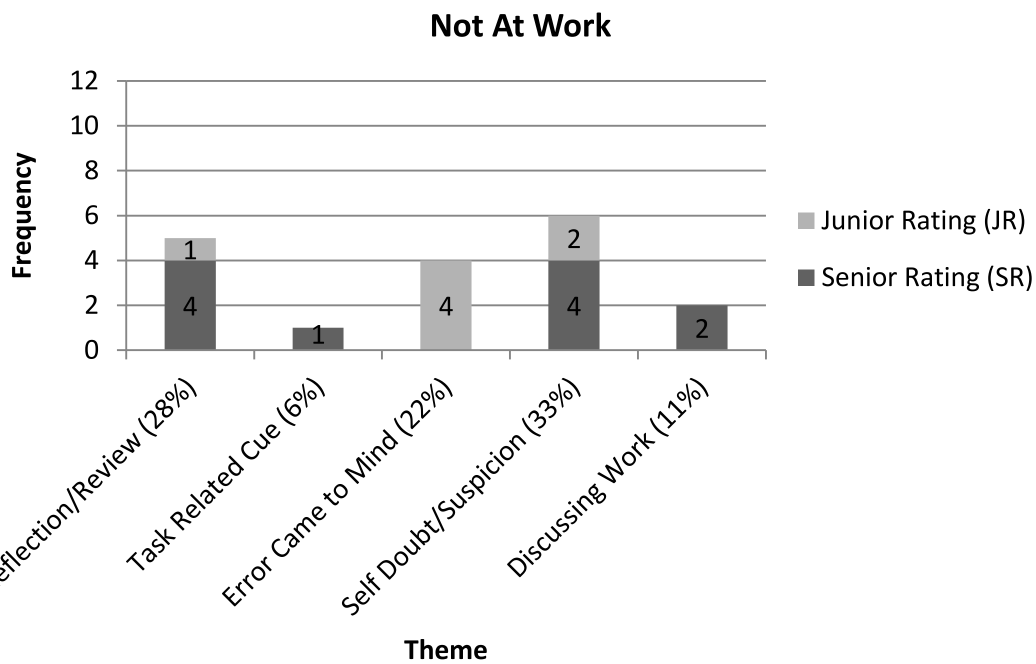


Figure 5.2. Frequency of themes related to environment and employment.

The five I-LED themes shown in Table 5.4 were grouped as: Intentional Review (IR) where the engineer consciously and deliberately reviewed past events before detecting the latent; and Unintentional Review (UR) where the engineer did not instigate a conscious and deliberate attempt to review past events prior to detecting the latent error. Here, it is argued IR accounts for the theme ‘reflection/review’ and UR accounts for the more spontaneous themes of ‘self-doubt/suspicion’, ‘discussing work’, ‘came to mind’ and ‘task-related cue’. Table 5.5 highlights this grouping against different environments associated with employment and specific locations. The UR group accounted for 75% (n=36) of all error detections: 50% (n=24) occurred At Work and 25% (n=12) occurred when Not At Work. The IR group accounted for 25% (n=12): 12.5% (n=6) occurred At Work and 12.5% (n=6) occurred whilst Not At Work. I-LED events were concentrated around the AMCO and aircraft hangar, accounting for 33% (n=16) of the specific locations At Work. Not At Work, error detections were move evenly spread across the specific locations shown in Table 5.5.

Table 5.5. Environment associated with review group and specific location.

Environment	Review Group	Location	Operative	Supervisor	Totals
At Work	IR	AMCO	1	0	**6**
		Hangar	1	1	
		Issue Centre	1	0	
		Crew room	1	0	
		Walking	1	0	
	UR	AMCO	4	3	**24**
		Hangar	3	3	
		Line	3	1	
		Maintenance Office	1	2	
		In aircraft	0	1	
		Walking	2	0	
		On board ship	0	1	
Not At Work	IR	Bed	0	1	**6**
		At home	0	1	
		Showering	0	1	
		Driving a car	1	2	
	UR	At home	0	3	**12**
		Bar	0	1	
		Cabin (bedroom)	2	0	
		Driving a car	0	1	
		Mess	3	0	
		Walking	1	1	

Data in Table 5.5 allowed a 2x2 contingency table to be constructed using categories for employment level and environment; null hypothesis being I-LED is equally likely to occur for each employment level for either physical environment in which the detection occurred. Chi-square test showed no significant association between employment and the environment in which the latent error was detected ($\chi^2_{(1)}$=1.42, p=ns), although 71% (n=17) of operatives detected their latent error At Work. A 2x2 contingency table was also constructed using the categories for review group and environment shown in Table 5.5; null hypothesis being IR and UR are equally likely to occur in each physical environment in which the detection occurred. Due to low frequencies a Fisher's Exact Test was carried out, which showed no significant association between categories (P=0.325, p=ns). Notably, 67% (n=24) of URs take place At Work. Chi-squared test was also carried out on a 2x2 contingency table constructed from Table 5.5 using the categories for review group and employment; null hypothesis being IR and UR are equally likely to occur between operatives and supervisors. The test showed no significant association between categories (P=0.37, p=ns). From Question 12 in Table 5.1, 75% (n=33 of 44) of participants reported they had experienced a false detection; examples being similar to the routine maintenance examples already highlighted. The thematic analysis of the responses to Question 13 are recorded in Appendix D and summarised in Table 5.6, which places 20 themes determined from the narratives in ranked order of frequency.

Table 5.6. Themes derived from Question 13 in ranked order of frequency.

Ranked Order	**Ranked Frequency of Themes** (n=55)
1st	Check work (n=13)
2nd	Use checklist/process (n=5)
	Avoid task pressure (n=5)
3rd	Avoid interruptions/distractions (n=4)
	Rest/break needed between tasks (n=4)
	Experience/skill needed (n=4)
4th	Training must be fit for purpose (n=3)
	Error awareness (n=3)
5th	Avoid tasks in parallel (n=2)
	Avoid rushing (n=2)
6th	Individual responsibility (n=1)
	Employer responsibility (n=1)
	Reward/incentives (n=1)
	Processes must be fit for purpose (n=1)
	Emphasise task importance (n=1)
	Avoid delays (n=1)
	Just culture (n=1)
	Use warnings (n=1)
	Influence of human performance (n=1)
	Influence of personality (n=1)

5.3.2.3 *Timing factors*

Responses to Question 6, 8 & 11 allowed the following timing factors to be determined. The majority of maintenance tasks were identified and carried out in error during the hours of 0800-2000, which correlates with the normal working day when not deployed away from the unit (i.e. not at sea embarked in a ship). Four tasks were outside of the normal working day and five participants did not report any timing data. Most narratives gave non-specific timings thus data were ranked according to the mean of the timings given by each participant. For example, if 1-1.5 hours was reported then 75mins was taken as the time for analysis. This process showed an outlier of 12,960mins, which was sifted to give a total of 42 reports that were analysed for timing factors. The time (T) between identifying a task (t) and the error event (e) was recorded as T(t-e) and the time between the error (e) and latent detection (d) was recorded as T(e-d). From the timing data reported in the 42 responses analysed, the overall mean for T(t-e) was found to be 206mins and 201mins for T(e-d). 60% (n=26) of latent errors were detected within an hour or less of occurring, whilst 70% (n=30) were detected within two hours or less. To test for significance, Spearman's Rho was calculated for the null hypothesis that there is no correlation between T(t-e) and T(e-d). A moderate positive correlation was found (r_s=0.66, $p<0.01$). This correlation is shown in Figure 5.3 with further timing data reported in Table 5.7, to show employment and themes against mean times.

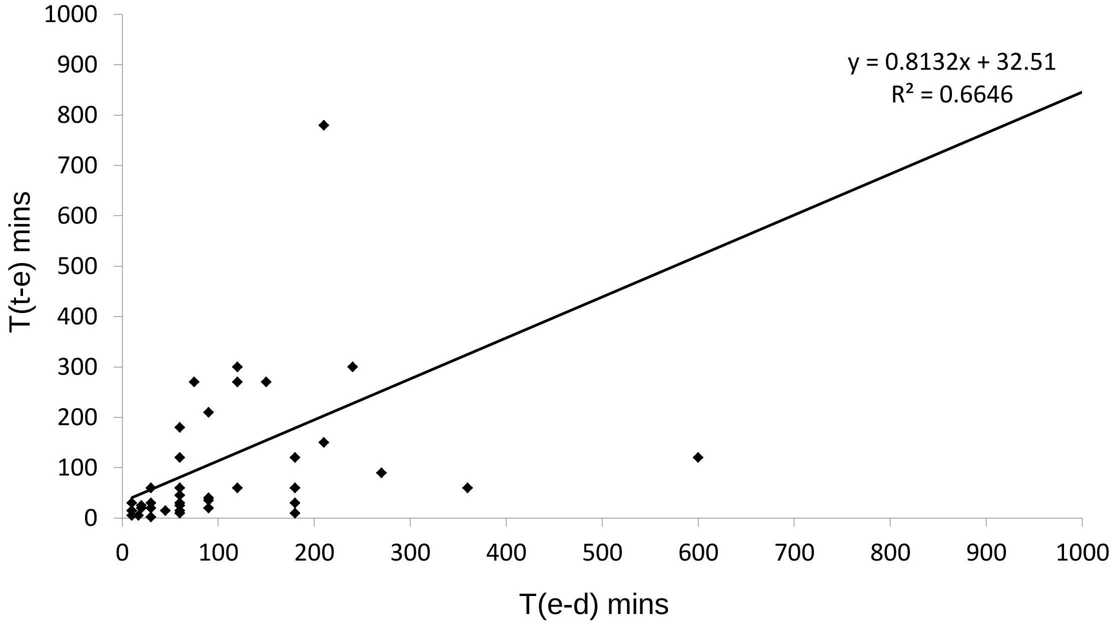


Figure 5.3. Correlation of timing data, T(t-e) and T(e-d).

Table 5.7. Mean detection times for employment and detection theme.

Employment/Detection Theme	Mean time T(e-d)
Operative	83mins
Supervisor	297mins
Reflection/review	195mins
Task-related cue	343mins
Error came to mind	61mins
Self-doubt/ suspicion	63mins
Discussing work	310mins

5.4 Discussion

5.4.1 *Maintenance task*

All participants who completed a questionnaire where able to recount personal examples of post-task I-LED, which aligns with widely accepted views that human performance variability and latent errors are common; suggesting the I-LED phenomenon is also prevalent (Reason, 1990; Hollnagel, 1993; Maurino et al., 1995; Perrow, 1999; Flin et al., 2008; Woods et al., 2010). Participants described routine maintenance tasks that were well practiced and thus habitual in nature, which is characteristic of highly developed schemata (Bartlett, 1932). Most responses also described carrying out several complex maintenance tasks such as an engine change or main gearbox replacement, although all the error events related to simple tasks. For example, forgetting to sign the aircraft documentation (simple task) as part of the overall task of aircraft flight servicing (complex task). This suggests I-LED is more likely to be associated with the detection of simple tasks (i.e. no one reported that they later recalled they had forgotten to carry out an entire flight servicing task). Since schema theory offers that only high-level schemata need conscious control for subordinate schema to trigger autonomously, the current data appear to support this position as the simple tasks described in the study were largely autonomous and triggered as a result of a higher-level task requirement. (Norman, 1981; Mandler, 1985; Cohen et al., 1986; Reason, 1990; Baddeley, 1997). In terms of PM theory, maintenance tasks were identified via a verbal brief or as part of a process and, since no participant reported using an external memory store such as written notes or electronic aid, it is likely that the engineer formed the intent to carry out the maintenance in the mind thereby creating an internal 'to do' list for subsequent PCM processing (Sellen et al., 1997).

5.4.2 *Error event*

Participants were asked to describe I-LEDs (i.e. they were not to recount errors detected post-task via a existing LED safety strategy such as process or supervisor checks). Using the GEMS categorisation of error (Reason, 1990), results showed the category and ratio of errors self-detected by the engineers to be broadly representative of wider maintenance error studies (refer to: Reason, 1990; Graeber and Marx, 1993; Latorella and Prabhu, 2000), which provides confidence that the current findings can be read-across wider contexts. Additionally, the error category did not appear to be affected by age or employment; provided the engineer was experienced for the required task.

Lapses were found to be the largest type of maintenance error detected via the I-LED phenomenon. Overall, there were recollections of a greater number of execution errors (slips and lapses) than planning errors (mistakes). The finding for execution errors included a low count of slips. This should be expected according to Sellen (1994) who argued this error type is likely to be detected proximal to the error event since the error is often evident immediately (i.e. dropping a tool). Blavier et al. (2005) found from their study of proximal errors that execution errors increase with complexity. Complexity is argued to be synonymous with aircraft maintenance environment and thus this may account for the high number of execution errors found in the study since, extrapolating Blavier et al's (2005) finding, a proportional number could have become latent errors that were detected via I-LED. Further, the dominant number of lapses aligns with Reason (2008) who found lapses to be the most frequent error type in this category. Woods (1984) and Kontogiannis and Malakis (2009) found that the proximal detection of execution errors is higher than planning errors. From a PCM perspective, planning errors are also less likely than execution errors to be detected proximal to the error event due the implicit lack of awareness of a genotype/phenotype mismatch as important external cues are not recognised during schema processing (Norman, 1981; Plant and Stanton, 2013b). This is characteristic of someone who possesses an incorrect perception of the external environment, leading to insufficient Situational Awareness (SA) for a particular task (Cohen et al., 1986; Plant and Stanton, 2013b). Thus this potential lack of awareness of planning errors that occur proximal to task execution may explain the number of mistakes that were later detected via the I-LED phenomenon.

Wilkinson et al. (2011) found experts have a special ability to detect errors, which is exhibited as an enhanced 'capacity' to detect important cues present in the external environment. This is arguably an attribute associated with the engineers in the current study since each participant was experienced for their particular employment and therefore more likely than trainees to benefit from an enhanced capacity to detect important cues distributed across the sociotechnical system. Consequently, this enhanced capacity also enhances or 'strengthens' schema processing to detect and respond correctly to important cues, which assists with the re-gain of SA (Brewer et al., 2010; Plant and Stanton, 2013a; Rafferty et al., 2013). Thus when a re-gain of SA does occur in the form of I-LED, it is argued that a higher number of lapses should be detected over mistakes or slips, as a higher proportion are not detected proximal to the error event and therefore proportionally more become latent errors.

5.4.3 *Error detection themes*

There was no significant difference between the detection themes except for the low frequency of participants reporting the 'discussing work' theme. Results showed post-task I-LED occurred more often At Work than Not At Work. Schema and distributed cognition theories could explain this finding for an operator immersed in a rich environment of distributed memory cues (Bartlett, 1932; Norman, 1981; Hutchins, 1995). For example, Grundgeiger et al. (2014) reported visual cues in the workplace increased occasions of PM recall compared to no cues. The narrative 'saw the spanner' highlighted in Table 4 exemplifies the impact of visual cues and is likely to account for the dominant number of 'task-related cues' At Work (see Figure 5.1, At Work). However, for other At Work detection themes highlighted in Table 5.3, the link to distributed cognition is less clear. For example, engineers that reported visualising a previous job, looking out the window or possessing a general disbelief in their work. These occasions are considered when discussing conceptual groups UR and IR.

When Not At Work, and therefore remote from the maintenance context, 18 examples of I-LED were reported. Referring to Figure 5.1 (see Not At Work), expectantly 'task-related cues' contributed the least to I-LED (n=1) with 'self-doubt/suspicion' the dominant category. The example in Table 5.4 reports feeling 'uneasy about something' when watching TV at home. DSA theory describes how SA is dependent on distributed cognition within the entire sociotechnical system; forming external memory structures within the physical world such as the aircraft maintenance environment (Hutchins, 2001; Stanton et al., 2014). For an I-LED event to occur whilst watching TV, for example, it is argued the cognitive capability of the experienced engineer must be distributed across unrelated environments and thus DSA theory appears to span other sociotechnical systems; suggesting the entire sociotechnical system is represented by interlinked sociotechnical contexts (At Work and Not At Work). For example, a main rotor gearbox change is a lengthy procedure requiring the hierarchical activation of multiple schemata. The experienced engineer will possess sufficient skill-rule-knowledge based behaviour (Rasmussen, 1982) to carry out the task they are trained to do, for which schema activation is supported by distributed memory stores (cues) in the maintenance environment such as written procedures, aircraft documentation, the physical aircraft, tool procedures, etc. Post-task completion, data suggest these typical cues or external memory stores remain available for latent review of the 'to do' list or internal markers. This facilitates a persistent opportunity for schema housekeeping and results appear to show this leads to I-LED both At Work and Not At Work. Smith et al. (2007) found PM retrieval also requires continuous monitoring for relevant cues to achieve task success whilst Grundgeiger et al. (2014) reported the phenomenon of automatic retrieval, for which it is argued SAS monitoring (Norman and Shallice, 1986) must exist post-task completion for I-LED to occur; a function of multi-process behaviour leading to the review of past activity.

The results showed 75% (n=36) of I-LEDs were grouped as UR; 24 I-LEDs occurred At Work and 12 occurred when Not At Work. For the latter, four I-LEDs occurred when resting and eight when engaged in unrelated activities such as watching TV, walking, showering, driving, etc. Arguably, all 12 UR examples occurred when engaged in well-learnt and non-complex activities; indicative of largely autonomous behaviour requiring unfocused attention or limited focal processing (Fitts and Posner, 1967; Brewer et al., 2010; Rasmussen and Berntsen, 2011). Involuntary Memory (IVM) research reports the spontaneous recall of a memory, which bypasses any conscious attempt to recall a specific memory and at some time after the PM intention was needed (Haque and Conway, 2001; Blavier et al., 2005). Rasmussen and Berntsen (2011) later argued that IVM is mostly associative and context dependent and usually cued by some aspect of the physical environment; being most likely to occur when attention is unfocused and thus requiring minimal execution control. This aligns with schema processing (Neiser, 1976) and whilst their work considered autobiographical IVM and did not take a systems approach, it is argued similarity to the current research can be drawn since developed schemata supports autonomous behaviour that characterises the experienced engineer and the engineer's unconscious ability to exploit DSA (Hutchins, 1995; Stanton et al., 2014). Sellen (1994) found that PM recall was more often due to contextual factors, as opposed to spontaneous or controlled recalls and that creating associations improved retrieval of relevant information. This aligns with Bartlett (1932) who argued 'literal' recall is less likely than recall as a result of reconstruction or interpretation of past events. Although Haque and Conway's (2001) spontaneity aspect is at odds with Sellen, it is thought more likely to be the result of the autonomy of schema housekeeping (Saward and Stanton, 2015a) as data for URs suggest the individual did not have control over schema processes, whilst the argument for unfocused attention appears accurate as all examples of I-LED occurred during periods of autonomous behaviour. This position also receives support from Plant and Stanton (2013b) who argued schemata are selected in a hierarchical pattern determined by the strength of the target activity or task (level of focal processing). Further, studies have shown that the conflict between on-going task monitoring and continuous monitoring for cues leads to interruptions or interference, which decreases operator performance (Norman and Bobrow, 1975; Einstein et al., 1997; Marsh et al., 1998). The impact of this divided attention can be influenced by the level of focal processing needed for a task (Brewer et al., 2010) and thus offer some explanation why periods of unfocused attention provide SAS the opportunity for schema housekeeping to take place; this catch-up period potentially influences I-LED.

Thus wider research appears to agree that UR (and IR) requires post-task reconstruction of the sociotechnical context to detect errors, which can occur during periods of unfocused attention. Distributed cognition is also believed to span unrelated environments and extend into the mind, for which the experienced engineer is capable of visualising the relevant sociotechnical system and reconstruct past events for I-LED to occur. Grundgeiger et al. (2014) argued recall can occur at work and in everyday unrelated environments and, arguably, this describes further the entire sociotechnical system. Since correct SA is considered to rely on schema processing of relevant cues as part of the PCM cycle, it is also argued SAS monitoring is persistent, and able to occur in unrelated environments, for past incorrect perceptions (schema mismatch) to be detected latently. This supports the concept of Latent Error Searching (LES) described in Chapter 2 within the detection themes self-doubt/suspicion and reflection/review that appeared to require reconstruction of past maintenance tasks to search for error. Thus At Work, whilst I-LED is most successful when post-task schema housekeeping takes place in the same or similar environment to that which the error occurred, significantly, the engineer appears to also possess the cognitive capability for remote access to these cues when Not At Work by internally contextualising past events. This extends PCM theory, which already reports to be a reliable method to account for human sociotechnical interaction within a given environment but now appears more widely distributed over interlinked sociotechnical contexts; coupled with persistent SAS monitoring (Plant and Stanton, 2013b). Notably, this is a characteristic of distributed cognition where correct operation in a sociotechnical system relies on internal and external structures or memory stores (Hutchins, 2001). Interpreting this further, by the very nature of being an experienced engineer, the engineer is very familiar and intimate with these schema cues, and thus it is offered that elements of the sociotechnical system have been 'absorbed' and are available in the mind if needed. This may offer an explanation as to why many latent errors were detected when remote from the working environment and also why the I-LED event appeared spontaneous to the engineer (supporting Haque and Conway, 2001). The net effect is that distributed cognition appears to extend beyond specific sociotechnical environments where an experienced engineer's ability to reconstruct events (and therefore identify system cues) in any environment is sufficient to trigger schema housekeeping; offering the opportunity for I-LED as the product of collaborative multi-processes. This also highlights an enduring linking of the mind back to the external environment relevant at the time the error occurred (Hutchins, 2001; Stanton et al., 2014). If system cues trigger schemata and these cues remain proximal or linked remotely in the mind, then it appears the distributed cognition concept extends to I-LED and is effective across everyday sociotechnical contexts.

Participants perceived checking their work for missed errors using a checklist/process to be most effect I-LED intervention according to the themes determined from Question 13. This is interesting finding as it arguably reinforces Reason's (1997) heroic concept since the air engineers in this study are keen to exploit ways that they can locally manage their detection and recovery from latent errors; as opposed to relying on an independent checker. Air engineers are also highly process-driven, which may drive their desire for a checklist/process although this in itself may indicate a lack of safety resilience in existing control measures such as maintenance processes or training. The concept of resilience and the integration of targeted LED interventions to achieve total safety are discussed in Chapter 7. The participants also suggested that I-LED events might be enhanced further if the check is conducted alone (avoiding interruptions/distractions) during a break/rest between tasks, thereby avoiding task pressure. Arguably, the themes captured in Table 5.6 could be indicative of weaknesses within the sociotechnical system associated with maintenance processes, which may benefit from targeted practicable interventions using system generated cues. Notably, the majority of LED suggestions provided by the participants are arguably organisational control measures enacted and managed locally by individuals (and teams) to maintain safety equilibrium through safe behaviours. This affirms the need from a human-centred approach to system safety based on understanding of typical human error effects, which was discussed in Chapter 3.

The potential for false error detections has also been reported and is argued to be a consequence of the largely autonomous nature of schema activation and persistent enquiry of the PCM through on-going SAS monitoring (Norman, 1981; Mandler, 1985; Cohen et al., 1986; Baddeley, 1997; Saward and Stanton, 2015a). Results showed 75% of participants reported they had experienced false alarms, which indicates multi-process I-LED behaviour can lead to false detections. Data fidelity did not allow further exploration of this observation and thus it is not known why distributed memory cues (either external or internally contextualised) triggered a false detection. Arguable though, this phenomenon may indicate the PCM is not infallible and perhaps further supports the earlier view that schema housekeeping is indiscriminate. Thus this may offer an explanation for I-LED occurrences that seemed to be detected by chance (or false detection) under the themes of 'came to mind' and 'self-doubt/suspicion'.

5.4.4 *Timing factors*

Data indicated significant correlation between T(t-e) and T(e-d) where 70% (n=30) of detections occurred within 2 hours of the error event and 60% (n=26) within an hour. This is an intriguing result as it suggests the PCM cycle possesses a particular frequency, for which a 'golden time window' of opportunity may exist for I-LED post-task completion. This appears to support the Patel et al (2011) finding that most errors are self-detected and recovered during the working period, which could provide an explanation for the supposedly spontaneous nature of detections reported by the engineers where later events appear to trigger I-LED.

The frequency of schema housekeeping may also be dependent on detection theme. Data shown in Table 6 revealed the lowest average I-LED times were for errors that came to mind and self-doubt/suspicion; both UR themes. This may be indicative of different influences on I-LED, i.e. the dependence on the autonomous PCM cycle to detect mismatches within a potential golden time window. As discussed, the majority of detections occurred whilst At Work and thus this finding is probably not surprising. However, whilst the majority of task-related detections occurred At Work, the average time for this category was the highest. This is surprising as it was anticipated the At Work environment would give rise to rapid I-LED via abundant task-related cues thus it may infer strong habit intrusion amongst engineers that are de-sensitised (and therefore low focal processing) due to the strength of these distributed memory cues. Of note, no significant difference between operative and supervisor across detection themes was found, provided they are experienced for the task required of them. The mean detection times in Table 5.6 show operatives did detect more errors at work and more quickly but this is considered to be due to their employment as junior engineers who spend the majority of their working day in the hangar or line, which is rich in task-related cues. Whilst this research is at an exploratory stage, the very existence of I-LED demonstrates time is a factor and for which it is argued system cues must be persistent for post-task schema housekeeping; otherwise I-LED is not possible.

5.5 Summary

Human error is inevitable and a daily occurrence, which provides impetus for the discovery of mitigation strategies through research. Understanding post-task I-LED may provide partial mitigation to achieve error resilience yet appears to be an under-researched area. Objective 2 looked to progress understanding of the nature and extent of the I-LED phenomenon by observing naval air engineers in the workplace, against which the current study hypothesised time, location and other system cues influence I-LED as the basis for an initial exploration using a multi-process framework applied to a questionnaire administered in group interviews. Data from naval air engineers confirmed the existence of I-LED, which appears to be prevalent within the naval aircraft maintenance environment. Having formed intent to carry out a task (or tasks) and therefore created a 'to do' list in the mind, engineers mostly suffered lapses involving simple tasks that were later detected. However, lapses may have dominated as a consequence of the reduced ability of genotype/phenotype processing to detect mistakes due to the implicit lack of awareness of importance system cues.

Latent error detections occurred more often At Work than Not At Work thus I-LED was found to be more successful when post-task schema housekeeping most likely takes place in a physical environment that is the same, or similar to, the physical environment in which the actual error occurred. DSA recognises that the strength and distribution of system cues are important for schema triggering thus it should be expected that the 'task-related' theme dominated At Work due to a high concentration of work related cues in the aircraft maintenance environment. The 'self-doubt/suspicion' theme appeared dominant when Not At Work despite detection themes for 'reflection/review' and 'error came to mind' being conceptually similar.

It is argued collaborative multi-processes that include theories on PM, SAS monitoring and schemata are effective for observing the I-LED phenomenon, which can manifest in other physical environments unrelated to that which the error occurred. Also, the very existence of I-LED indicates important cues remain available for post-task schema housekeeping to detect past errors, for which there may be golden window for successful I-LED. Here, it is thought the entire STS may be represented by interlinked sociotechnical contexts from which the air engineer can remotely access relevant cues by visualising/reconstructing past tasks in the mind. Combined with the argument that schema housekeeping is largely autonomous and persistent, this may also explain why the air engineers reported Not At Work themes widely. This extends distributed cognition thinking beyond the need to remain proximal to the error event or physically immersed in the same system contexts to where the error actually occurred. Further, the argument that post-task schema housekeeping may be indiscriminate provides an explanation for occasions of false alarms, or conversely, chance detections.

It is argued time, location and other systems cues trigger post-task I-LED. Using a sociotechnical approach combined with multi-process theory advances current systems thinking whilst unlocking the role of PCM and distributed cognition in I-LED may lead to systemic interventions aimed at improving error resilience. Further research is needed to mature the exploratory nature of the current study: to understand how the entire system of interlinked sociotechnical contexts contribute to I-LED; how the PCM links to the world in which the error occurred for the visualisation/reconstruction of past events; and consequently, to develop practicable interventions to enhance post-task I-LED within a potential golden time window of opportunity as close to the creation of the latent error as possible. Since the concept of human error has broad applicability, it is anticipated current research will be benefit to the wider community interested in safety resilience using a systems perspective to minimise the consequences arising from latent error.

This exploratory study confirmed the presence of the I-LED phenomenon in a cohort of naval air engineers, which addresses Objective 2 described in Chapter 1. The following chapter expands on the findings of the current study to addresses Objective 3 by observing a further cohort of naval air engineers in operating squadrons using a diary study. The main aim of the following study reported in Chapter 6 is to identify practicable I-LED interventions that can be used during routine normal operations to help control human error effects and therefore enhance safety resilience.

Chapter 6: A golden two hours for I-LED

6.1 Introduction

As discussed in previous chapters, undetected error in any safety critical system becomes a latent error that can contribute to a future safety failure thus the detection of latent errors is an essential element of effective safety management (Rasmussen and Pedersen, 1984; Reason, 1997; Shorrock and Kirwan, 2002; Wiegmann and Shappell, 2003; Flin et al., 2008; Aini and Fakhru'l-Razi, 2013). A system failure occurs when there is inadequate control of sociotechnical factors (across multiple environments) within a defined operating context, which impacts human performance (Leveson, 2004; Woods et al., 2010). In a safety critical system, this can lead to a hazardous condition due to system-induced error effects (Stanton et al., 2009a).

Errors or erroneous actions are a normal by-product of human performance variability induced by the sociotechnical environment thus a systems approach to error research is essential in seeking out interventions that prompt the successful recovery from latent error; the systems view now being widely accepted (Hutchins, 1995; Dekker, 2014; Reason, 2008; Woods et al., 2010; Cornelissen et al., 2013; Hollnagel, 2014; Chiu and Hsieh, 2016). Indeed, Reason (1990) highlighted it is only with the benefit of hindsight that it is possible to label behaviour as erroneous (in that an action led to an undesirable outcome or safety failure). In adopting the systems view, some research has rejected the label 'human error' in favour of 'human performance variability', which includes both normative and non-normative performance (Woods et al., 2010; Dekker, 2014). This approach emphasises the broad spectrum of human behaviour, rather than a dichotomy, and therefore a need to engineer resilient systems (Hollnagel et al., 2006). As discussed in Chapter 3, 'human error' can remain a meaningful term to describe performance variability or human error effects, provided it is used only as a trigger for the analysis of broader sociotechnical issues across the design of the safe system of work (Stanton and Baber, 1996; Reason and Hobbs, 2003; Reiman, 2011). Thus the term 'human error' or erroneous act is argued to refer to any situation where the required performance was not enacted as expected due to system induced influences. As such, the term error refers to performance variability, which encapsulates a range of human interactions within a given sociotechnical environment that includes non-normative and normative accepted behaviours in the workplace (Reason, 1990; Woods et al., 2010; Cornelissen et al., 2013). Here, the term latent error is used simply as a signpost to residual errors (system failures generating a latent error or risk to the safety system) that were not detected prior to an action or proximal to the action event, i.e. system-induced errors that pass undetected and therefore lie hidden in the Sociotechnical System (STS) rather than being a failing of individual (or team).

Chapter 2 introduced the relatively unexplored phenomenon of Individual Latent Error Detection (I-LED) in response to the seemingly spontaneous self-detection of latent errors post-task completion. A cohort of naval air engineers in Royal Navy aircraft maintenance reported this phenomenon, where I-LED appeared to offer resilience against latent errors. Combining a systems view of human error with a multi-process approach to error research, Chapter 5 offered early findings from an exploratory study that considered retrospective accounts of I-LED events from a sample of naval air engineers. The participants reported I-LED to be prevalent and that time, location and other system cues appeared to be important. It was recognised that retrospective recall is susceptible to memory decay effects thus the exploratory study in Chapter 5 required a follow-on study to answer the second main research question given in Chapter 4. This question asks what is the nature and extent of the I-LED events from a systems perspective. I-LED describes events where system failures are successfully recovered post task completion through individual safety behaviour that sees system cues trigger the recall of hidden latent errors. Undetected errors that lie hidden pose an escalating risk to safety due to its potential to combine with other system failures to create a causal path to an accident (Reason, 1997; Perrow, 1999; Matsika et al., 2013). The I-LED model derived in Chapter 4 is based upon the bowtie representation of controlling hazards and highlights how I-LED can act as an additional control to mitigate for the risk escalation posed by undetected human error in the system. Thus I-LED arguably aligns with human performance that goes right, before suffering an adverse effect such as an accident (Reason, 2008); in other words, Safety II events when designing system controls from the modelling accident causation (Hollnagel, 2014).

Due to the apparent paucity of I-LED research, Chapter 2 reviewed literature for transferrable theories. This led to a multi-process approach to I-LED research that combines theories on Prospective Memory (PM), Supervisory Attentional System (SAS) monitoring and schemata. The PM element refers to the creation of intent to carry out an action and the SAS for monitoring of the schema-action-world cycle, which is characterised by the Perceptual Cycle Model (PCM). Schema theory, embedded within the PCM, highlights the human interaction with the STS via the bottom-up (BU) processing of external sensory data against top-down (TD) knowledge of the world (schemata) within a perceptual cycle (Neisser, 1976; Cohen et al., 1986; Plant and Stanton, 2013a). This forms the transactional relationship between a schema-action-world cycle and system cues in the external world that trigger intended actions (Neisser, 1976; Norman, 1981; Mandler, 1985; Stanton et al., 2009b; Plant and Stanton, 2013a). Studies on PM indicate that intentions (schema selection) are 'loaded' into memory to act upon later, which generates a 'to-do list' or internal marker (Sellen et al., 1997; Marsh et al., 1998; Van den Berg et al., 2004). The SAS described by Norman and Shallice (1986) is thought to be the attentional mechanism to continually monitor the external environment for external cues and monitor the perceptual cycle for correct execution of intent on the 'to-do' list (Norman, 1981; Norman and Shallice, 1986; Smith, 2003; Einstein and McDaniel, 2005; Saward and Stanton, 2015b). The SAS is also argued to regulate schema housekeeping, which is a term used to simply highlight the function of monitoring the perceptual cycle to confirm an action is completed as well as collecting feedback from the action to facilitate learning and the acquiring of experience (Saward and Stanton, 2015b). Developed schemata that form internal memory structures, which can be accessed to respond to a particular task, are known as genotype schemata whilst phenotype schemata refer to the actual response when executing a task (Neisser, 1976; Reason, 1990). Thus schema housekeeping is thought to highlight the cyclic update of genotype schema (for schema learning) by reviewing previous schema-action-world information and thereby providing the opportunity for the detection of latent errors (Saward and Stanton, 2015b).

PM research has also found that the successful recall of intentions is cue dependent and can be triggered automatically by external cues present in environmental contexts (Tulving, 1983; Bargh and Chartrand, 1999; Guynn et al., 1998; Einstein and McDaniel, 2005). Particularly, easily recognised cues in the external environment, being mostly visual or auditory, are effective triggers of internal markers where written word cues have been found to be more likely to trigger recall than picture cues (Kvavilashvili and Mandler, 2004; Mazzoni et al., 2014).

Sellen (1994) offered that an operator could fail to detect an error because the success of the action could have been imperceptible; indicating the schema-action-world cycle is dependent on cue recognition (e.g. where an oil filler cap was not quite seated correctly or a similar but wrong lubricant was used on a component). Autonomous schema housekeeping may later highlight the genotype/phenotype mismatch; accounting for why latent errors can appear to come to mind spontaneously (Reason, 1990; Stanton et al., 2009b; Einstein and McDaniel, 2005). If cue information was imperceptible at the time an activity was carried out then differences in the activity or location associated with an I-LED event needs consideration. Findings from Chapter 5 highlighted the link between I-LED and cognition distributed across different sociotechnical environments (Hutchins, 2001; Stanton et al., 2014; Grundgeiger et al., 2014). Here I-LED was argued to be most successful when post-task schema housekeeping takes place immersed in the same environment to that which the error occurred, although latent errors occurring in the workplace were also detected similar or unrelated surroundings. This extended task-related cue recognition across a range of unrelated sociotechnical environments where different environments could be accessed for cue information by internally visualising/reconstructing past activity. For example, when at home, driving a car, walking, showering, etc. Further, and by extending transferable theories on memory, I-LED is thought more likely to occur when alone (not interacting with others) and mostly during periods of unfocused attention such as inactivity, day dreaming or engaged in largely autonomous activities that do not require high levels of concentration on the task in-hand (Kvavilashvili and Mandler, 2004; Smallwood and Schooler, 2006; Rasmussen and Berntsen, 2011).

PCM theory describes a schema-action-world cycle (Plant and Stanton, 2013a) therefore time must be associated with the frequency of the cycle. It was argued in Chapter 5 that the perceptual cycle persistently reviews past task performance through schema housekeeping, for which distributed cues must remain available across sociotechnical environments for I-LED events. This could facilitate a 'golden time window' for I-LED to occur. Initial findings indicated most latent errors were detected within a time window of two hours of occurring, which receives some concurrence from Patel et al (2011) who highlighted 75% of errors committed by expert clinical staff were detected and recovered within 10 hours whilst at work. It was also argued that this persistence is largely autonomous, leading to the unintentional review of a past task that perhaps accounts for seemingly spontaneously chance detections, although the intentional review of past task is expected to be more successful than the autonomous condition.

Using the multi-process approach to systems thinking described above, the following study is designed to advance existing literature associated with I-LED via the real-world study of naval air engineers. To determine whether this cohort exhibits normal cognitive behaviours, literature was reviewed for an appropriate instrument to employ. The Cognitive Failures Questionnaire (CFQ) at Appendix E scores an individual's propensity for everyday cognitive failures using 25 questions scored 0-100 against a 5-item Likert coding (Broadbent et al., 1982). A high mean score (>51) indicates a propensity for cognitive failures (Broadbent et al. 1982). Whilst organisational safety performance has rightly moved away from focusing on individual human failings to a system induced view of erroneous acts, knowledge of individual performance variability within a defined cohort is argued to remain important in anticipating the level of resilience that must be engineered into safe systems within the workplace (Reason, 2008;

Woods et al., 2010; Reiman, 2011; Cornelissen et al., 2013). Wallace et al. (2002) administered the CFQ questionnaire to US Navy personnel whilst Bridger et al. (2010) studied a large cohort of naval personnel in the Royal Navy. Both found these cohorts to exhibit normal performance variability representative of skilled workers, which is a relevant benchmark to inform the current study. Literature also indicates that those with a high CFQ score are more susceptible performance variations leading to erroneous acts, due to poor executive function, yet they are likely to have developed a personal coping strategy in the knowledge that they are prone to cognitive failures (Reason, 1990; Wallace et al., 2002; Mecacci and Righi, 2006; Day et al., 2012). Applying systems thinking, it is argued that this should be interpreted differently: that those with a high CFQ score are likely to be less receptive to external cues that trigger the necessary schema response, for which unreported behaviours may have been created that engage with the sociotechnical environment to engineer resilience.

Thus the aim of the current study seeks to understand how individuals engage with system cues for successful I-LED with the aim of advancing knowledge on the nature and extent of I-LED so that practicable interventions can be identified to enhance resilience in safety critical. This supports Objective 3 stated in Chapter 1, for which it was hypothesised that the exploratory findings from Chapter 5 would remain applicable in a real-world study and confirm that most I-LED events occur within two hours of the erroneous act; significantly, when alone during periods of unfocused attention. Further, sensory data from familiar everyday cues present within the engineer's workplace are expected to facilitate successful I-LED through engagement with the perceptual cycle, which is a finding from the study conducted in Chapter 5. The hypothesis drives the requirement for real-world study to understand what promotes Safety II behaviour in the workplace in terms of I-LED, where it is believed further safety resilience is achievable through successful latent error detections. A diary study is selected as an effective method to capture everyday I-LED events over a protracted period in naturalistic environments and without biasing the data through intrusive observations (Reason, 1990; Cassell and Symon, 2004; Robson, 2011) whilst the CFQ is administered to simply affirm normal cognitive behaviours in naval air engineers by relating to research from wider populations.

6.2 Methodology

6.2.1 *Participants*

A convenience sample was conducted (Robson, 2011), which comprised representative numbers of operative and supervisor naval air engineers from the target population in Royal Navy helicopter squadrons. Air engineers all train and operate to the same standards and practices thus significant differences do not exist between squadrons in terms of the working environment or employment, which need accounting for in the analysis of data. Six squadrons were available for the study, consisting of 695 engineers, of which 173 engineers participated (mean age=29.99 years, sd=6.81, range 18-48). This represents 25% of the population and includes both males (n=164) and females (n=9). Female participants accounted for 5.2% of the sample, which is representative of the population. As the low count of females is not statistically significant, no separate analysis of female responses could be conducted within the scope of the current study. Flanagan (1954) argued that the number of events was more important that number of participants, for which Twelker (2003) recommended no less than 50 events were needed for data to be meaningful. Thus 173 participants were considered acceptable to yield sufficient events for analysis within the resources available for the study although 60% attrition was anticipated due to participant dropout or unusable diary entries thus the minimum number of returned diaries was expected to be 70 and therefore sufficient for analysis.

Ethics approval was received from Southampton University (Ethics No. 13496) and a Participant Information Sheet (PIS) was created in accordance with Ministry of Defence research ethics committee guidelines.

6.2.2 *Diary design*

A self-report diary was used to capture everyday I-LED events observed in the workplace, thereby avoiding intrusion but with adjacency and detail (Reason, 1990; Cassell and Symon, 2004; Robson, 2011). The diary at Appendix F was constructed according to Flanagan's (1954) Critical Incident Technique (CIT) where the term critical simply refers to a significant I-LED event reported by the participant. Neutrally worded questions were generated according to multi-process theories shown in Table 6.1. Intentionally, the diary was not designed against questions from the CFQ as the diary was designed to capture system factors. Free text descriptions of I-LED events were avoided since Schulter et al. (2008) found experienced nurses found it hard to describe their error behaviours.

Questions were designed to give largely quantitative responses, as the exploratory study in Chapter 5 was qualitative. To help further ensure construct validity, diary methodologies were reviewed for good practice (Oppenheim, 1992; Sellen et al., 1997; Cassell and Symon, 2004; Johannessen and Berntsen, 2010; Mace et al., 2011; Robson, 2011).

6.2.3 *Piloting*

A squadron not involved in the main study was approached for 10 air engineers to practice administration and test the diary booklet. A small group of university research staff also tried the diary for general usability and question comprehension. Feedback from the pilot was provided via a follow-up interview. Based on Wiegmann and Shappell's (2001) guide for an effective taxonomy, participants were asked to comment on: the comprehensiveness of the diary questions; whether the questions were sufficiently wide-ranging and captured everything they wanted to record about their I-LED event; and how usable they found the diary booklet. The general readability of the PIS shown at Appendix G was also assessed against the Flesch reading ease score and amended to achieve a score of 60.1 (standard readability). Based on piloting, changes were also made to the administration and diary booklet to remove repetition, typographical errors and ambiguity in some questions.

6.2.4 *Data collection procedure*

Approval for the study was received from local engineering management prior to participants receiving a standardised verbal brief, which included an explanation of each diary question. They were also provided with the participant information sheet at Appendix G. Naval air engineers receive flight safety briefs and training on error types (GEMS: Reason, 1990) as part of the UK MoD aviation error management system. However, the researchers confirmed participant understanding of error types during the verbal brief and instructions were printed in the diaries, which included examples. The CFQ, participant register and consent forms were then completed prior to issuing the diary booklet. Participants were asked to record each I-LED event as near to the occurrence as possible to counter memory decay effects. To avoid the completion of the diary causing an unsafe distraction, a notepad was included in the booklet for participants to make quick notes for later completion. The notepad also allowed participants to record any additional comments they wanted to record to avoid limiting any important data not considered in the design of the study. After two months, the researchers personally collected completed diaries to preserve anonymity from line managers.

Table 6.1. Diary Questions.

Factor	Question	Response Options (additional comments in brackets not published in diary)
PM	Q1. Please give a brief description of the error event.	General narrative (to understand context for I-I-LED event)
Time	Q2. At what time did the error event occur?	Time of day
PCM	Q3. What type of task was it?	Complex / Simple / Don't Know (looking for task complexity)
Cue	Q4. What was the cue to do this task?	Event / Time / Both
PCM	Q5. What was the error type?	Slip / Lapse / Mistake / NK (according to Reason's (1990) GEMS)
Location	Q6. Where were you when the error occurred?	AMCO / Hangar / Line / Maintenance office / Issue centre / Storeroom / Aircraft / Workshop / Flight Deck / Other (At Work locations)
Time	Q7. At what time did you recall the error (post task completion)?	Time of day (to calculate time between the error occurring and detection)
Location	Q8. Where were you when you recalled the error?	AMCO / Hangar / Line / Maintenance office / Crew room / Issue centre / Storeroom / Aircraft / Workshop / Flight Deck / Home or Mess / Bed / Vehicle / Gym / Other (At Work and Not At Work locations)
SAS	Q9. What were you doing when you recalled the error?	Planning/preparing maintenance activity / Conducting similar maintenance activity / Conducting dissimilar maintenance activity / Walking / Driving a vehicle / Exercising (e.g. cycling, jogging) / Showering / Eating / Socialising (e.g. in a bar) / General work-related discussion / Daydreaming / Resting / Entertainment (i.e. reading, TV, internet, etc) / Sleeping / Other
SAS	Q10. Did you intentionally review your past tasks/activities?	Yes / No
SAS	Q11. (If Q10 'yes') Was this part of your personal routine?	Yes / No
PCM	Q12. On checking your work, was the error:	Real / False alarm (looking for successful detection of an latent error)
Cue	Q13. Did anything in your immediate location appear to trigger the error recall?	Sound / Equipment / Document / Smell / Taste / General vista / Other (looking to identify system cues)
Cue	Q14. What were you thinking about at the time of the error recall?	Work-related thoughts / Non work-related thoughts
SAS	Q15. Were you alone when the error was recalled?	Yes / No
PCM	Q16. The specific error was very clear to me.	Likert coding: Strongly Agree=1, Strongly Disagree=5 (Clarity of error)
PCM	Q17. I was very confident that my past task was in error.	Likert coding: Strongly Agree=1, Strongly Disagree=5 (Error confidence)
SAS	Q18. The error recall occurred when I was highly focused on the activity at Q9.	Likert coding: Strongly Agree=1, Strongly Disagree=5 (Task focus)

6.3 Results

6.3.1 *Description of sample*

37% (n=64) of engineers returned their diaries, which is close to the anticipated maximum of 40% determined from piloting. The mean age of those who returned their diary was 30.70 years (sd=7.41, range 19-48). 38% (n=24) of returned diaries were blank, as the participant had not experienced an I-I-LED event during the two months of the study. The 40 completed dairies contained 51 usable entries, after 13 entries were dismissed due to conflicting responses or the recorded error example was not an I-LED event. Overall, the minimum number of CIT events recommended by Twelker (2003) was achieved. A Kolmogorov-Smirnov test on age within the sample of 64 engineers who returned their diaries showed $D(64)=0.13$, $p<0.01$; indicating the distribution of sampled mean ages deviate from a normal distribution, positive skews towards a mode of 28. However, this is representative of the population in naval aircraft squadrons where there are approximately 2.5 times more operatives of a younger age than older supervisors.

6.3.2 *Analysis*

Category variables from the diary questions were mapped against each other to construct a simple 87x87 matrix. The matrix was not used for analysis except to facilitate a targeted approach to data analysis. The matrix provided a general indication that I-LED events were particularly associated with simple event-based tasks involving lapses. These events were mostly detected accurately (few false alarms) in the workplace without the intentional review of a past task and whilst attending to an on-going task working alone. Here, thinking about work and the presence of physical objects (cues) appear related. Thus the following analysis focuses any these areas.

6.3.2.1 *CFQ scores*

The mean CFQ score for the 64 engineers who returned their diaries was M=38.00 (n=64, sd=10.77, se=1.34), for which a Kolmogorov-Smirnov test showed $D(64)=0.10$, p=n.s; indicating the distribution of sampled mean CFQ scores do not deviate significantly from a normal distribution. The mean CFQ score for air engineers who returned their diary but reported no I-LED events was M=35.71 (n=24, sd=10.56) whilst M=39.37 (n=40, sd=10.78) for those reporting a I-LED event. Whilst the mean CFQ score was slightly higher for those who reported an attentional failure, the mean is still low within normal range and a t-test showed no significance between group means ($t=1.32$, $df=62$, $p=n.s$), although a small effect exists ($r=0.2$). Participants were also asked whether they intentionally reviewed (IR) past tasks for errors or if recall appeared to be spontaneous and therefore an unintentional review (UR) occurred. Those with a high mean CFQ score (≥51) reported slightly more UR (57%, n=8) than IR (43%, n=6) and those with a low mean CFQ score reported more URs (70%, n=26) than IRs (30%, n=11). A 2x2 contingency table was constructed using categories for high and low mean CFQ scores against UR and IR, for which a Chi-square test showed no significant association ($\chi^2_{(1)}=0.79$, $p=n.s$).

6.3.2.2 *Diary Responses*

Question 1 provided context to confirm no significant difference in operating environment existed compared to the initial study conducted in Chapter 5. Thus, intentionally, no qualitative analysis was attempted. Questions 2 & 7 were used to calculate the time (T) between the error (e) and latent detection (d), recorded as *T*(e-d), for which Table 6.2 provides a summary of mean times for *T*(e-d) against location. A Kolmogorov-Smirnov test on timing data showed $D(51)=0.36$, $p<0.05$; indicating the distribution of the times for *T*(e-d) deviated from a normal distribution (positive skew=2.58). The distribution gave a mean time for *T*(e-d) =120mins (n=51, sd=216, se=30, range 2-1020mins) with a mode of 30mins and median of 30mins. Notably, 78% (n=40) I-I-LEDs occurred within 120mins. Question 3 recorded latent errors associated with either complex or simple tasks. For example, a complex task included maintenance activities such as rigging flying controls and in-depth fault diagnosis. Examples for simple tasks include checking oil levels, returning tools, basic data entry tasks and logistics activities such as sending and receiving stores. Participants reported 14%(n=7) complex tasks and 86%(n=44) simple tasks. Responses to Question 4 indicated 92%(n=47) were event-based, 2%(n=1) task-based and 6%(n=3) were recorded as both. For event-based activities, 64%(n=30) were associated with UR and 36%(n=17) were associated with IR, for which 71% (n=12) of this group reported against Question 11 that their IR was part of a personal routine (not part of a mandated procedure). A 2x2 contingency table was constructed using the categories for review type against the main cue for the task carried out in error. Due to low frequencies a

Fisher's Exact Test was carried out, which showed no significant association ($P=1.0$, $p=n.s$). Counts for IR and UR are shown against each activity in Table 6.3.

Table 6.2. Error Locations.

Location (n=51)	Response	Count	Mean time T(e-d) (min)	Example
Q6: Location of Error Occurrence	AMCO	19		
	Hangar	8		
	Line	3		
	Maintenance Office	2		
	Issue Centre	8		
	Storeroom	3		
	Aircraft	4		
	Workshop	0		
	Flight Deck	2		
	Other	2		Crew room, Head Office
Q8: Location of I-LED (ungrouped)	AMCO	15	106	
	Hangar	9	24	
	Line	3	19	
	Maintenance Office	1	15	
	Issue Centre	3	45	
	Storeroom	0	-	
	Aircraft	3	28	
	Workshop	0	-	
	Flight Deck	3	23	
	Crew room	2	45	
	Home/Mess	5	273	
	Bed	1	420	
	Vehicle	2	392	
	Gym	0	-	
	Other	4	324	Locker room, briefing room, bar(x2)

Reason's (1990) GEMS taxonomy was used in Question 5, which expands on Norman's (1981) research that described error types based upon the incorrect use of schemata. Significantly more lapses were reported than mistakes and slips: 90% (n=46); 6% (n=3); and 4%(n=2), respectively. Thus the post-task detection of latent execution errors (slips and lapses) represented 94% of all maintenance tasks reported by participants with planning errors (mistakes) accounting for 6%. Table 6.4 provides example narratives against the GEMS taxonomy and also Norman's (1981) schema-related error types for completeness.

Derived from Questions 6 & 8, Table 6.2 also provides a count for locations where the error occurred and I-LED event. 73%(n=37) error events were detected in the same or similar environment to that which the error occurred. Note that the AMCO is the Air Maintenance Coordination Office where most aircraft paperwork is controlled and maintenance organised. The Issue Centre is where ground equipment and tools are stored and controlled. The Line and Flight Deck are where aircraft operations are conducted, which is similar to a Ramp in civilian contexts. These locations could be grouped as environments At Work and Not At Work as shown in Table 6.3. This shows 80% (n=41) I-LED events occurred whilst At Work and 20%(n=10) whilst at Not At Work. A 2x2 contingency table was constructed for environment against review type. Fisher's Exact Test showed no significant association (P=1.0, p=n.s), although UR was dominant At Work (n=27) and Not At Work (n=7). Table 6.3 also shows activity at the time of recall, reported against Question 9. This indicates 25%(n=13) participants were engaged with similar maintenance task, 20%(n=10) were planning or preparing to conduct maintenance task or 14%(n=7) were simply walking (between activities). The remaining activities (n=21) are highlighted in Table 6.3, noting that activities covering dissimilar maintenance, exercising and entertainment are not included, as participants reported none. Table 6.3 also shows 33% (n=17) of participants intentionally reviewed past tasks.

Table 6.3. General environment against associated factors.

Environment (Q8)	Activity (Q9)	Review (Q10) IR	Review (Q10) UR	Work Thoughts (Q14a) Past	Work Thoughts (Q14a) In-hand	Work Thoughts (Q14a) Future	Non Work Thoughts (Q14b) Past	Non Work Thoughts (Q14b) Moment	Non Work Thoughts (Q14b) Future	Physical Trigger (Q13) Item	Physical Trigger (Q13) Example
At Work (n=41)	Planning / preparing maintenance (n=10)	6	4	4	4	2				Document=5 Vista=1 Other=1	*Aircraft documentation* *Scenery inside building* *None specified*
	Conducting similar maintenance (n=13)	5	8	2	9	2				Equipment=4 Document=6 Vista=1 Sound=2	*Computer, rotor blades* *Aircraft documentation* *None specified* *Aircraft noise, headset volume*
	Walking (n=7)	2	5	1	2	3			1	Equipment=5 Other=1	*Aircraft, tools, toolbox* *Felt keys in pocket*
	Eating (n=1)		1						1	-	*None specified*
	General work discussion (n=3)	1	2	1		2				Other=1	*None specified*
	Daydreaming (n=3)		3	1		1		1		Vista=1	*None specified*
	Resting (n=1)		1					1		-	*None specified*
	Other (n=3), i.e. changing clothes, paperwork & auditing		3		2			1		Equipment=2 Document=1	*Screw bag* *Aircraft documentation*
Not At Work (n=10)	Driving vehicle (n=1)		1					1		Sound=1	*Work-related topic on car radio*
	Showering (n=2)		2				1	1		Equipment=1 Other=1	*Keys* *None specified*
	Socialising (n=2)	1	1	1				1		Vista=2	*None specified*
	General work discussion (n=1)		1	1						Sound=1	*Colleague's voice*
	Resting (n=2)	1	1	1				1		Document=2	*Aircraft documentation*
	Sleeping (n=1)	1		1						-	*None specified*
	Other (n=1), i.e. readying for work		1					1		Other=1	*None specified*
	Totals	**17**	**34**	**13**	**17**	**10**	**1**	**8**	**2**	**40**	

Table 6.4. Example narratives against the GEMS taxonomy (Reason 1990) and Norman's (1981) schema-related error types.

Example Narrative	Erroneous act (error) classification	
	GEMS (Reason 1990)	Schema action (Norman 1981)
I did not replace the oil filler cap correctly………had to go back and check'. *'Walking from the hangar to the flight deck I dropped a tool in my pocket'.*	Slip	Correct intention selected but faulty schema(s) activation.
'Having prepared a Lynx [helicopter] *for flight……the book* [aircraft documentation] *was completed. Just prior to launch, I realised that I hadn't cleared a Pt1 entry* [statement of required maintenance]*'.* *'Forgot to fit main rotor spectacles* [rotor blade securing device]'.	Lapse	Correct intention selected but schema(s) not triggered.
'Card raised [maintenance paperwork] *for a maintenance task required post flying serial…….incorrect aircraft annotated on paperwork'.* *'Failed to co-ordinate* [complete] *a maintenance work order correctly'.*	Mistake	Incorrect formation of intent. Wrong schema selected based on incorrect perception of external sensory data.

Question 13 asked participants to record anything in the immediate physical environment that they believed might have triggered their error recall. Responses are shown in Table 6.3, for which aircraft documentation accounted for 35%(n=14) and aviation equipment 30%(n=12). A 2x4 contingency table was constructed for environment against triggers for Documentation (n=14), Vista (n=5), Sound (n=4) and Equipment (n=12). Other (n=5) was not used, as participants did not provide examples. A Fisher's Exact Test showed no significant association (P=0.42, p=n.s); however, 30% (n=12) of all reported triggers were At Work and related to aircraft documentation followed by 28%(n=11) aviation equipment.

Table 6.3 also highlights responses to Question 14, which asked participants to record what they were thinking at the time their I-I-LED event. 78% (n=40) reported work-related thoughts and 22% (n=11) non work-related thoughts. Worked-related thoughts ranged from thinking about past maintenance activities, to the task in-hand through to maintenance to be carried out at a later time. Non work-related thoughts ranged from past personal errands, simply existing within the 'moment' through to thinking about a personal task to be done later. Examples include a previous social event, in the moment watching TV or thinking about what PC game to play later. When an I-I-LED event occurred, 59% (n=30) of participants were alone according to the responses to Question 15 (i.e. not actively engaged with another person such as talking or working on a task together), during which 87% (n=26) occurred when carrying out largely autonomous tasks requiring little focused attention. Aviation related examples include planning and conducting simple maintenance tasks (n=8) such as basic aircraft servicing, tool checks and simple logistic tasks. Non-aviation related included walking (n=7), driving a car (n=1), showering (n=2), daydreaming (n=3), resting (n=2), sleeping (n=1) and other (n=2) such as changing clothes and getting ready for work.

Question 12 indicated that all participants checked their work when a latent error came to mind, for which 92% (n=47) found the error to be real whilst 8% (n=4) experienced a false alarm. Figure 6.1 describes the distribution of responses (n=50) to the Likert coding specified for Question 16, 17 & 18. Participants generally agreed 46%(n=23) or strongly agreed 36%(n=18) that their specific error was very clear to them. Participants were uncertain 26%(n=13) or agreed 26%(n=13) that they were very confident in their past task being in error whilst 28%(n=14) strongly agreed. 30%(n=15) strongly agreed that they were highly focused on the activity they reported at Question 9. This was closely followed by 28%(n=14) who agreed although 20%(n=10) strongly disagreed.

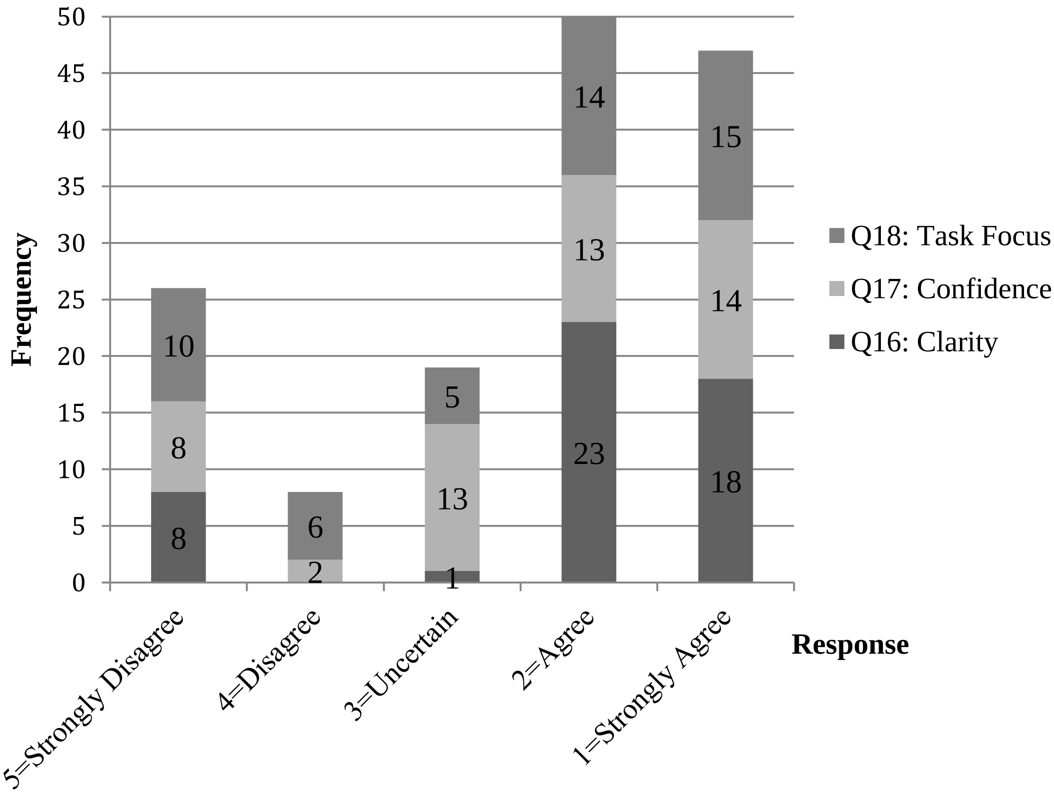


Figure 6.1. Responses to questions on task focus, confidence and clarity.

6.4 Discussion

6.4.1 *Individual factors*

6.4.1.1 *CFQ scores*

CFQ scores were not used to predict I-LED events or propensity for human failings. The mean CFQ score for participants who returned their diary was similar to other studies of naval personnel (Wallace et al., 2002; Bridger et al., 2010). The low mean CFQ score indicated the sample of air engineers possessed good executive function normally found in skilled workers (Broadbent et al., 1982). Studies have shown this helps cope with high workloads (Finomore et al., 2009; Bridger et al., 2010). However, participants described routine habitual tasks thus workload did not necessarily influence I-LED. The majority of I-LED events were associated with simple tasks. Arguably, the routine nature of everyday tasks infers low arousal. This may account for the high number of simple tasks although good executive function should result in increased cognitive awareness. Thus it can only be surmised that complex tasks tend to be more safety critical. Expectedly, an organisation's safety system attempts to defend critical tasks with more layers error protection (Safety I: Hollnagel, 2014) than simple tasks; perhaps resulting in fewer examples of I-LED involving complex tasks. A high CFQ score may indicate someone who is likely to be less receptive to external cues, against which behaviours may have been created that promote resilience. However, the sample possessed a low mean CFQ score and since more URs than IRs were reported, results appear to support literature that reports cohorts of skilled workers are less likely to need to deliberately check their work (compared to less skilled workers with high mean CFQ score) (Reason, 1990; Mecacci and Righi, 2006; Day et al., 2012). However, the researchers expected a greater number of IR than UR events as air engineers operate in a safety critical environment. A possible explanation is that the reported errors were of a potentially minor nature and everyday experience (e.g. forgetting to return equipment, keys left in pocket, basic data entry errors, etc). Thus general behaviours may exist within the cohort of naval air engineers where everyday minor tasks are not considered to represent sufficient concern to warrant deliberate checking. Here, the systems approach looks to offer mitigation either by promoting cues to achieve I-LED or through organisational resilience to undetected latent errors.

6.4.1.2 *Error type*

Lapses were associated with most I-LED events. Error research often reports the dominance of lapses, which offers an account for the overall high number of execution errors (Woods, 1984; Reason, 2008; Kontogiannis and Malakis, 2009; Blavier et al., 2005; Saward and Stanton, 2015b). The low count of I-LED events involving slips was expected as action errors tend to be detected proximal to the error event due to the transparency of the action (Reason, 2008), for which the action-world element of perceptual cycle also supports this expectation, as action errors should be readily apparent during performance monitoring. Arguably, mistakes tend to be less evident to attentional mechanisms due to the implicit lack of awareness of the genotype/phenotype schema mismatch for a given task, which may account for the low count in I-LED events associated with planning errors. Therefore, the post-task detection of mistakes is likely to be problematical for the PCM since important cues are simply not recognised (Norman, 1981; Plant and Stanton, 2013b). This incorrect perception of the world element of the PCM creates a lack of situational awareness. When situational awareness is absent during the perceptual cycle, it is argued that schema housekeeping is ineffective unless an important cue is recognised later. Thus reviewing past tasks can lead to a re-gain of PCM situation awareness as the genotype/phenotype schema mismatch between intent and the external world is identified from system cues that trigger error recall. The fact that this activity occurs after a task is completed may add to PM theories such that the internal marker or 'to-do' list is not deleted from memory upon completion; otherwise there would be no reference against which to conduct schema housekeeping. Also the detection of latent errors without a conscious attempt to review past tasks appears to confirm the presence of the SAS and an autonomous capability in schema housekeeping over time, although it is unclear whether this autonomy is systematic or simply dependent on cue recognition and is therefore indiscriminate.

6.4.2 *Sociotechnical factors*

6.4.2.1 *Time*

Most I-LED events occurred within two hours of the error event, which is a similar finding from the study in Chapter 5. This is an important finding as Plant and Stanton (2013a) highlighted PCM theory involves a schema-action-world cycle, for Chapter 5 argued that the perceptual cycle persistently reviews past task performance and thus time must be associated with the frequency of this cycle; facilitating a 'golden window' in which most work-related I-LEDs occur. Although the standard deviation for the current study was large, indicating the distribution of mean times would benefit from a larger sample to improve statistical confidence, timing data represent real-world evidence. Additionally, the correlation with a separate sample of air engineers offers confidence that there appears to be a relationship between time and the perceptual cycle, which can be persistent. *T*(e-d) for IR was found to be almost three times quicker than UR; indicating deliberately focused PCM attention can identify a latent error more quickly than the autonomous condition. In each case, I-LED events demonstrate information about a completed task remains accessible to the perceptual cycle, even though the intended task may have been removed from the internal 'to-do' list. Here it is perhaps autonomous schema housekeeping that is responsible for continued engagement with the perceptual cycle over time although deliberate intervention via an intentional review is also effective. If there is indeed a delayed cycle time associated with I-LED then accommodating this delay in maintenance planning may reduce the likelihood of latent errors transitioning to flight. However, this would be a challenging intervention in a real-world operating context.

6.4.2.2 *Environment*

I-LED is thought to be most successful when schema housekeeping takes place in the same or similar environment to that which the error occurred (Saward and Stanton, 2015b). In the current study, most I-LED events occurred At Work in the same or similar location to that which the error occurred (e.g. an error occurring in the hangar and was later recalled in the AMCO). This seems reasonable as most

I-LEDs occurred within a time window of two hours whilst the engineers were still working. Work-related I-LED events also occurred when Not At Work although there were fewer reported but this does provide evidence that the PCM is able to remotely link to workplace cues to detect past errors, despite being physically present in a different sociotechnical environment. However, there are significantly greater delays to I-LED when Not At Work as highlighted in Table 6.2. In most cases though, error recall was associated with a cue. This demonstrates the importance of system cues distributed across environments to trigger recall.

6.4.2.3 *Cues triggering recall*

Participants reported familiar and recognisable workplace cues that they perceived to trigger schema recall. At Work, participants reported physical work-related cues such as sounds, aircraft paperwork, ground support equipment, toolbox, etc. Not At Work, participants reported physical items such as keys or a screw bag but also indirect perceptions of work-related cues. For example, a participant reported thinking about aircraft paperwork at home before realising an entry was made in error, another participant reported holding a general discussion about work with a colleague when a past error came to mind and one via an aircraft related news item on the radio. This appears to highlight the perceptual cycle's dependency on cues to trigger I-LED, which can involve the internal visualisation or phonological review of work-related cues in addition to physical cues away from the workplace. If the perceptual cycle can access representations of work-related cues when not in the workplace, either by visualising or reconstructing past activity internally, it is therefore argued important cues must remain available through residual memories and be sufficiently meaningful to trigger any genotype/phenotype schema mismatch; leading to successful I-LED (Reason, 1990; Stanton et al., 2009b; Saward and Stanton, 2015b). Kvavilashvili and Mandler (2004) found memories of past events where mostly triggered by easily recognised physical cues in the external environment, which are mostly visual or auditory. In the current study, At Work aircraft documentation and aviation equipment were prevalent whilst only two occasions of sound-related triggers were reported whilst At Work (aircraft noise and headset volume). Further, Mazzoni et al. (2014) argued that written word cues are more likely to trigger past memories (and thus I-LED) than picture cues. Although theirs was a laboratory-controlled experiment, current data appear to support this position since written words are implicit with aircraft documentation. Of note, the picture cues they employed were card cues and not physical objects encountered in the workplace. The only work-related pictures that the researchers found in the workplace (apart from technical diagrams in maintenance manuals) are those on flight safety posters but participants did not report I-LED events involving posters thus no further analysis could be attempted.

For I-LED events where no physical trigger was perceived, this could indicate that the participant was simply not aware of the trigger or confirms autonomous schema housekeeping; perhaps giving rise to chance detections. In this situation, the general environment may be the trigger as opposed to specific cues. For example, Sellen (1994) found that intentions are often recalled due to contextual factors rather than spontaneous retrievals. Thus simply being immersed in an associated environment or recreating associations internally may aid I-LED.

Few I-LED events were associated with a false alarm, which suggests schema housekeeping often identifies latent errors correctly. Here participants mostly agreed or strongly agreed that their error was clear to them, although they were slightly less confident that the past task was actually in error. For example, "I don't think I replaced the oil filler cap correctly, but did I?" Arguably, this may imply weaknesses can lie in the transactional relationship between schemata and the action-world element of the PCM rather than the actual schema being faulty. I-LED events often occurred working alone on another task, which requires little focused attention. This seems to suggest the PCM has capacity to attend to schema housekeeping, even when attending to an on-going task, which may limit false alarms provided other people do not distract the engineer. Few participants thought about work-related topics when Not At Work whilst most reported thoughts 'in the moment' and 'task in-hand'. Both are argued to be largely unfocused activities associated with autonomous behaviour and therefore may offer further evidence that cognitive capacity is afforded to schema housekeeping during these periods of activity. This should be expected according to Kvavilashvili and Mandler (2004) who found memory recall is most likely during periods of unfocused attention either during periods of inactivity or engaged in largely autonomous activities that do not require high levels of concentration on the on-going task. This risks a lack of cue recognition needed to assure situation awareness of the perceptual cycle proximal to the error event but also seems to suggest the PCM has in-built capacity to attend to an on-going activity whilst conducting schema housekeeping. This argument appears to receive support from

Wilkinson et al. (2011) who similarly found expert operators exhibit the capacity to respond to cues related to the on-going task whilst also engaging with the external environment for error checking. That said, Figure 6.1 shows participants also reported they were highly task focused when the I-LED occurred. Since all reported tasks are argued to be routine (see Table 6.3), it is considered more likely that they were not highly focused in terms of cognitive demands but more that the participant simply means it was the only task they were engaged with.

6.5 I-LED Interventions

The significant number of I-LED events associated with lapses may indicate weaknesses in a cues ability to trigger the intended schema action (Norman, 1981). Thus safety-focused organisations should consider the 'strength' of existing cues as an intervention to help enhance an error-detecting environment through assured engagement with the perceptual cycle. If physical objects (aviation equipment) and word cues (aircraft paperwork) mostly influence accurate I-LED, this may offer other avenues of engagement with the perceptual cycle. For example, specific word cues strategically placed alongside data entry areas in aircraft paperwork (i.e. the maintenance process or signature sheet) such as 'check units', 'panels, 'keys, 'tools', etc. This deliberately targets the triggers reported by participants. Aircraft paperwork (hard copy or electronic paperwork) is often completed in a separate location to where actual maintenance is conducted, therefore placing related paperwork near to where maintenance or supporting activities are carried out may improve transactional relationships; potentially reducing error initiation and/or enhancing I-LED. For example, signing for aircraft work as near to the aircraft as possible by moving necessary paperwork to the aircraft or issuing the air engineer with a portable e-tablet so specific task elements can be intentionally reviewed whilst remaining immersed in the same physical environment; thereby avoiding dissociation of sociotechnical context. Further, messages on Flight Safety posters could be replaced with simple images of relevant objects or perhaps use small display stands positioned in locations such as the AMCO or Line. Displaying actual physical objects associated with common errors could enhance cue recognition. For example: an oil dipstick; padlock and key; fuel filler cap; or indeed a scaled model of the aircraft. A formal 'stop and check' of simple tasks, even for minor tasks, may offer effective intervention. This is thought to be most effective if conducted within two hours of a completed task and alone to avoid distraction, and if conducted in the vicinity of where the task was executed. Interventions are considered especially important for simple everyday habitual tasks carried out alone.

Here the 'Stop, Look and Listen' strategy used in UK road safety campaigns could be applied to air safety. 'Stop' refers to the PCM cycle-time, 'Look' refers to sensing physical cues or the internal visualisation of past tasks and 'Listen' refers to phonological cues that could simply include the internal voicing of the 'to-do' list. Importantly, the golden two hours window in which most I-LED events occurred is an intervention on its own but clearly any of the interventions described above are likely to shorten detection times (depending on when the intervention is initiated). Thus the above provides direction for the design of additional LED interventions to help defend the right side of the I-LED model shown in Figure 4.3.

6.6 Study Limitations

Naturalistic research is clearly challenging and limited the data that could be collected but ecological data was essential to gain the necessary insight into erroneous acts with successful recoveries in the workplace, for which it is believed the current study has advanced understanding on I-LED. Analysis was limited to 51 usable I-LED events, which may mean I-LED is not as prevalent as thought or that the two months given to complete the diary was not long enough for more I-LED events to occur. Feedback from squadron engineering management is thought to provide a further explanation for the low return. It was highlighted that participant workload was very high and so they were not always able to make diary entries whilst a number of engineers were re-employed away from the squadron or on a short notice course. Additionally, the self-report diary approach may have biased the count of I-LED events due to increased vigilance. Thus future I-LED research would benefit from study of a larger sample over a longer period in a cohort that is able to commit fully to completing diary entries. Since the study was limited to a population of highly skilled engineers, a sample of unskilled workers should be considered as well as scenarios involving less familiar tasks and/or high workloads. In the study of human performance variability, only the context changes (Robson, 2011; Cheng and Hwang, 2015) thus it would be advantageous to conduct I-LED research in other workplace contexts where there are clearly more sociotechnical factors of interest than could be covered in the current study.

It was beyond the scope of the current study to report the safety risk of not detecting the latent errors highlighted in the current study. To make this assessment requires hierarchical task analysis and accident causation modelling to explore how particular latent errors or erroneous acts might contribute to a safety occurrence. However, the potential benefits of integrating I-LED interventions as additional safety control within an organisation's existing safety system are discussed in Chapter 9, which uses the I-LED model derived in Chapter 4 to highlight the role of I-LED interventions in helping to reduce risk escalation. Modelling of the entire At Work and Not at Work environments, to report frequencies of all complex/simple tasks carried out by the engineers in all locations where erroneous acts occurred and later recalled, was also beyond the scope of the current study. Participant high workloads and the safety critical nature of the observed squadrons did not permit this additional data collection as more extensive diary questions and/or separate observations would have been necessary, i.e. participants would need to report all complex/simple tasks carried out each day, in addition to 24/7 tracking of participant movements to report location frequencies. Thus, the risk/benefit of I-LED interventions, modelled against frequencies for all possible maintenance-related activities would warrant separate research.

6.7 Summary

The aim of the current study has been to advance knowledge of the nature and extent of I-LED events from a system perspective and to progress Objective 3, which is identify practicable interventions that enhance I-LED events in safety critical contexts in support. A diary study was used to observe naval air engineers in the natural workplace, which was designed around a multi-process approach to systems research was used that combines theories on PM, SAS and the schema theory within the PCM. Additionally, the CFQ was administered to simply affirm that the sample exhibited normal cognitive behaviours associated with skilled workers thus the current findings are likely to be transferrable to other populations of skilled workers. Previously unreported I-LED events appear to show successful safety behaviour (Safety II events) to be effective upon the deliberate review of past tasks within a golden time window of two hours of the erroneous act occurring; notably during periods of unfocused attention and whilst working alone in the same or similar sociotechnical environment to that which the error occurred. Several sociotechnical factors associated with I-LED were studied so that practicable interventions could be identified, which are anticipated to enhance I-LED and therefore contribute to safety barriers in the workplace. Application of these practicable I-LED interventions using a systems approach is considered especially important for simple everyday habitual tasks carried out alone where perhaps individual performance variability or human error effects are most likely to pass undetected if there are deficiencies in an organisation's safety controls or defences. It has been argued that I-LED interventions are likely to offer further resilience against human performance variability by helping to re-gain SA within the perceptual cycle through deliberate engagement with system cues; particularly physical objects such as equipment or written words. However, it is recognised that the interventions identified in the current study need to be deployed within naturalistic real-world contexts to operationalize and test their true benefit in terms of risk mitigation, frequency and effectiveness over time. By definition, I-LED compliments Safety II events by supporting individual safety behaviour yet any I-LED intervention is also likely to support Safety I control strategies and thus should be integrated within an organisation's safety system. Thus it is believed safety critical organisations should look for further resilience using I-LED intervention techniques that deliberately engage with system cues across the entire sociotechnical environment and full range of normal workplace behaviours to trigger recall, as opposed to chance detections; thereby providing opportunities for enhancing safety barriers as mitigation for system-induced human error effects.

The potential I-LED interventions identified in the current study satisfy Objective 3 in the current research and will be tested in Chapter 7 using a new cohort of naval air engineers who are observed in their natural working environment. The study aims to understand which I-LED interventions deliver the greatest safety benefit using system cues available in the working environment and is therefore designed to address Objective 4, which seeks to understand the effectiveness of I-LED interventions in the workplace.

Chapter 7: I-LED interventions: Pictures, words and a stop, look, listen

7.1 Introduction

Chapter 2 considered some of the many definitions covering the term human error, from which it was argued human error is simply a colloquial expression used to flag error effects or erroneous actions that must be contextualised and explained against system causes (i.e. situational error) to be a meaningful. Ambiguity in definitions, leading to a misunderstanding of error analysis, was explored further in Chapter 3 to address concerns that the term is out-dated when analysing safety failures within complex sociotechnical systems. New terms such as erroneous acts, human performance variability or system failures have emerged to describe error effects associated with human activity where the real causes of safety failures are deep-routed in system factors such as organisational decisions, design, equipment, management oversight and procedures (Woods et al., 2010; Dekker, 2014; Stanton and Harvey, 2017). Application of a systems perspective opens a more productive dialogue on performance variability that includes normative and non-normative behaviours and therefore a need to engineer resilient workplace safety systems. This encompasses an operator's ability to self-monitor for system hazards (traps) and correct as necessary to help manage safety at a local level in the workplace (Stanton and Baber, 1996; Reason and Hobbs, 2003; Woods et al., 2010; Reiman, 2011; Cornelissen et al., 2013). Chapter 3 argued the term human error can survive as a valid descriptor in systems safety but only if it is used carefully to highlight the need to analyse the causal effects of safety failures generated by the system and not by the individual. For the purpose of the current research, human error that passes undetected becomes a latent error, which can impact future safety performance (Reason, 1990). Here the term latent error refers to the residual effects created when the required performance was not enacted as expected due to system-induced sociotechnical traps generated by the organisation, i.e. system failures that pass undetected and therefore lie hidden (Reason, 1990).

Examples of everyday failures might be leaving the gas hob on when leaving the home or failing to lock the door of their house. Both could have potentially negative consequences, if left undetected. Arguably, most people have experienced the phenomenon of later, and spontaneously, recalling that the gas hob has been left on or they failed to lock the front door. This chapter focuses on naval aircraft maintenance where common examples include the later realisation that a tool wasn't removed from the aircraft engine bay, an oil filler cap wasn't replaced after replenishing the reservoir or the aircraft documentation wasn't completed correctly. These typical examples of maintenance provide the catalyst to design practicable system interventions for use in the aircraft maintenance where the timely and effective detection of latent errors can be critical to safe operations. The following chapter explores the effectiveness of a several Individual Latent Error Detection (I-LED) interventions applied to the workplace. This addresses Objective 4 in the current research, which is to understand the effectiveness of I-LED interventions during normal operations in the workplace.

Chapter 5 highlighted that the I-LED phenomenon has been observed where errors suffered by naval air engineers at work appear to be later detected spontaneously by the individual at some point post-task completion, and without reference to recognised procedures. Chapter 6 found I-LED to be most effective when engaging with system cues that trigger recall within a time window of two hours. Detection appeared to be improved whilst the engineer worked alone in the same environment that the error occurred; particularly if physical cues such as equipment and written words were present. This suggests a level of safety exists within the workplace that has not previously been accounted for in organisational safety strategies. Human error is often quoted as contributing to 70+% of accidents (Helmreich, 2000; Wiegmann and Shappell, 2003; Adams, 2006; Flin et al., 2008; Reason, 2008; Woods et al*.,* 2010; Saward and Stanton, 2015) but this belies systemic causes that do not adequately control or manage human performance variability in achieving workplace safety (Leveson, 2004; Morel et al., 2008; Amalberti 2013). I-LED research adopts the systems perspective where it is system cues that trigger recall but from a human-centred approach (Stanton and Salmon, 2009) to reveal understanding of how individual acts of post-task error detection contribute to total safety within complex sociotechnical systems. This involves the interaction between humans and technical aspects of the environment such as equipment, technology and workplace processes (Walker et al., 2008; Niskanen et al., 2016).

The step-change from studying error as a causal attribution of blame to a symptom of wider systemic issues has led to a paradigm shift in the etiological approach to safety performance or total safety using systems thinking (Leveson, 2004). Little is known about individual error detection (Blavier et al., 2005; Saward and Stanton, 2015), although it is argued I-LED can offer a further shift in safety thinking. The phenomenon addresses everyday errors that that could be considered insignificant but where accident causation modelling later revels complex paths of latent error convergence within the system as a whole. It is argued safety is created through managing risks by controlling hazards (system traps) that can cause harm. The management of risks posed by system hazards is represented in the I-LED model introduced in Chapter 4 and encompasses all system-induced operator errors, regardless of perceived significance. Morel et al. (2008) observed total safety is the product of controlling safety risks (system controls such as rules and procedures, training and experience, supervisory controls, etc) and managing safety risks locally (through the adaptive capabilities of operators within system controls). Therefore it is believed that the safety aim of an organisation should not be preventing all errors occurring but more towards using a systems approach to risk management of latent errors by promoting resilience using a total safety approach This approach encompasses Situational Awareness (SA) re-gain through I-LED events discussed in Chapter 5; especially where safety control mechanisms are exhausted through exceptional conditions (Hollnagel et al., 2006; Amalberti, 2013; Chatzimichailidou et al., 2015; Saward and Stanton, 2017). This can include occasions where operators find rules and procedures are ineffective or unavailable for a task, equipment is poorly designed or not available or organisation-driven error promoting conditions such as fatigue, task pressure, workplace distractions, etc.

Kontogiannis (2011) demonstrated that error detection could be used in the design of error tolerant systems, which supports resilience and contributes to the mitigation of system-induced error effects to help assure total safety in the workplace. This view is similar to Hollnagel's (2014) modelling of accident causation, which highlighted Safety II events where safety is managed effectively at the local level in complex sociotechnical environments despite a myriad of system influences on human performance. Here, it is essential the operator possesses error detection skills in a working environment that promotes the cues needed to detect and recover from system induced latent errors (Cornelissen et al., 2013). I-LED is a Safety II strategy aimed at supporting operator detection of their latent errors post-task completion. Thus current research is not focused on error prevention but the management of operator engagement with system cues to help support the timely detection of latent errors before they propagate and combine with other factors to become an accident (Reason, 1990). For example, Amalberti (2013) noted that routine error rates can be high but the true safety performance of a safety critical organisation should be judged against the rate of detection and recovery since the risk of error comes from its consequences if not intervened early. He noted that, in addition to established safety rules and procedures, the safest hospitals are those with the overriding ability of its operators to detect their errors before an unwanted consequence occurs. It is argued that a safer aircraft maintenance environment is similarly one in which its operators possess effective I-LED skills.

The I-LED study described in Chapter 6 found system cues such as time, location and other socio-technical factors, that are present within the workplace and other environments such as at home, could trigger successful I-LED. Their findings were based on a research using schema theory, which describes information represented in memory about our knowledge of the world we interact with to carry out actions (Bartlett, 1932). The associated schema-action-world cycle is characterised by the Perceptual Cycle Model (PCM), which describes the transactional relationship between the operator and system cues in the external world (sociotechnical environment) that trigger intended actions (Neisser, 1976; Norman, 1981; Mandler, 1985; Stanton et al., 2009a; Plant and Stanton, 2013). The execution of an action requires the bottom-up processing of information from system cues in the world against top-down prior knowledge from memory (schema) to enact the action successfully (Neisser, 1976; Cohen et al., 1986; Plant and Stanton, 2013a). It is important to note this function since I-LED relies upon system cues to trigger a review of past schema-action-world cycles to determine the success of previous actions (Saward and Stanton, 2017). Visual cues are particularly effective cues to trigger I-LED events (as opposed to other senses) where written word cues and physical objects have generally been found to be more likely to trigger recall than picture cues (Kvavilashvili and Mandler, 2004; Mazzoni et al., 2014; Saward and Stanton, 2017). Chapter 6 argued HFE designed I-LED interventions that make use of physical objects and written word cues as well as a 'Stop, Look and Listen' (SLL) approach are most likely to be effective for I-LED. For the SLL approach, the 'Stop' refers to pausing on-going activity to facilitate a review by the PCM, 'Look' refers to sensing physical cues, written words or the internal visualisation of past tasks and 'Listen' refers to phonological cues from internally 'voicing' activity associated with past tasks or simply listening to sounds in the external environment.

Amalberti and Wioland (1997) showed errors suffered by skilled operators can be frequent whilst experience improved an operator's ability to detect more of their own errors due to an enhanced 'capacity' to detect important cues present in the external environment (Blavier et al., 2005; Wilkinson et al., 2011). The current study observes a new cohort of naval air engineers in the workplace that are grouped by experience: junior 'operatives' and more experienced 'supervisors'. Thus it was hypothesised that the supervisors in this study would commit more errors than the operatives yet detect more of their own errors. Further, any I-LED intervention would improve the self-detection of latent errors due to the deliberate schema-action-world review of past actions. Word cues were thought more likely to trigger recall than pictures for supervisors (Kvavilashvili and Mandler, 2004; Mazzoni et al., 2014) as they spend more of their time managing maintenance documentation than operatives. Finally, the SLL intervention was hypothesised to be the most effective I-LED intervention for both operatives and supervisors since the technique is arguably the only intervention to be observed that promotes the review of past actions using internal cues in memory and physical objects in the sociotechnical environment; thereby offering the potential to maximise the PCM's I-LED capability. Chapter 2 argued that the PCM also exhibits an autonomous schema 'housekeeping' function where the routine monitoring of the schema-action-world cycle already provides a level of error checking and is also used to collect feedback from completed actions to facilitate learning and the acquiring of experience. This housekeeping function is thought to explain why I-LED events were reported by previous cohorts of naval air engineers where latent errors were recalled within a time window of two hours of the error occurring, and thus it was anticipated the control groups described in the method would also experience I-LED events without an intervention applied.

7.2 Method

7.2.1 *Participants*

The Royal Navy Air Engineering and Survival Equipment School (RNAESS) was selected for the current study as it provided an accessible, safe and controlled environment in which to observe I-LED events. Here two training squadrons exist, which emulate operating squadrons using aircraft and standard maintenance procedures, and is therefore representative of the real-world environment. One squadron provides maintenance courses to operatives and the other to supervisors. An operative is junior in rank and authorised to conduct simple aircraft maintenance tasks such as aircraft flight servicing and other supervised tasks. A supervisor is more senior in rank and authorised to carryout more complex maintenance tasks such as in-depth aircraft fault diagnosis, coordinating aircraft documentation and leading maintenance teams. Participants comprised 120 naval air engineers attending maintenance courses during the period May 2016 to February 2017. The sample included males (n=108) and females (n=12) in two groups of 60 (supervisors and operators). The low count of females is consistent with the population. Combined (supervisors and operators) mean age=24.92 (sd=4.1, se=0.37, range=17-38). Supervisor group mean age=27.43 (sd=3.02, se=0.41, range=23-38) and the operator group mean age=22.42 (sd=3.47, se=0.45, range=17-30).

Ethics approval was received from University of Southampton (Ethics No. 19329) with consent forms and information produced in accordance with Ministry of Defence research ethics guidelines.

7.2.2 *Design*

The study was piloted using representative courses of 12 operatives (comprising nine males and three females) and 12 supervisors (comprising 11 males and one female), whom did not form part of the main study. No significant issues were highlighted and the pilot confirmed the RNAESS was a suitable environment in which to observe I-LED events.

Instructor availability to conduct observations and the additional constraint that each intervention had to be simple and quick to complete, to avoid impacting on-going training, resulted in a maximum of four interventions and a control condition that could be tested in the current study. Based on the findings from the study conducted in Chapter 6, the four interventions were designed using picture cues, word cues and SLL approach with the dependent or outcome variable for this study being an I-LED event.

RNAESS instructors were consulted and a review of literature carried out to identify system cues most associated with typical maintenance errors (Hobbs and Williamson, 2002; Latorella and Prabhu, 2000; Liang et al., 2010; Rashid et al., 2010; Reason and Hobbs, 2003; Saward and Stanton, 2015; Wiegmann and Shappell, 2001). Twenty cues were identified as a manageable number to include in a simple booklet of flashcards. Where necessary, cues were contextualised for the naval aircraft maintenance environment and tailored to reflect differences between operative and supervisor roles as shown in Table 1. Each cue was represented as a word or picture, as well as a combination of both the word and picture for a particular cue. Examples are included at the Appendices: Appendix I shows a flashcard picture of the torch highlighted in Table 1; Appendix J shows the MF700C; Appendix K shows a combination of picture and words for the oil filler cap; and Appendix L shows a combination of picture and words for maintenance checks cue. The word, picture or combined cues were compiled separately as flashcards in A5 booklets. Each booklet comprised 20 flashcards containing one of the 20 word cues on each page in bold black print (Arial text, 72 point) or picture (non-complex colour image on a plain background, 6”x4”) or combination of the word and cue. Eight separately numbered booklets were produced for each of the three intervention techniques (SLL did not need a booklet). Each booklet contained exactly the same words or pictures but the order cues appeared was randomised within each booklet to remove ordering effects and to help reduce participants learning the sequence of words and therefore becoming de-sensitised.

Representative practical tasks were selected through further consultation with the RNAESS instructors, which encompassed the following general aircraft maintenance categories: aircraft documentation/paperwork; logistics tasks; aircraft servicing; and aviation support tasks. Specific tasks were identified to reduce variance and they were also tasks that the participants would carry out regularly during their course. This allowed the interventions to be tested on well-practiced tasks that were observed at the end of each course during consolidation periods, which arguably limited any significant effects due to early stages of learning (Fitts and Posner, 1967). For each practical task shown in Table 1 (five for operatives and five different tasks for supervisors to allow for differences in their employment), the instructors carried out basic error analysis with the researchers to identify the potential number of erroneous acts for each task.

Table 7.1. System cues and practical tasks for operatives and supervisors.

System Cues (Explanation given in brackets where applicable)		**Practical Tasks** (Typical, well-practiced maintenance tasks)	
Operative	**Supervisor**	**Operative**	**Supervisor**
Toolbox	Toolbox	1. Aircraft flight servicing	1. Specifying independent checks
Padlock	MAP (Military Publication)	2. Air system charge	2. Component removal
Keys	Keys	3. Oil replenishment	3. Hangar brief & checks
Screw bag	PPE (Personal protection equipment such as goggles, mask, gloves, etc)	4. Component Torqueing	4. Coordinate aircraft paperwork in GOLDEsp
Dipstick	Questions (part of supervisor process)	5. Aircraft jacking	5. Component receipt & despatch checks
Panel	Panel		
Filler cap	Maintenance checks		
Circuit breaker	Circuit breaker		
MF731 label (paper tag showing component serviceability)	MF731 label		
Torque wrench	Torque wrench		
Aircraft 700C (aircraft maintenance paperwork)	Aircraft 700C		
Tool tally	FOD (Foreign object debris)		
Socket	Socket		
Cowling	Cowling		
Tyre	Hangar checks (safety procedures)		
Aircraft	Aircraft		
Pen	Pen		
GOLDEsp (e-database for paperwork)	GOLDEsp		
Torch	Torch		
Lubricant	Lubricant		

7.2.3 *Observations*

Within the period of the study, five operative courses and five supervisor courses were available, during which five practical tasks per participant per course only could be observed due to available resources and to avoid disturbing on-going training. RNAESS instructors were trained by the researchers to conduct the observations, as it was not possible for the researchers to be present every day over the period of the study. Each group was allocated 12 participants to one of the five intervention categories. Each course was loaded with more than 12 engineers thus there was sufficient redundancy to ensure the required observations could be achieved. The first course for each group acted as a control where instructors observed participants without a deliberate intervention applied. The four interventions were then introduced separately in the subsequent courses. This approach simplified data collection and helped removed biasing due to potential cross contamination between interventions. For each intervention, including the control, participants were observed over five tasks thus a total of 600 observations were recorded.

7.2.4 *Procedure*

Participants received a brief on the study at the start of their course, which was prepared by the researchers to ensure consistency and accuracy of instructions, and each participant was provided with the Participant Information Sheet (PIS) shown at Appendix H. Each participant was issued a participant number and completed a register that recorded their course number, gender and age. The instructors observed the tasks during consolidation periods at the end of their course. This procedure was adopted to help ensure the participant had sufficiently practiced the task to become a learnt skill. The instructor discretely observed the participant carrying out the task then issued the intervention technique to the participant post-task completion. This was timed so that the technique was not issued immediately after completing the task but within the two hour I-LED window. The instructor selected a booklet at random and gave it to the participant who was asked to work through all 20 words and/or picture flash cards whilst alone. If asked to try the SLL intervention, the participant was given a brief on the intervention before trying the technique. After the intervention, the participant returned to the instructor who recorded their feedback using the observer form shown at Appendix M.

7.2.5 *Data analysis*

Detection sensitivity theory can be used to highlight differences in hit rates and false alarms (Stanton and Young, 1999; Fawcett, 2006; Stanton et al., 2009b). For I-LED research this is the difference between LED events leading to true latent errors being detected compared to false alarms or no recall at all, which allows the strength of effectiveness of each I-LED intervention to be determined. A 2x2 contingency table can be constructed to determine the signal sensitivity or effect of each I-LED intervention as shown in Table 7.2.

Table 7.2. 2x2 contingency table for I-LED signal detection calculations

Recall		Latent Error: Yes	Latent Error: No
	Yes	TP (Hit)	FP (False Alarm)
	No	FN (Miss)	TN (Correct Rejection)

TP – Number of true positives observed (hit: where recall resulted in a true error detection)
TN – number of true negatives observed (correct rejection: where no error was committed or recalled)
FP – number of false positives (false alarm: where no error was committed but recall caused participant to check their work)
FN – number of false negatives (miss: where an error was committed but not detected)

Matthew's coefficient (phi) coefficient (Matthew 1975) can be calculated from the binary values recorded in the contingency table using following equation for Phi (Φ).

$$\Phi = \frac{(\mathrm{TP}\ \mathrm{x}\ \mathrm{TN}) - (\mathrm{FP}\ \mathrm{x}\ \mathrm{FN})}{\sqrt{(\mathrm{TP}+\mathrm{FP})(\mathrm{TP}+\mathrm{FN})(\mathrm{TN}+\mathrm{FP})(\mathrm{TN}+\mathrm{FN})}}$$

A coefficient of +1 represents perfect positive correlation whereby the I-LED intervention led to all latent errors being detected. A coefficient of 0 represents no correlation, whereas a coefficient of -1 indicates a perfect negative correlation.

7.3 Results

A sift of returned data revealed that the majority of the observer forms shown at Appendix M were not completed fully, which meant that only data for Questions 1, 2, 6, 7 & 8 could be analysed.

Table 7.3 shows operatives experienced 144 errors, detected 45.8% (n=66) and missed 54.2% (n=78) whilst supervisors experienced 270 errors, detected 23.9% (n=65) and missed 75.6% (n=205). These findings are represented in Figures 7.1 & 7.2 across each intervention for operatives and supervisors. The detection sensitivity Phi (Φ) for each intervention is also recorded in Table 7.3 and represented in Figure 7.3.

Figure 7.1 shows the operatives in the control group experienced some I-LED events, achieving 33% (n=11) hits out of the total observed errors for this group without an intervention applied. Table 4 records a negligible Phi value (Φ=0.04) for the control group as these engineers experienced a similar number of false alarms (n=10). The operatives that tried the SLL intervention achieved the most significant I-LED performance of all the operatives observed in the study with 73% (n=16) hits, which aligns with the strong Phi (Φ= 0.55) for this group. Interventions using words, pictures and the combination of pictures and words all achieved improved I-LED performance compared to the control group, achieving: 45% (n=10) hits for words; 44% (n=17) for pictures; and 43% (n=12) for combined (associated Phi values shown in Table 7.3). Figure 7.2 shows the supervisors also experienced some I-LED events in the control group, achieving 6% (n=6) hits out of the total observed errors for this group without an intervention applied. This result aligns with the very weak Phi (Φ=0.15) recorded in Table 7.3, which is higher than the value recorded for operatives since the supervisors in the control group experienced no false alarms. The SLL intervention also achieved the most significant I-LED performance of all the supervisors observed in the study with 70% (n=21) hits, which aligns with the very strong Phi (Φ= 0.78) recorded in Table 7.3 for this group. The value for Phi is higher than for operatives who achieved more hits (73%), as the supervisors did not experience any false alarms when using the SLL intervention. Supervisors achieved improved I-LED performance when using the words and combined interventions, achieving 33% (n=34) hits for words and 12% (n=6) for combined. The Phi value for the combined intervention was very weak (Φ= 0.14) whilst the words intervention produced a negligible negative correlation (Φ= -0.07) as shown in Table 7.3. Supervisors achieved 3% (n=1) hits for pictures. This is less than the 6% hits experienced by the control group, which also recorded a higher value for Phi (Φ=0.15) than the supervisors using the picture technique (Φ=0.01) as shown in Table 7.3 and Figure 7.3. The results shown Figure 7.3 indicate the operatives experienced improved detection sensitivity compared to supervisors using the I-LED interventions for words, pictures and combined. These interventions had little effect on I-LED performance for supervisors compared to the control group whilst the results for the operatives show these engineers all experienced improved detection sensitivity compared to their control group. The results in Figure 7.3 also show the superiors experienced a greater detection sensitivity using the SLL intervention than for operatives, with a strong Phi value (Φ=0.55) for operatives and a very strong value for supervisors (Φ=0.78).

Table 7.3. Observations for operatives and supervisors.

Group	Sensitivity Factors	Intervention					Totals
		Control	SLL	Words	Pictures	Combined	
Operatives	Observed Errors	33	22	22	39	28	144
	Hits (TP)	11	16	10	17	12	66
	False Alarms (FP)	10	8	4	4	2	28
	Miss (FN)	22	6	12	22	16	78
	Correct Rejection (TN)	24	34	37	27	34	156
	Phi (Φ)	0.04	0.55	0.41	0.33	0.45	0.36
Supervisors	Observed Errors	53	29	103	33	52	270
	Hits (TP)	3	21	34	1	6	65
	False Alarms (FP)	0	0	8	1	1	10
	Miss (FN)	50	8	69	32	46	205
	Correct Rejection (TN)	36	39	11	38	29	153
	Phi (Φ)	0.15	0.78	-0.07	0.01	0.14	0.25

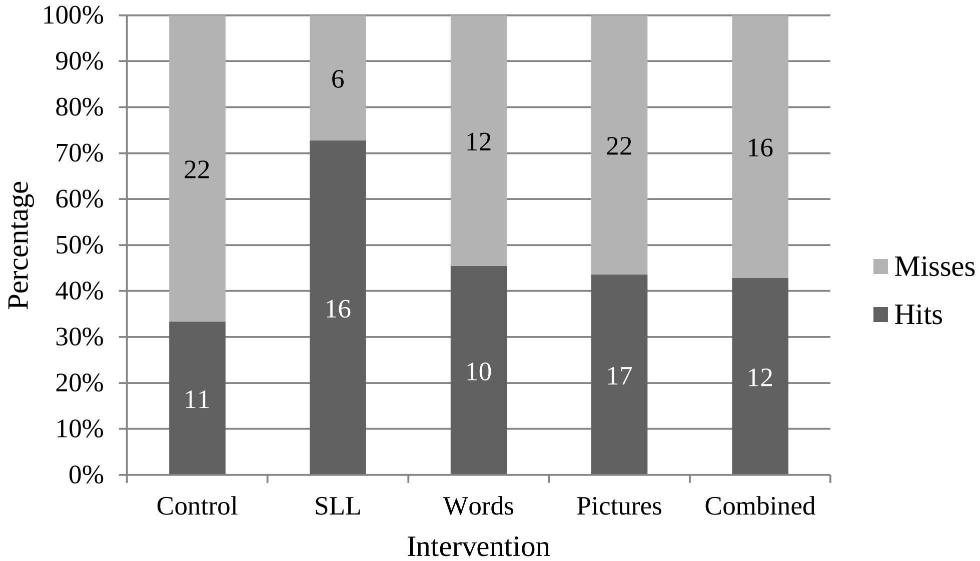


Figure 7.1. Percentage misses and hits for operatives.

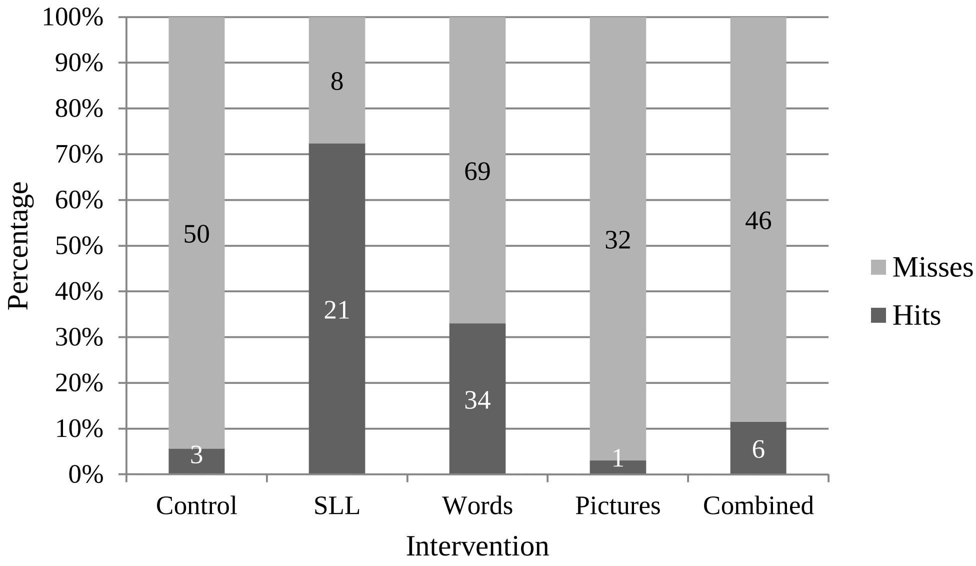


Figure 7.2. Percentage misses and hits for supervisors.

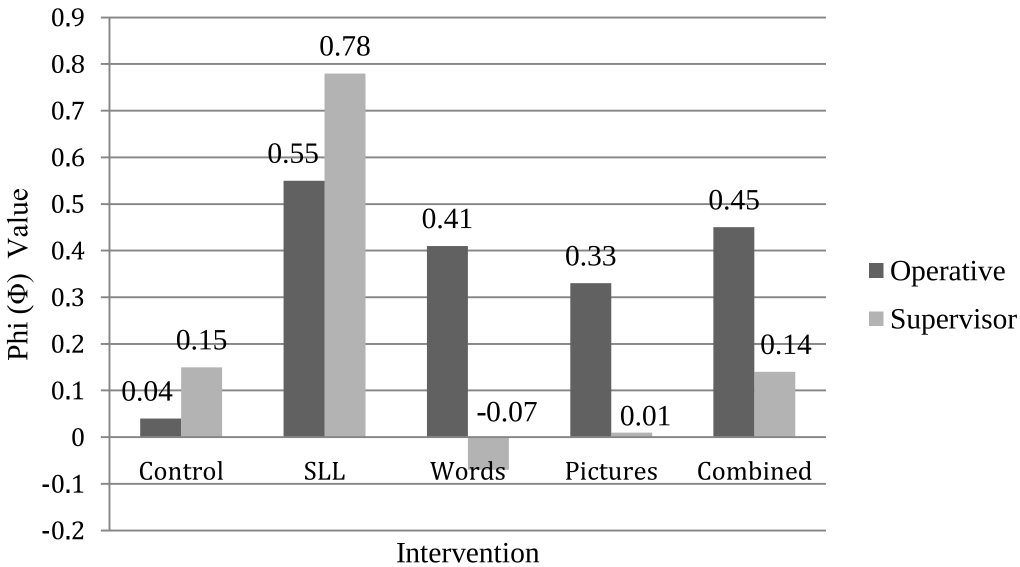


Figure 7.3. Phi (Φ) for each intervention.

7.4 Discussion

7.4.1 *I-LED intervention performance*

Errors committed by skilled operators can be high yet they also possess the ability to detect more of their own errors due to an enhanced ability to detect important cues present in the external environment (Amalberti and Wioland, 1997; Blavier et al., 2005; Wilkinson et al., 2011). This research has shown supervisors committed almost twice as many errors as operatives, which only partially supports this position as the operatives detected a higher percentage of their latent errors than supervisors (45.8% compared to 23.9%). Operatives and supervisors were equally expert for their tasks observed in this study, although the tasks for the supervisors were more complex than the simple maintenance tasks carried out by operatives. The study in Chapter 6 found that I-LED is particularly effective for simple habitual tasks thus this may explain why operatives experienced an overall higher detection sensitivity than supervisors when using an I-LED intervention (Φ=0.36 for operatives compared to Φ=0.25 for supervisors).

The results showed the presence of I-LED without an intervention applied although the detection sensitivity was negligible for operatives and very weak for supervisors. This was expected as Chapter 6 reported that latent errors could be detected within a two-hour time window if simply remaining immersed in the same environment to that which the error occurred. With an intervention applied, it was anticipated I-LED performance would see a significant improvement compared to the control due to the deliberate and targeted engagement with relevant system cues. Detection sensitivities for operatives showed a generally good improvement in I-LED performance across all interventions compared to their control group. The supervisors experienced negligible improvements in I-LED performance when using the words, pictures and combined interventions. Significantly, supervisor I-LED performance was worse than their control group, except for the SLL intervention.

The SLL intervention was effective for both groups of naval air engineers, which was expected as the intervention does not require significant focused attention, compared to working through flashcards, and it is the only intervention that supports engagement with potential internal cues and external visual and auditory cues in the surrounding environment to trigger recall. The SLL intervention was particularly effective for supervisors, which may support the earlier argument that skilled operators possess an enhanced ability to detect important cues, but perhaps only if ‘taking a moment’ to reflect on their surroundings and thoughts rather than focusing on a document such as flashcards. Arguably, the activity of reviewing the flashcards may have caused a distraction during the schema-action-world cycle due to this focused attention (Kvavilashvili and Mandler, 2004; Brewer et al*.*, 2010; Rasmussen and Berntsen, 2011). This finding receives some support from Amalberti (2013) who noted that operator performance could be assessed through an individual’s ability to detect and recover from error, which requires an element of self-reflection or metacognition, which is thought to further facilitate the schema-action-world cycle review of past tasks.

Operatives were also found to be generally responsive to directed engagement with cues found in the booklets, where the combination of pictures and cues was slightly more effective than pictures or words alone. Table 4 shows significantly more detections (hits) for supervisors using the word intervention. This should be expected as the sample of supervisors suffered approximately 4.5 times more errors than the sample of operatives who tried the word intervention. However, although the findings were not statistically significance, operatives experienced a greater detection sensitivity using word cues than supervisors (Φ=0.41 for operatives compared to Φ=-0.07 for supervisors). This is a surprising result, as the supervisor role requires more time spent working with aircraft maintenance documentation and processes than physically working on aircraft. The word cues were carefully chosen to be contextually relevant thus the fact this intervention produced a slight negative effect may suggest the continued immersion in a 'word-rich' environment desensitises the supervisor to word cues, rendering the intervention ineffective for supervisors. The picture flashcards led to substantial number of hits for operatives whilst pictures and combined flashcards produced a significant detection sensitivity result for operators compared to supervisors, who experienced similar numbers of errors. The word flashcards resulted in a good detection sensitivity for operatives though, which supports the view that written word cues are more likely to trigger recall than picture cues (Kvavilashvili and Mandler, 2004; Mazzoni et al., 2014; Saward and Stanton, 2017). Finally, the detection sensitivity for individual tasks for supervisors and operatives was also calculated for each I-LED intervention, including the control samples. No significant results were found, which indicated a latent error associated with a particular task was no more likely to be detected than for any other task.

Overall, the SLL intervention was found to be the most effective intervention for naval air engineers with supervisors experiencing the greatest benefit. The other three interventions were ineffective for supervisors, showing similar performance to the control group. Operatives experienced an enhanced I-LED performance across all interventions compared to the control group. The findings generally support the position that visual cues can be effective triggers, for which the SLL intervention is likely to be the most effective I-LED intervention tested in this study.

7.4.2 *I-LED contribution to safety-related risk management*

I-LED is argued to enhance safety-related risk management systems within safety critical sociotechnical contexts as the interventions help guide operators to engage with system cues to achieve timely detection of latent errors. This gives rise to Safety II events, which can also benefit to Safety I controls as part of a total safety approach (Morel et al., 2008; Amalberti, 2013; Hollnagel, 2014). Arguably, a resilient safety system is created from effective risk management both at the organisational and operator levels (Naderpour et al., 2014; Chatzimichailidou et al., 2015; Niskanen et al., 2016). Thus it is argued I-LED is a practicable safety strategy due to its contribution to Safety II events, which should be integrated within an organisation's risk management system to enhance overall safety. This requires systemic changes to safety-related training and maintenance processes (Safety I) and the routine local application of I-LED interventions during normal operations (Safety II) to help mitigate for everyday workplace error effects such as those experienced by naval air engineers, as described earlier. This is where the greatest benefit of the I-LED phenomenon is thought to exist, where routine habitual tasks can generate high error rates and where safety risks might be perceived as low by operators (Amalberti, 2013; Saward and Stanton, 2017). Arguably, I-LED can also help counter other potential consequences of latent errors, which are not safety-related, such as overall system performance, social-economic gains and political and reputational value (Kleiner et al., 2015). Before introducing any I-LED intervention to enhance safety resilience, it is likely that the organisation will want to explore the cost versus benefit of integrating the additional control measure within their existing safety strategy, which is considered in Chapter 9.

7.5 Study Limitations

Observing and measuring multiple interacting sociotechnical factors during normal workplace operations to determine detection sensitivity with absolute confidence is challenging (Harvey and Stanton, 2013) and modelling of the entire network of sociotechnical environments (at work and not at work) to analyse I-LED events in all locations was beyond the scope of the study. This could limit the reported effectiveness of the interventions observed although the two squadrons observed in the current study are closely related to other naval aircraft squadrons observed in Chapter 6 where data were collected to design the four interventions. In their study of prospective memory, Kvavilashvili and Mandler (2004) argued association priming improved memory recall. Thus it could be argued that the association with simply using an intervention was the primer or trigger for general Latent Error Searching (LES) described in Chapter 2. The presence of general LES could account for the latent error detections seen in this study as opposed to specific cues contained in a booklet that triggered the recall of specific latent errors. For example, did a picture of a pen trigger the recollection that a written record had been made incorrectly or did simply taking time to read through the booklet provided a sufficient pause between maintenance tasks for routine schema housekeeping to occur. The current study attempted to collect data to account for general LES effects but the absence of data recorded by the observers limited this ability.

7.6 Summary

The aim of this study was to understand the effectiveness of I-LED interventions in the workplace, which satisfies Objective 4. I-LED has been shown to offer further mitigation for erroneous acts or system failures occurring in safety critical organisations, such as the aircraft maintenance environment observed in this study. Arguably, I-LED interventions are effective at enhancing the timely detection of latent errors and therefore help to avoid adverse consequences such as a latent errors networking with other latent factors to create a causal path to an accident. An effective intervention is context sensitive and maximises engagement with system cues. It is for this reason that the SLL intervention is likely to have been the most effective technique for both operatives and supervisors, as it immersed the engineers in their relevant sociotechnical environment. The SLL intervention is also a flexible technique that the operator can tailor independently during normal operations in the workplace. I-LED interventions should improve overall safety performance within an organisation, for which there are likely to be many more potential interventions than the four described in the current study. This may be especially true for habitual tasks carried out alone or for tasks perceived to be low risk where human performance variability could pass unchecked, with the potential for errors to pass undetected.

Organisational resilience comes from a safety-related risk management that matches human performance variability with system-based approaches. It has been argued safety is created through effective risk management that matches human performance variability with systemic approaches. The I-LED phenomenon is thought to offer a significant contribution to Safety II events provided interventions are designed into Safety I strategy through training enhancements and safety processes. This requires a system perspective, as the organisation needs to embed I-LED interventions within its overall safety system to ensure operators receive the training, are given time to conduct the intervention, and context dependent cues are available in the workplace.

I-LED research offers a further step-change in safety thinking by helping to manage system induced human error effects by facilitating Safety II events through the application of I-LED interventions post-task completion. Successful I-LED limits occasions for adverse outcomes to occur, despite the presence of existing controls as shown in the I-LED model described in Chapter 4. I-LED interventions applied to normal operations in the workplace should be of benefit to any safety critical organisation seeking to further enhance their existing safety system. The next chapter explores the integration of I-LED interventions within existing safety systems whilst Chapter 9 assesses the benefits of this safety strategy.

Chapter 8: Organisational resilience through a total safety management approach to system safety

8.1 Introduction

Chapter 2 described the creation of latent error when system-induced human error is not detected proximal to the task. The processing of the external environment with the selection and enactment of schemata to carry out a task correctly typifies the elements needed for Situational Awareness (SA), which is essential for the execution of tasks without error (Plant and Stanton, 2013a; Rafferty et al., 2013); SA being *the cognitive processes for building and maintaining awareness of a workplace situation* (Flin et al., 2008, p. 17). This cognitive processing needed for SA is described by the Perceptual Cycle Model (PCM: Neisser, 1976; Smith and Hancock, 1995) described in Chapter 5, which highlights the cyclic bottom-up (BU) perception and processing of external data from sensory inputs with top-down (TD) prior knowledge (schemata) to respond correctly to a task (Cohen et al., 1986; Plant and Stanton, 2013a). Here, the latent error manifests when reality does not match the schema plan and is characteristic of insufficient or a lack of SA within the PCM. Chapter 2 further highlighted that a latent error can network with other safety failures to create a causal path or chain of events within the Sociotechnical System (STS) with the potential to cause harm; worst-case being an accident. Chapter 4 discussed the concept of system controls to reduce, mitigate or remove the risk of hazards transitioning to a safety failure that can lead to harm. The presence of effective system controls to provide a level of safety resilience within the STS can be represented by the I-LED model also introduced in Chapter 4. The model highlights the interconnecting network of latent errors and other safety failures borne from hazards that can find a path to cause harm if not controlled within the STS. Chapter 7 tested several I-LED interventions in the workplace to study their effectiveness as additional safety controls to help promote SA re-gain through the timely detection of latent errors, which in turn enhances safety resilience.

Resilience is a safety strategy that is dependent on the effective management of hazards using system controls applied to the workplace that must be managed across the entire network of potential hazards with the STS (Reason, 2008; Woods et al., 2010; Amalberti, 2013; Hollnagel, 2014). A Safety Management System (SMS) describes the organisational arrangements to identify and apply safety controls in the workplace (Leveson, 2011). When combined with Morel et al's (2008) total safety approach that seeks to control risk generated by hazards present in the STS, Total Safety Management

(TSM) emerges. TSM extends the SMS construct to account for the entire network of systems within systems comprising 'as designed' and 'as done' controls to achieve the required level of safety resilience in the workplace (Hollnagel, 2014; Leva et al., 2015). TSM therefore signposts a wider systems approach to organisational safety resilience that reaches across all aspects of the operating environment; optimising the overall performance of the organisation to achieve its safety aims (Cooper and Phillips, 1995). Consequently, this can produce wider benefits such as improved productivity, which is discussed in the next chapter when considering the cost versus benefit of I-LED interventions integrated within a TSM approach. The current chapter reviews the elements shown in Figure 8.1, which proposes a TSM construct for delivering system safety; against which it is argued that optimising safety controls within the construct shown constitutes organisational resilience. This includes the integration of I-LED interventions such as those described in Chapter 7, against which it will be argued that the success of a TSM approach for safety resilience is predicated on competent operators who are the front-line users of I-LED interventions during every day normal operations.

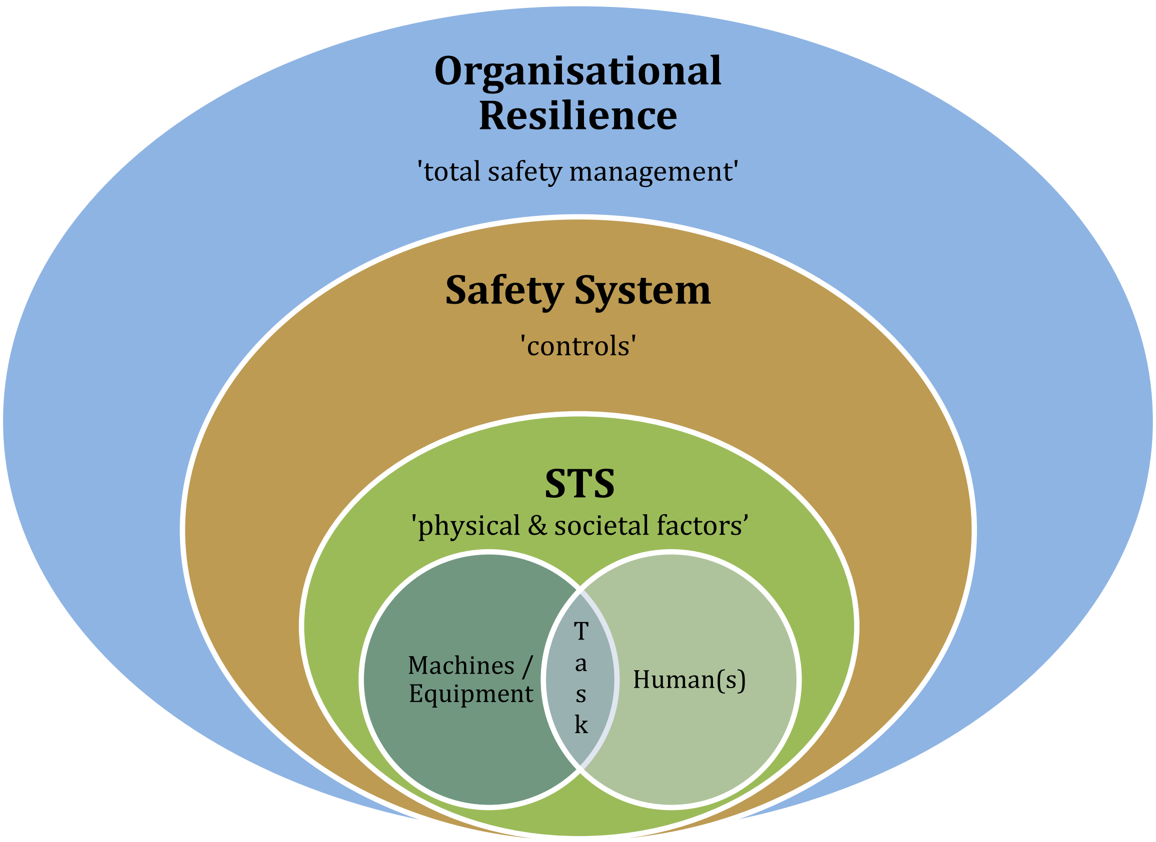


Figure 8.1. Total safety management construct depicting organisational resilience.

8.2 TSM Construct for Organisational Resilience

Human error effects are inevitable and occur daily (Reason, 1990; Hollnagel, 1993; Maurino et al., 1995; Amalberti, 1996; Perrow, 1999; Weigmann and Shappell, 2003; Wood et al., 2010). Safety resilience requires effective system controls applied to the operating environment but also encompasses the human ability to adapt and overcome safety-related disturbances in complex STSs, which includes limiting the inevitability human error effects due to system-induced performance variability (Hollnagel et al., 2006; Woods et al., 2010). Chapter 2 highlighted that the naval air engineer maintains aircraft and equipment in the dynamic and complex STS for military operations, which gives rise to multiple safety-related hazards. Here the engineer operates in multiple environments such as the maintenance office where aircraft documentation is completed and tasks planned; the maintenance hangar; stores for parts; issue centre to collect tools; and the aircraft operating line (ramp) or ship's flight deck to launch, turn-around and also service aircraft. Compounded further by: time pressures; extremes of weather; constantly changing requirements due to emergent work or changes to the flying programme; and resource constraints in terms of equipment, spares and people; operating aircraft from temporary airfields with very limited resources; operating from a moving platform whilst embarked in a warship; working on armed aircraft; and significant operational imperatives. Figure 8.2 provides context through a typical extreme cold-weather operating environment with further examples given at Appendix A.

Figure 8.2. Naval air engineers working in an extreme cold weather environment.

It is widely recognised that resilience comes from progressive safety strategies that address system deficiencies through the identification and control of the network of hazards existing in the STS that can cause human failures leading to harm (Hutchins, 1995; Hollnagel et al., 2006; Reason, 2008; Woods et al., 2010; Leveson, 2011; Cornelissen et al., 2013; Stanton et al., 2014; Hollnagel, 2014; Dekker, 2014; Chiu and Hsieh, 2016; Saward and Stanton, 2017). A resilient system therefore can detect and recover from safety failures caused by system hazards before they can cause harm. A key function of I-LED is its contribution to resilience in naval air engineers by helping to mitigate for the inevitability of error across the full range of operating contexts and human performance factors. In the case of I-LED, Reason (2008) viewed humans as 'heroes' where behaviour exists that adapts to system failures to produce a safe recovery, which supports resilience. Similarly, Hollnagel's (2014) modelling of accident causation highlighted Safety II events where the adaptive capability of human operators can locally overcome or avoid system failures whilst his Safety I analogy refers to error avoidance and capture through the planning and delivery of effective safety controls aimed at defending against identified hazards. I-LED is a Safety II example where system cues trigger recall of latent errors upon which a 'heroic' recovery can be made. Thus it is believed that the safety aim of an organisation should not be preventing all errors occurring as it is arguably impossible to identify the entire network of potential system hazards and exceptional circumstances that can cause harm. The aim should be to maximise safety resilience as an enabler to achieving the required safety performance by mitigating performance variability induced by gaps or weaknesses in system controls. The following sections argue organisational resilience comes from a TSM approach that recognises the need to optimise system controls with safe behaviour associated with competent operators to help ensure successful latent error detection occur before a causal path leads to harm.

8.2.1. *Human factors integration within the STS*

Amalberti (2013) highlighted that there are few models describing a framework for a global approach to the management of safety other than that generated at the local level to meet the specific safety needs of an organisation. Harris and Harris (2004) offer their '5M's' model to describe the complex sociotechnical relationships between worker, equipment and the organisation. At the centre of the 5M model is the requirement for Human Factors Integration (HFI) between the (hu)**M**an-**M**ission-**M**achine, against which the broad science of Human Factors and Ergonomics (HFE) considers the network of sociotechnical interactions between elements comprising humans, society, the environmental and technical aspects of the system including, machines, technology and processes (Edwards, 1972; Reason and Hobbs, 2003; Woo and Vincente, 2003; Carayon, 2006; Walker et al., 2008; Amalberti, 2013; Wilson, 2014; Niskanen et al., 2016). These networks can be complex in aircraft maintenance in terms of the number of interactions between systemic factors such as tools, equipment, procedures, organisational decision-making, operator training and experience (Edwards, 1972; Reason, 1990; Reason and Hobbs, 2003). A **M**anagement layer encapsulates the HFI elements, which recognises the need to manage safety controls within the STS. Harris and Harris (2004) also highlighted the dichotomy between physical and societal **M**ediums where controls within the STS must balance 'what can be done' within the organisation's physical medium against 'what should be done' as judged or directed by a wider social-political factors within the societal medium. In safety terms, it is argued social-political factors will drive the level of safety performance needed by the organisation to meet regulatory and legal requirements (international, national and Defence), revenue projection, productivity, cost of litigation (cost of a safety failure), cultural influences and public perception of the organisation's safety credentials; especially for safety critical industries such as construction, oil and gas, nuclear, commercial aviation, medical and transportation (Hendrick, 2003; Stanton and Baber, 2003; Goggins et al., 2008; Amalberti, 2013). Arguably, safety equilibrium is achieved when the organisation reaches consensus on what should be done against what can be done within the physical operating environment; encompasses the operating environment, equipment design, training of competent operators, procedures, etc. Expectedly, military organisations manage safety against similar societal considerations, albeit revenue is replaced with the delivery of safe and cost-effective capability. Harris and Harris (2004) 5M's 'what can be done' in the physical medium can be further delineated through Hollnagel's (2014) 'as designed' controls and 'as done' safety strategy, for which the latter relates to safe behaviours in the workplace. I-LED interventions are dependent on system controls such as training, formalised procedures and, critically, the availability of cues to trigger recall (Saward and Stanton, 2017). Like the PCM described in Chapter 5, the effectiveness of the TSM model shown in Figure 8.1 relies upon BU / TD matching of real-world safety behaviour in the workplace with 'as designed' safety controls. This requires clearly defined contexts and limitations comprising 'what can be done' in the operating environment and assurance of 'as done' safety behaviour associated with competent individuals and teams (Morel et al., 2008; Amalberti, 2013; Harris and Harris, 2004; Hollnagel, 2014; Stanton and Harvey, 2017).

Deficiencies in an organisation's system controls can lead to uncontrolled hazards that transition to safety failures. Organisational accidents occur when there is insufficient SA of the hazards that cause system failures and/or there is ineffective control of the interacting component parts of the STS (Leveson, 2004). Thus safety is created through effective risk management of hazards (Amalberti, 2013; Saward and Stanton, 2017), for which Morel et al. (2008) argued total safety is the product of controlling safety risks within the physical medium (such as rules and procedures, training and experience, supervisory controls, etc) and managing risk based activity locally through the adaptive abilities of competent operators. This is an important function of the proposed TSM model as it takes Morel et al's (2008) total safety strategy to complement Leveson's (2011) focus on system controls alongside the dichotomous strategies offered by Hollnagel's (2014) causation model (Safety I&II approaches) and Harris and Harris (2004) view of the STS medium (what should be done vice what can be done). What can be done and controlled in the physical medium raises a further dichotomous situation where a resilient organisation must work hard to close the gap between 'as designed' controls and the real-world 'as done' safety behaviour in the operating environment. Here I-LED promotes the operator's ability to self-monitor for system hazards and correct as necessary to help manage safety at a local level in the workplace; thereby contributing to resilience. Arguably, this function of I-LED facilitates 'as done' Safety II behaviour in the workplace that helps counter safety failures combing to create a causal path to harm (Stanton and Baber, 1996; Reason and Hobbs, 2003; Hollnagel et al., 2006; Woods and Hollnagel, 2006; Woods et al., 2010; Reiman, 2011; Cornelissen et al., 2013). I-LED interventions need to be integral to the safety system to be effective, which was highlighted in Chapter 7. Therefore I-LED is also argued to contribute to resilience through Safety I strategies provided it is integrated fully within each element of the TSM. The following explores each element of the TSM construct in more detail.

8.2.2 *Safety System*

The safety system needs to articulate the strategy by which safety is to be managed within an organisation (Johnson and Avers, 2012) although Kleiner et al. (2015) noted that there is no globally agreed format for a management strategy, which supports Amalberti's (2013) comments earlier. At the organisational level, Leveson (2011) offered a SMS must describe how safety hazards are mitigated through structured safety controls appropriate to each level of responsibility in an organisation alongside a safety policy within the SMS that clearly defines safety boundaries with other organisations. Leveson also recognised the need to populate the workplace with competent operators who must be appropriately trained and risk aware. These are similar competence attributes reported by Flin et al. (2008), which is considered later. Thus the safety system element shown in Figure 8.1 attempt to highlight the layers across which safety risks are identified and controlled within an organisation. The STS element is important as it provides the context and limitations for hazards across the network of HFI interfaces in the STS (Leveson, 2011), i.e. the safety system must be a good fit within the STS so that the 'as designed' and 'as done' elements are matched to facilitate maximum HFI safety performance (Hollnagel, 2014).

I-LED research aims to maximise resilience through Safety II events associated with the detection of latent errors. It is argued that a safety intervention is unlikely to be successful if not theory-driven and matched to the requirements of the organisation's safety aims and objectives. Aligning to Leveson's (2011) SMS, this supports continual improvements in safety capabilities but requires management buy-in and leadership, changes to policy and training/education. The most effective safety interventions are therefore integrated with the enduring safety goals or strategy of an organisation rather than short-term activities such as occasional training sessions, and operators should be actively involved with interventions as this drives safety behaviour (Mullan et al., 2015). I-LED research in Chapter 6 described a golden window of two hours in which most latent errors were recalled. Simply waiting for schema housekeeping to occur within a time window of two hours is an example of passive intervention if there are no other safety controls in place or existing controls are ineffective. This intervention becomes an active intervention or system control if the maintenance organisation mandates a two hours break after all maintenance is completed before the aircraft is authorised for flight. I-LED interventions comprising the word and picture booklets plus Stop, Look & Listen (SLL) are all examples of active interventions. Applying Mullan et al's (2015) view on safety interventions, it can be argued that the active application I-LED interventions is most likely to deliver greater safety benefit than simply waiting for chance recall within the golden window of two hours. This provides further agreement that I-LED interventions should be integrated throughout the safety system to form a long-term strategy in support of resilience against system-induced latent errors.

8.2.3 *Organisational Resilience*

A safety system involving complex activity should focus on resilience to counter the human effects from performance variability as well as the emergence of unexpected safety disturbances (Woods et al., 2010); especially for safety critical organisations that need to be safe or even ultra-safe where one disastrous accident per 10 million events is aspired to (Amalberti, 2001), e.g. in aircraft maintenance. To aspire to safety resilience, the organisation should recognise that every element in the network of sociotechnical interactions contributes to the organisation's safety goals; where networks of multiple hazards exist that must be identified and controlled to create safety (Leveson, 2011; Plant and Stanton, 2016). A key function of the TSM construct is its resilience to safety disturbances within the STS, which suggests a TSM approach is appropriate to help the overcome safety-related challenges associated with the typical naval aircraft maintenance environments described earlier. The TSM construct in Figure 8.1 depicts a generalised framework for resilience in a safety critical organisation that is founded on competent operators, i.e. the 'human' component in the Harris and Harris (2014) 5M's model. However, it is recognised that the generalised construct belies the multiple interacting sub-sets and complex communication paths within a network of systems in systems that constitute the living and ever-adapting world of sociotechnical networks (Hollnagel, 2014; Stanton and Harvey, 2017), i.e. networks comprising political, regulation, technical, economic, educational and cultural influences on human performance that directly impact the effectiveness of control measures embedded within the TSM construct (Kleiner et al., 2015). Resilience also reflects the need to optimise control measures at the organisational level through to the competence of individual operators in the workplace (Reason, 2008; Woods et al., 2010; Amalberti, 2013; Hollnagel, 2014)

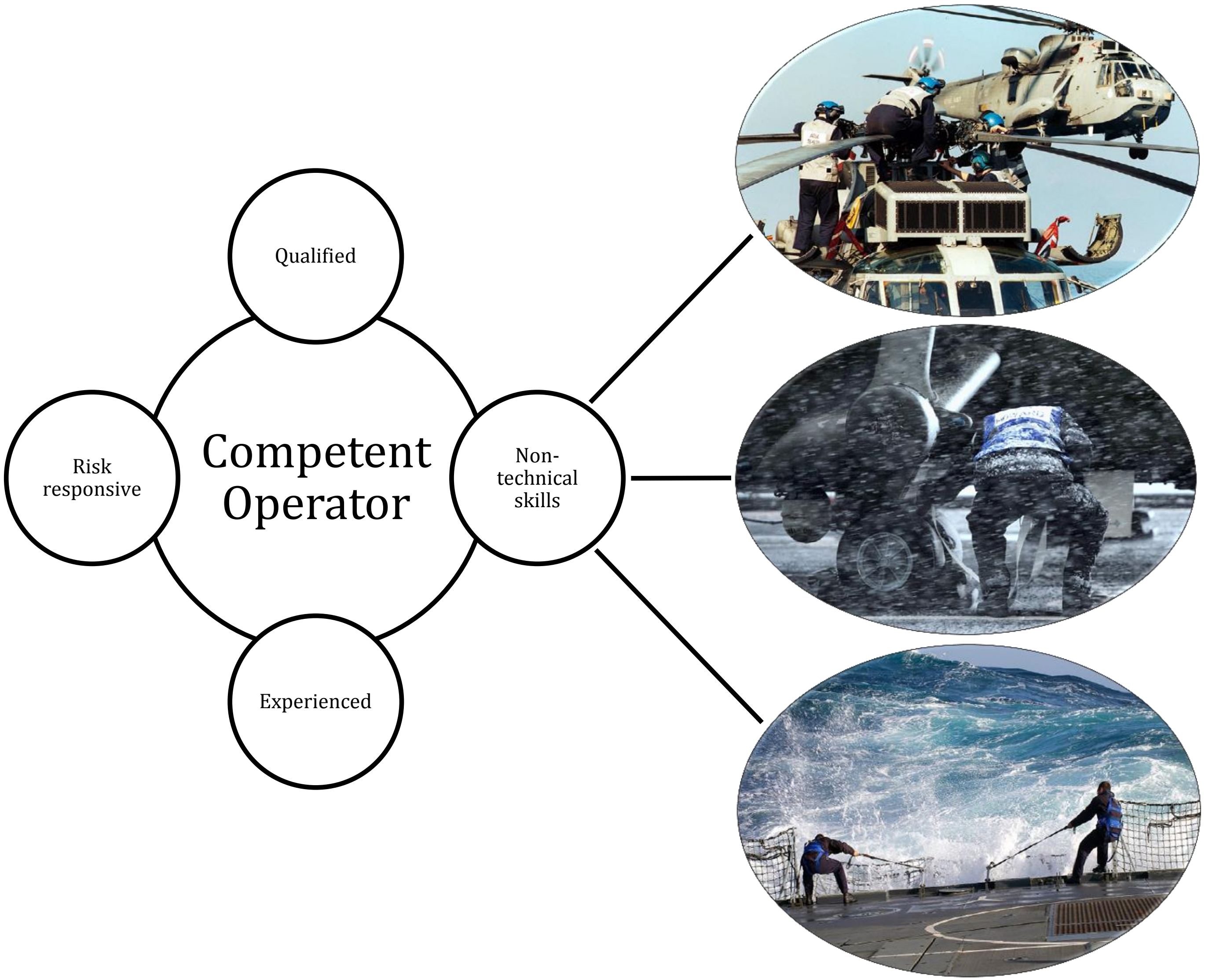
8.3 Operator Competence

It has been argued that the TSM approach to system safety is predicated on the presence of competent operators in the workplace, i.e. the heroes (Reason, 1990). This is not being critical of human error effects as the following section discusses, as it is the system that determines the level of competence required (Hollnagel, 2014: 'as designed') and not the individual. The following section argues that additional mitigation for system-induced errors comes from enhancing the HFI element of the 5M's model by ensuring competent operators in the workplace, which is a Safety II function (Hollnagel, 2014). Competence characterises the expert operator and is especially important where safety controls are exhausted through exceptional conditions (Hollnagel et al., 2006; Reason, 2008; Amalberti, 2013; Chatzimichailidou et al., 2015; Saward and Stanton, 2017). This can include occasions where operators are exposed to system-induced hazards. For example: existing rules and procedures are found ineffective or unavailable for a specific task, equipment is poorly designed or not available or other sociotechnical factors such as fatigue, task pressure and workplace distractions that can all lead to safety failures due to human error effects.

To help avoid safety failures in aircraft maintenance, as for most safety critical activities, the organisation can take an error suppression approach to safety that relies on networks of safeguards and interlocks for controlling risks within the operating context, i.e. by maximising the use of documented procedures and exacting standards, reinforced with a quality management to help protect against system failures (Kontogiannis, 2011). Accident causation modelling continues to yield additional system controls to mitigate for potential causes of safety failures, which can include training, new procedures and more 'human friendly' machines and equipment. This increases error suppression, which might be counter-productive from a systems perspective due to imposing excessive demands on human performance that may compromise the adaptive safety behaviours seen in competent operators (Amalberti, 2001). Amalberti also argued that over-optimising controls through processes and error-tolerant designs can reach a point where it is counter-productive to improving safety as the system needs to benefit from an element of flexibility to adapt to exceptional circumstances or uncontrolled system hazards that lead to error. This aligns with Rasmussen's (1997) concern that limiting the adaptive flexibility of operators overly constrains the safety system and arguably dilutes resilience through limiting Safety II events. Prescribed safety controls are essential in a resilient safety system (Leveson 2011, Hollnagel 2014) but, arguably, the ability to adapt to unidentified system hazards or unplanned exceptional circumstances also requires the cognitive skills to respond effectively rather than overly relying on error suppression techniques. Reason (1997) is sympathetic to the human condition and also offered increasing the number of safety controls increases complexity that can create new opportunities for human error effects. As mentioned previously, Reason (2008) later offered the view of humans as heroes since they exhibit the ability to adapt to exceptional circumstances to detect and recover from their own errors. Indeed, humans continually adapt to their surroundings and modify behaviour in response to the often-dynamic nature of an STS. Studies have shown that competent operators rely on system controls for safety critical activities but are also able to adapt their performance to manage recoveries from a significant amount of their own errors (Kanse, 2004; Thomas, 2004; Nikolic and Sarter, 2007; Flin et al., 2008; Malakis et al., 2010a:b). Kontogiannis (2011) argued that the error suppression approach could be relaxed in favour of promoting error detection and correction in operators, e.g. through the use of I-LED interventions. Arguably, this highlights the need for a level of safety behaviour in operators, which is a product of system controls matched with competent operators; especially for the exceptional circumstances highlighted earlier.

Dekker (2014) reminds safety organisations that it is rare an individual goes to work to cause an accident (his 'bad apple' analogy) and thus safety failures should be mitigated through system controls at the organisational level rather than relying on consistent human performance. But to design a safe environment in which humans operate successfully, you must have knowledge of human shaping factors – otherwise you do not know what deficiencies you are mitigating for and therefore the level of competence required in operators, i.e. what controls need to be designed and integrated within the safety system. Without knowledge of human behaviour, it is not likely system deficiencies can be mitigated through control measures that create resilience. For example, the analysis of diaries completed by naval air engineers in Chapter 7 found those with a high CFQ score are likely to be less receptive to external cues that trigger the appropriate schema response. Arguably, you cannot design effective system cues (accounting for system deficiencies) if you have insufficient knowledge of how receptive your general cohort are to certain cues. For pilots, the aircrew selection process facilitates mitigation for the safety expectations of the flight deck. When tackling safety deficiencies within this environment, it would be extremely challenging to design the flight deck to accommodate the full range of cognitive behaviours associated with all walks of life – unless your design goal is to remove the pilots completely. Arguably, if any human can fly a plane, operate a nuclear power plant, conduct medical operations or maintain complex aircraft then all conceivable system deficiencies will need to mitigate for all extremes of potential variance in operator competence. Therefore without a human-centred approach to error and safety, the STS view is perhaps counter-intuitive, as you will end up removing the human from the system to achieve the safety aim (via autonomous machines). This approach to safety is likely to be too costly (in terms of financial costs), currently technically impossible for all operating environments and socially unacceptable. We may end up here in the very far future but currently society still needs to use all available tools to design safety controls to account for performance variability, which arguably includes Reason's (2008) heroic recoveries concept. Assuring operator competence is a safety control and is therefore argued to be essential for a resilience approach for a safety critical organisation.

A competent operator possesses the necessary error detection skills (awareness of the genotype / phenotype mismatch described in Chapter 5) to respond effectively to system cues. This includes a capacity for schema housekeeping to occur within the PCM, during which the perceptual cycle automatically reviews the effectiveness of BU / TD cognitive processing associated with past events; as opposed to detections that might occur due to chance. Here I-LED interventions are argued to promote error detection post-task completion without risking error suppression since all the interventions tested in Chapter 7 were 'process light' yet promoted SA re-gain within an operator's perceptual cycle. Thus it is argued employing I-LED interventions improves operator competence to be ensured in the workplace, in pursuit of organisational resilience. The subject of organisational resilience is not a new concept though (refer to: Kleiner et al., 2015; Niskanen et al., 2016) but helping to ensure safe behaviours through enhanced operator competence, combined with I-LED interventions integrated within the TSM construct in Figure 8.1, is argued to be a new safety concept. Figure 8.3 provides a visual representation of the network of factors influencing operator competence, which are discussed in the following section.



- **Physical / mental limitations** (picture shows engineers working at height on an aircraft moving on a ship. Clothing and helmets limit movement and hearing)
- **Physiological factors** (picture shows an engineer working in extreme cold and wet conditions)
- **Psychological factors** (picture shows engineers struggling to position flight deck safety nets in extreme seas that could create fear, stress, etc)

Figure 8.3. Factors influencing operator competence (all pictures Crown Copyright ©).

8.3.1 *Qualified and experienced*

A resilient safety system needs to ensure operators are trained and possess the necessary skills to work safely and effectively in the operating environment (Flin et al., 2008). For example, a naval air engineer needs to be trained not only in aircraft maintenance but also in air operations, ship operations, logistics, quality assurance and military skills. This presents a significant training burden, which needs to also ensure the engineer is sufficiently experienced for a given task. Importantly, experienced operators that have become experts exhibit the enhanced ability to detect and recover from their errors, which includes the detection of latent errors post-task completion (Wilkinson et al., 2011; Saward and Stanton, 2015b). Thus qualification and experience are argued to be essential components of competence.

8.3.2 *Non-technical skills*

Competency is borne from safety controls comprising technical and non-technical skills (Flin et al., 2008). For aircraft engineers technical skills typically include the use of tools and equipment, fault diagnosis, use of technical publications, following technical procedures, physical skill-of-hand, etc. Non-technical skills are the *cognitive, social and personal resource skills that complement technical skills* (Flin et al., 2008 p.1). The non-technical skills element of the competence model is expanded in Figure 8.3 and has been developed from a concept by Campbell and Bagshaw (2002) who offered human performance variability can be influenced by the Performance Shaping Factors (PSF) shown, which generally refers to sociotechnical factors that can increase occasions of human error or erroneous acts (Kirwan, 1998). PSFs relate to an individual's response to system-induced factors associated with physical/mental limitations, physiological conditions and psychological conditions; all of which are argued to be characteristic of non-technical skills. These PSFs align with descriptions of non-technical skills, for which examples include (but not limited to): physical/mental limitations – anthropometric reach, cognitive ability, vision, strength, etc; physiological conditions – extremes of weather, heat, vibration, noise, ship roll, etc; and psychological conditions – stress, fear, mental fatigue, etc. PSFs can influence safety behaviour (Kirwan, 1998) as the effects can manifest as reduced operator readiness (for a task). Particularly, studies have shown that PSFs mostly influence cognitive performance and therefore the error detection ability of the perceptual cycle, leading to insufficient SA (Gould et al., 2006; Liang et al., 2010; Plant and Stanton 2013a). I-LED has been cited as offering an additional safety control to further mitigate for error events. Arguably, if the organisation does not control the influence on operator competence due to PSFs then this might impact the ability to enact an I-LED intervention successfully.

Flin et al. (2008) also highlighted seven examples of non-technical skills: SA; decision-making; communication; teamwork; leadership, managing stress; and coping with fatigue. These non-technical skills could all be considered PSFs. Particularly, I-LED events occur when on-going schema housekeeping (Saward and Stanton 2015a) or surrounding cues trigger a review of schemas applied to past tasks, i.e. the schema-action-world cycle. This cognitive processing of cues associated with the workplace is essential for SA re-gain. Naturalistic Decision Making (NDM) refers to occasions where people decide to act based upon relating prior experience to their perception of real world events and is therefore schema driven and can also be related to the PCM (Klein, 2008; Plant and Stanton, 2013a). This draws synergies with decisions made in response to schema selection and enactment based upon the perception of cues to trigger the decision making process. Thus it could be viewed that I-LED is an example of NDM. However, NDM is concerned with making decisions based upon informed choices whilst I-LED is concerned with the recall of past errors when triggered by a related system cue. Thus I-LED is believed to offer a distinct addition to the non-technical skills defined by Flin et al. (2008).

8.3.3 *Risk responsive*

Whilst adjunct to the other elements of the competence model shown in Figure 8.3, being responsive to risks is an ability predicated on an operator being qualified, experienced and personally ready for the task in-hand. Without these preceding elements, arguably the operator is not likely to recognise safety risk (borne from hazards present in the STS) in terms of where system failures might occur and how to respond effectively. Leveson (2011) highlighted the need for risk awareness throughout the operating environment. This could see the operator take action to avoid the system failure; to correct for the failure proximal to the error event or detect and recover a latent error before it networks with other safety failures in the STS to form a causal path. Thus it is argued risk responsive is the product of being risk aware and possessing the skills to respond effectively to a safety failure, which might be highlighted through an I-LED trigger.

8.4 Summary

There appears to be few models describing an agreed safety strategy for achieving organisational safety resilience. Thus a TSM construct has been proposed to highlight the hierarchical relationship between safety 'as done' (Safety II) by competent operators in the workplace through to the 'as designed' (Safety I) controls needed for system safety. It is recognised that the generalised hierarchy of TSM construct introduced in this chapter belies the complexity of real-world operating environments where multiple interacting sub-sets and complex communication paths within a network of systems in systems reflects the true living and ever-changing nature of a STS. However, it has been argued that the TSM construct provides utility in a simple framework from which to understand the layers across which safety needs to be optimised to achieve resilience. It has been further argued safety resilience is dependent on the ability of the system to promote safe behaviours, which is predicated on the presence of competent operators in the workplace who possess the necessary technical and non-technical skills that help mitigate for system-induced human error effects. Operator competence, and therefore safe behaviour, depends on system controls, which is congruent with systems thinking. I-LED is a safety control that is non-technical skill, which promotes SA re-gain without risking error suppression. To achieve the Safety II benefit, it has been argued I-LED interventions need to be applied at the local level by competent operators who are qualified, experienced, risk responsive and able to enact an I-LED intervention despite being immersed in PSFs. Chapter 5 highlighted HFE designed I-LED interventions that engage with system cues are especially important for simple everyday habitual tasks carried out alone or for tasks perceived to be low risk where perhaps human error effects are most likely to pass undetected if there are deficiencies in the organisation's safety-related defences. Thus when successfully integrated within the safety system, I-LED is believed to contribute to organisational safety resilience through improved operator competence.

Enhanced safety resilience through I-LED interventions integrated within a TSM approach to system safety should be of benefit to any safety critical organisation seeking a progressive safety strategy. The cost versus benefit arguments associated with this approach is considered in the following chapter.

Chapter 9: Assessing the Benefits of I-LED Interventions

9.1 Introduction

The previous chapter offered safety is created from effective risk management that controls hazards across the Sociotechnical System (STS), at the organisational level through to individual operators in the workplace. I-LED interventions facilitate individual operator engagement with system cues to detect latent errors, which arguably improves operator competence in the form of an additional non-technical skill that acts as a system control. This supports risk management by helping to re-gain Situational Awareness (SA) leading to the detection of system-induced latent errors post-task completion (Naderpour et al., 2014; Chatzimichailidou et al., 2015; Niskanen et al., 2016). Further, it is believed I-LED interventions integrated within Total Safety Management (TSM) approach to safety resilience helps counter a potential risk escalation as shown in the I-LED model introduced in Chapter 4. Thus it has been argued the I-LED phenomenon offers a paradigm shift in safety thinking as it offers a new control strategy for an organisation seeking to enhance its safety resilience.

The introduction of any new safety strategy is likely to incur financial costs as well as other resource implications such as training, new procedures and time to conduct the intervention. Thus the costs versus benefit of integrating I-LED interventions within an existing organisational safety strategy needs to be assessed. Assessing the benefit of a safety intervention can be problematical though; not least as Weick (1987) recognised *safety as a dynamic non-event,* thus you do not necessarily know a specific safety control avoided a safety failure or defeated a causal network that could have resulted in harm. This was evident during the literature review in Chapter 2, where only three occasions of I-LED events reported in the Air Safety Management System (ASIMS) database were found for naval aircraft maintenance. Here it was argued the database might hide the true effectiveness of safety controls due to under-reporting of failures and non-reporting of safety successes. Therefore it is difficult to calculate truly representative costs associated with the benefit of specific safety controls.

The following chapter assesses the benefit of I-LED interventions as an additional safety control, versus the financial costs and wider resourcing issues. This contributes to Objective 5, which is to assess the benefit of integrating I-LED interventions with organisational safety strategies to enhance resilience. To create safety through effective risk management, the risk analysis process identifies hazards and their potential impact upon system safety, and therefore the benefit of specific safety controls needs to be considered first. Thus the ASIMS database introduced in Chapter 2 is accessed for examples where I-LED interventions might have countered the hazardous events reported in the database, before calculating the cost of introducing an I-LED intervention as a new control measure.

9.2 Risk Analysis

Risk is the likelihood that an uncontrolled hazard will result in undesirable outcome, measured against the impact or severity of the hazardous outcome such as an accident. Where the outcome threatens life, this can be denoted as Risk to Life or RtL (JSP 892, 2017; HSE, 2017). UK naval aviation is conducted within complex sociotechnical environments, delivered around the globe; from land bases in the UK with full aircraft support facilities to deployed temporary airfields with very limited facilities, and from large multi-aircraft carriers to small single-aircraft ships. The naval air engineer operates within these operating contexts where safety-related hazards are an inherent and reasonably foreseeable part of normal operations. Risk analysis helps ensure these hazards are understood and safety controls implemented to protect naval aircraft maintenance from undesirable outcomes.

System-induced human error effects are widely cited as the most significant contributing factor in safety failures that lead to accidents; for which error is both inevitable and a daily occurrence (Reason, 1990; Hollnagel, 1993; Maurino et al., 1995; Perrow, 1999; Wiegmann and Shappell, 2003; Flin et al., 2008; Woods et al., 2010). Amalberti and Wioland (1997) showed errors suffered by highly trained and competent operators (such as engineers) can be frequent but are either inconsequential or detected and corrected before leading to an undesirable outcome. However it is also recognised that many error events pass undetected to become a latent error that poses a risk of harm if not detected later; either as a singular event or if networked with other safety failures to form a causal path (Reason, 1997; Reason and Hobbs, 2003; Graeber and Marx, 1993; Hollnagel, 1993; Maurino et al., 1995; Perrow, 1999; Flin et al., 2008; Lind, 2008; Woods et al*.,* 2010; Aini and Fakhru'l-Razi, 2013). From a systems perspective, the I-LED model described in Chapter 4 represents this causal path created from uncontrolled hazards that transition to latent error if not detected. The I-LED model also highlights the potential for multiple system failures to escalate risk or severity due to the confluence of the associated latent errors. Saward and Jarvis (2007) sampled 4,428 ASIMS occurrence reports across UK military aviation and found an average of 5.25 system failures exist per occurrence with the majority of these occurrences recorded with an event severity of only negligible, i.e. no injury to personnel or damage to an aircraft was experienced as a consequence. Chapter 2 cited a study by Graeber and Marx (1993) that analysed occurrence reports from a major airline over three years. From 122 maintenance errors they found: omissions (56%); incorrect installations (30%); and wrong parts (8%). The CAA (2009) commissioned a study of UK civil aviation mandatory occurrence reports involving jet aircraft (years 1996-2006) to find incorrect maintenance actions and incomplete maintenance contributed 53.1% and 20.7% to be present, respectively (total n=3284 mandatory reports). Physical examples include: loose objects left in the aircraft; fuel caps unsecured; and cowlings or access panels unsecured (Latorella and Prabhu, 2000). The majority of the examples posed no immediate consequences but arguably generated a latent error that could have networked with other system factors to cause harm. For example, the engine cowl doors were left unlatched on an Airbus A320-231, which resulted in the doors detaching in flight (AAIB, 2000). The aircraft returned safely, avoiding an accident, but if the doors impacted the aircraft fuselage or struck someone on the ground then the consequences clearly would have been much more severe. A search in ASIMS (2017) provided a example where maintenance error led to severe outcome when the engineers omitted to reconnect the flying controls after maintenance on a military jet aircraft. The error remained undetected and resulted in the loss of the pilot and aircraft. Relating to the I-LED model, the hazard is the flying controls can be left unconnected. Safety controls to mitigate for this maintenance error event encompass procedures, documentation, training of competent engineers and supervisor independent checks to avoid or detect the safety failure. If not detected via these typical control measures, the now latent error presents a system risk, for which additional safety controls such as pre-flight checks and a visual check the flying controls before departure are examples of further measures designed into the safety system to detect the latent error condition. In this example though, the latent error was not detected and contributed to a causal path until it was too late to make a safe recovery.

The ASIMS search provided a further example where a securing nut and bolt assembly was fitted incorrectly on a helicopter tail rotor system. Again the latent error remained undetected creating a new risk with the potential for the aircraft to crash. In this example though, the aircrew that made a successful emergency landing by responding in time to the subsequent failure of the tail rotor during flight. Here, controls designed to counter risk escalation defeated a causal path to a more severe outcome. Arguably, an I-LED intervention might have been of benefit as an additional safety control in all the above examples to help detect the latent error before risk escalation. The potential costs of integrating I-LED interventions as an additional safety controls to benefit a more resilient safety system are considered in the following section.

9.3 Calculating the Benefit of Safety Controls

The need to demonstrate the benefit of safety controls has long been recognised in human factors research where their effectiveness against cost in terms of safety, economic, productivity and social-political factors needs to be calculated (Hendrick, 2003; Stanton and Baber, 2003; Goggins et al., 2008). Micheli and Cagno (2009) conducted a survey of small to medium organisations to find that safety was a priority but 80% (n=109) of the organisations struggled to implement safety interventions due to the lack of financial evidence. Cost Benefit Analysis (CBA) assesses the cost effectiveness of safety controls aim at mitigating for potential safety failures (Stanton and Barber, 2003; Goggins et al., 2008). Therefore safety controls need to be selected carefully using a risk analysis process and be based on demonstrable theory shown to yield a reduction in injuries or death whilst also improving overall system performance without disproportionate impact on time or financial costs (Gilbert et al., 2007; Leveson, 2011). Mullan et al. (2015), in their analysis of safety interventions within the construction industry, reviewed several safety intervention studies to find that legislation alone was not effective (at preventing injuries in the workplace) but interventions that changed behaviours through the active involvement of operators based on theory were effective. Further, an intervention should be applied long-term to become part of routine safety activity rather than single training event or safety campaign. Similarly, Leveson (2011) argued investing in safety long-term benefits a reduction in injury/death rates, improves productivity and overall output, and other goals such as socio-political status. But new safety controls can lack appeal to the organisation if they are poorly designed or applied incorrectly to the workplace, and thus the safety benefit is not likely to be justified. Critically, Mullan et al. (2015) noted that operators should be actively involved in the safety interventions rather than a working to a new management process, as this empowers safe behaviours. Johnson and Avers (2102) found that improving system safety through strategies that improve the operators working environment also improved overall operator performance or heroic recoveries through non-technical attributes such as empowerment and job satisfaction (Flin et al., 2008; Reason, 2008; Woods et al., 2010). Reason and Hobbs (2003) argued that maintenance errors are mostly attributable to financial losses or an impact to productivity rather than being directly causal to injuries or deaths; simply because of the number of system controls present in safety focused organisation. The ability of I-LED interventions to counter other potential consequences of latent errors hidden in the system might also benefit the wider aims of an organisation such as improved productivity, overall system performance, social-economic gains and political and reputational value (Kleiner et al., 2015). Thus carefully designed I-LED controls can offer real-world benefits to the local management of safety but must be theory-driven, engage directly with operator cognitive skills, be appropriate to the context employed and integrated within the overall safety system.

The mathematical calculation is relatively straightforward but it is the compilation of sufficiently accurate data on financial costs that possesses the greatest challenge to CBA calculations or assessing the Return on Investment (ROI: Johnson and Avers, 2012). The UK Health and Safety Executive (HSE) injury figures (HSE: 2016) show in 2015/16 the UK suffered 144 deaths, 72,702 injuries and, between 2013/14-2015/16, an estimated £4.8bn in economic costs due to injury or death. The Federal Aviation Authority (FAA: 2017) and HSE both offer online tools for ROI/CBA analysis. The HSE (2017) CBA checklist considers the costs of integrating the safety intervention into normal operations as well as training and the enduring support infrastructure needed to maintain a safety control long-term. The checklist is purposely designed to assess the financial benefit against what should be done versus what can be done proportionate to avoiding RtL and/or environmental damage, and not the wider benefits such as improved productivity, damage to equipment, economic or socio-political gains. Johnson and Avers (2012) noted though that it is extremely challenging to calculate accurate and meaningful financial costs due to the complexity of the STS and expertise needed on factors such as equipment costs, training, cost of life or injury and impact on lost output. Both ROI/CBA tools recognise the dependency on accurate cost data to model a valid cost versus benefit argument or percentage return on the investment, especially as many benefits offer the intangible gains discussed. Indeed, the realisation of an organisational accident from a causal path of undetected safety failures can come as a complete surprise to a safe or ultra-safe organisation that already invests heavily in their safety system (Amalberti, 2013). Here, it can be argued that if a new safety control is proportionate to the population that could reasonably benefit from reduced exposure to RtL, and it is not cost prohibitive, then the safety control should be introduced since not doing so could weaken safety resilience (Johnson and Avers, 2012; Amalberti, 2013; HSE, 2017).

Despite the challenges of CBA/ROI analysis, Objective 5 for the current research seeks to assess the benefit of I-LED interventions that have been argued to help enhance safety resilience. Thus the following section analyses the RtL associated with typical maintenance-related error events reported in ASIMS, from which representative CBA and

ROI calculations are provided for the introduction of an I-LED intervention tested in Chapter 7.

9.4 Analysis of I-LED Interventions

9.4.1 *Method*

The same ASIMS database interrogated in Chapter 1 was accessed for all Royal Navy maintenance-specific safety reports from aircraft squadrons over the period 31st March 2012 to 1st April 2017 (ASIMS, 2017). The population of naval air engineers employed in aircraft squadrons was approximately 1700 during this period and five years was sampled to provide sufficient number of reports that could be analysed within the resources available for the current research. The search returned 1571 reports over this period, which included: technical factors such as failed or worn components; data integrity issues; design issues; ineffective equipment or procedures; environmental factors such as adverse weather, erosion or corrosion issues and the impact of operating conditions on aircraft maintenance; and Performance Shaping Factors (PSF: Kirwan, 1998). PSFs were described in Chapter 8 and encompass physiological, psychological and physical limitations that influence human performance leading to error effects. The reports were filtered for human performance factors only to align with the current research aims. This returned 627 reports for analysis.

The narrative from each report was reviewed for latent errors (as opposed to system failures detected proximal to the reported event) and further filtered for reports where an I-LED intervention might have been of benefit. To achieve this filtering process, knowledge and experience of naval aircraft engineering and aircraft types was essential to interpret the technical narratives contained in the ASIMS reports (Schluter et al., 2008). To maintain the quality of the analysis, if a report contained insufficient data about the error event to claim that an I-LED intervention might have been effective, the report was discarded to avoid biasing the analysis. The researcher had full access to the database as part of his normal employment as an Air Engineer Officer (AEO). No identifiable or protected information (personal details, locations, aircraft types, and equipment serial numbers) were accessed from ASIMS during the data mining and the narratives were analysed within a MoD restricted IT network. Since this type of data is freely accessible to AEOs, no ethics approval was required. To test for inter-rater agreement, another AEO was used as an independent assessor to conduct a 100% review of the 627 reports, which included agreement on the potential to benefit from an I-LED intervention and the categories for 'latent error condition' and 'risk' shown in Table 9.1. Cohen's Kappa was calculated on the frequencies shown as opposed to percentage agreement to correct for any chance agreement (Robson, 2011). This found k=0.88, indicating very good agreement on which reports an LED intervention is likely to have been of benefit.

Data mining revealed 40% (n=249) of the 627 filtered reports to have the potential to benefit from one of the individual LED interventions tested in Chapter 7. Table 9.1 shows précised narratives of typical error events recorded in ASIMS (bracketed text explains technical terms and 'xxxx' is included where identifying information has been redacted). The latent error is shown along with an estimate of the worse case perceived risk if the latent error condition had not been detected. The narratives have been grouped and counted according to the ASIMS perceived safety severity (ASIMS, 2013b) listed below; noting that an I-LED event is argued to provide mitigation for each severity type. Additionally, the 1st party Valuation of Prevented Fatality (VPF) amount has been quoted against each severity using HSE (2017) data, which includes a valuation for injury:

- **A-High**. There are few or no remaining safety controls that could credibly have prevented a loss of life or significant injury, leaving consequence to chance (VPF = £1,336,800 – single death).

- **B-Medium**. The safety controls are weak or can be missed, leaving a clear path to loss of life or significant injury (VPF = £772,000 – averaged single death and permanently incapacitating injury).

- **C-Low**. The safety controls appear adequate in the protection they offer against loss of life or significant injury (VPF = £20,500 – serious injury).

- **D-Negligible**. There is no readily conceivable means through which this occurrence could have led to a loss of life or significant injury (VPF = £530 – minor injury requiring one week off work).

Table 9.1. Example narratives from ASIMS reports.

ASIMS Severity	Example narratives	Latent error condition	Worse case perceived risk
A-High (n=14)	*"The APU (Auxiliary power unit) fire bottle cartridge was found electrically disconnected during the AFS (after flight servicing)."*	Fire protection inoperative	Uncontrolled fire leading to loss of aircraft and/or life
	"I asked one of the AETs to remove the cable cutter cartridges (from an aircraft rescue hoist). The AET tasked with removing the cartridges then informed me that there were no cartridges fitted. I went over to the hoist and confirmed there were no cartridges in place."	Cable cutter inoperative	Aircraft unable to break-free if cable snagged leading to loss of aircraft and/or life
	"During entry into right hand side front seat ……….. it was noticed that the holding open strut was upside down on the door. With the jettison handle fully forward it was impossible to move the door out of the airframe (for an emergency escape)."	Pilot egress route blocked	Loss of life in an emergency
B-Medium (n=80)	*"During task to replace the wire locking with split pins, post successful test fight, it was noted that the yellow main rotor blade pitch change link had been incorrectly built."*	Main rotor system installed incorrectly	Significant vibration on start and potential damage
	"During EGR (engaged ground-run) ……… accessory GB (gearbox) inlet and exhaust cooling duct grilles found to be blanked with black masking tape."	No gearbox cooling	Over heating leading to aircraft emergency
	"On completion of a period of flying oil was observed leaking from the transmission bay port and starboard common overboard drains ……….. the MRGB (main rotor gearbox) oil filler cap was found not fitted."	MRGB oil uncontained	Oil depletion leading to aircraft emergency
	"Myself and LAET xxxx were tasked with fitting xxxx wedges and functional test on the aircraft Chaff & Flare system. Each of the 2 wedges required 6 bolts but we only had 8 available. We fitted these (4 on each) so LAET xxxx could continue with the functional testing while I tried to obtain the other bolts through main stores as we had no other available manpower at the time and there was no squadron stores personnel working. After lengthy searching, I discovered that the NSN we had for the bolts was no longer valid and I would have to talk to MODS Control to find an alternative number …….. but nobody at MODS Control. On returning to the aircraft, the M147 System had failed its functional test. I explained the situation with the bolts to LAET xxxx and we decided to ensure the system is serviceable before trying to locate the remaining 4 bolts. Around 18:00 we completed a functional test on the xxxx system and proceeded with returning the tools and completing the aircraft documentation (making the aircraft serviceable for flight). On my way to work this morning at xxxx I realised our error."	Chaff and flare system installed incorrectly	Fuselage damage and/or failure of chaff and flare system

Table 9.1. Example narratives from ASIMS reports (continued).

ASIMS Severity	Example narratives	Latent error condition	Worse case perceived risk
C-Low (n=135)	*"During an MTF (maintenance test flight) walk-round, the flying maintainer spotted that all five pitch change rod upper bolts were orientated incorrectly."*	Tail rotor system installed incorrectly	Vibration / minor damage on aircraft start
	"On xxxx, I was tasked with moving aircraft xxxx. After moving about 2 metres I noticed something move on the starboard side and stopped the move ……… the bonding lead had snapped as it had still been attached to the aircraft."	Bonding lead not removed	Fuselage damage
	"During the walk round prior to a PTF (partial test flight) it was noted that the starboard hydraulic oil filler cap and access panel had been left open."	Hydraulic oil free to escape	Damage and/or emergency landing
D-Negligible (n=20)	*"Whilst preparing for engineering rounds a Supervisor reported a spanner had been found resting on the Detachment Hydraulic Rig located just outside of the front of the Hangar."*	Metal object on aircraft operating area	
	"The Aircraft Commander opened xxxx MF700 (aircraft documentation) and found an open entry. The engineering line was informed and they removed the book coordinate correctly."	Full serviceability of aircraft not known	D-negligible risk not reported as no reasonably foreseeable consequence
	"Upon start-up of xxxx for an EGR (engaged ground-run) the blade fold display indicated that the No2 rotary actuator was showing as a yellow. On investigation the electrical connector for the No2 rotary actuator was found disconnected."	Blade fold inoperative	

9.4.2 *Findings*

ASIMS data recorded 627 maintenance events relating to human performance, which is 125.4 error events or 0.07 per engineer per year. This is an extremely low number considering human error occurs daily (Maurino et al., 1995; Perrow, 1999; Reason and Hobbs, 2003; Wiegmann and Shappell, 2003; Flin et al., 2008; Woods et al., 2010). This perhaps confirms naval aircraft maintenance activity is already very safe or that maintenance error is under-reported or passes undetected to create a hidden latent error. Indeed, applying Bird's (1969) theoretical safety triangle, there are likely to be many thousands of unreported safety-related events that occur in a large organisations. Thus the absence of safety data compounds the challenge to demonstrably cost the true benefit of safety controls such as I-LED interventions. All examples in Table 9.1 are typical maintenance error events (Rasmussen, 1997; Amalberti, 2001; Reason and Hobbs, 2003), which arguably highlights the need for broadly applicable system controls designed to counter the typical hazards shown in Table 9.1, as it will be challenging to design theory-driven bespoke safety controls for specific events.

Analysis of ASIMS found 14 potential I-LED reports recorded with a high severity. The examples in Table 9.1 show that the worst-case RtL through fire, crash landing and/or the inability to escape in an emergency. Since each aircraft involved in the 14 maintenance-related reports is crewed with a minimum of two, there is a potential for loss of life or major injury to 28 crewmembers. The complexity of costing military personnel and equipment damage is beyond the scope of the current research but using the HSE (2017) VPF figures highlighted earlier, representative CBA and ROI calculations for the SLL intervention described in Chapter 7 are provided in the following section.

9.4.3 *Estimating the cost of an I-LED intervention*

To illustrate the potential cost versus benefit of integrating an I-LED intervention within the naval aircraft maintenance safety system, the SLL intervention described in Chapter 7 can be costed in general terms. This intervention has been selected as it was found to be the most effective safety control when compared to the other interventions tested. The approximate average capitation rate (cost to Defence, as opposed to salary) for a naval air engineer is £62,000 who is employed in aircraft maintenance around 210 days a year (allowing for training courses and extraneous military duties not involving aircraft maintenance). Thus the approximate cost to Defence per day is £295.24, from which a

Maintenance Man-hour (MxMHr) = £36.90 (allowing for an eight hours working day). An air engineer is estimated to work on 10 maintenance tasks per day, for which the SLL intervention will take two minutes to enact at a cost of £12.30 per working day (MxMHr x 20mins). The SLL intervention was found to be quick to apply and did not require any additional material such as a booklet, printed procedure or equipment. Thus the cost of this new safety control is argued to be simply the cost of initial training plus the time to apply the SLL intervention to each maintenance task per working day. Thus the cost of the SLL intervention for one air engineer over one year is £2,620 (initial training £36.90 + £12.30 x 210 days, and assuming refresher training will be included within existing annual human factors training). Chapters 4 & 5 highlighted the target population consists of around 1,700 naval air engineers employed in UK naval aircraft helicopter squadrons. Thus the total Cost of Integration (CoI) in this population is £4,454,000 in the first year. The CoI is the cost of integrating the SLL intervention throughout the safety system across the four event severities recorded in ASIMS. Thus the CoI per event severity is £1,113,500. Table 9.2 has been constructed with the CoI, from which illustrative CBA and ROI have be calculated; noting that the analysis does not include additional costs such as equipment damage, third party harm or damage to the environment.

Table 9.2. SLL intervention cost calculations (represented over one year)

No. Events (Table 9.1)	**Severity** (Table 9.1)	**Likelihood** (events per yr)	**VPF** (£)	**RtL Value** (£)	**Phi, Φ** (Table 7.4)	**CoI** (£)	**CBA** (£)	**ROI** (%)
14	High	2.8	1,336,800	3,743,040	0.67	1,113,500	1,394,337	125
80	Medium	16	772,000	12,352,000	0.67	1,113,500	7,162,340	643
135	Low	27	20,500	2,767,500	0.67	1,113,500	740,725	66.5
20	Negligible	4	530	10,600	0.67	1,113,500	-1,106,398	-

Likelihood – Average number of ASIMS events per year

VPF – HSE (2017) valuation of prevented fatality or injury

RtL Value – Valuation based upon average number of event severity per year (likelihood) x VPF

Φ – Phi (Φ: Matthew 1975) for the SLL intervention is given in Table 7.4 (average score for operatives and supervisor combined)

CoI – cost of integrating the SLL intervention

Figures for CBA and ROI can be calculated as follows (Stanton and Young, 1999; Johnson and Avers, 2012; HSE, 2017):

- CBA (£) = [(RtL) x (detection performance, Φ)] – (CoI)
- ROI (%) = CBA / CoI

CBA and ROI calculations shown in Table 9.2 suggest the most significant financial benefit comes from the SLL intervention applied to Medium severity events, due to the higher RtL value. High severity events also suggest significant financial benefit. High and Medium events were anticipated to show significant CBA and ROI can be achieved since a credible and reasonably foreseeable RtL exists in the maintenance error events recorded in ASIMS.

The majority of the 249 potential I-LED occasions found in ASIMS where recorded with a Low or Negligible severity, which supports Amalberti and Wioland's (1997) finding that errors made by highly trained and competent operators are either inconsequential or detected and corrected before leading to an undesired outcome. Notably, Chapter 4 described some risks associated with uncontrolled hazards can cause a system failure but pose little impact to overall system safety if not detected. The calculated values in Table 9.2 appear to support this view in that the Low severity events showed a small financial benefit compared to High and Medium events whilst the Negligible category reported a negative CBA and therefore no ROI against the potential RtL shown. It has been highlighted that an organisational accident is rarely the result of one error effect since it is more usually it is the confluence of more than one safety failure that creates a causal path to an accident (Amalberti, 2013). Also, the study in Chapter 6 reported that habitual tasks carried out alone or tasks perceived by the individual to be low-risk were at particular risk of human performance variability. Thus it is believed that even the Low or Negligible event occurrences recorded in ASIMS could also benefit from an additional safety control such as an I-LED intervention due to the risk of latent errors networking to form a causal path, as highlighted in the I-LED model described in Chapter 4.

The SLL intervention is the simplest I-LED intervention of those tested in Chapter 7. Although the information and subjectivity of the narratives from ASIMS meant that it was difficult to decide with confidence which specific LED interventions offers the greatest safety benefit, it is argued that the SLL intervention benefit also comes from its broad applicability across various maintenance activity. The other three interventions require additional resources to be considered in the cost calculations. For example, the booklets containing words and pictures need to be produced in sufficient quantities to be widely available on an aircraft squadron, which averages around 120 engineers per squadron. These booklets also need to be managed carefully to ensure they are used effectively and do not in themselves become a loose article left on an aircraft; rendering the latent error countermeasure redundant. This presents a practicable issue to ensure all engineers have access to the booklets at anytime and in any location or operating environment. This can be managed in a UK base but rapidly becomes impracticable when maintenance is deployed in the field. There will also be an on going cost to ensure the booklets are regularly updated to reduce the chance of engineers becoming desensitised to the words and/or pictures. It is thought that the management of these challenges is likely to reduce the benefit of the booklets above and beyond existing LED safety controls such as supervision or procedural checks mentioned earlier.

9.5 Summary

This chapter has assessed the benefits of introducing I-LED interventions as an additional safety control within naval aircraft maintenance to enhance resilience, which addresses Objective 5 in the current research. The benefit of an I-LED intervention comes from its integration with an organisation's safety system to form part of an enduring long-term safety strategy to engender and control safety behaviours in the workplace (Mullan et al., 2015). Analysis of ASIMS data revealed occasions where latent error events might have been prevented if an I-LED intervention had been used as an additional safety control. Risk analysis against VPF figures suggest significant CBA and ROI can be achieved where the perceived severity of the reported safety failure is High or Medium. Here, a credible and reasonably foreseeable RtL existed in the maintenance error event reported in ASIMS. The representative calculations also showed a small CBA / ROI argument for Low severity events and a negative return for Negligible events.

Chapter 4 highlighted that little is known about how networks of latent errors form to create a causal path to an accident, especially for everyday routine and perhaps less safety critical maintenance tasks such as those reported in Chapter 6. Since organisational accidents are rarely the result of a single safety failure (Amalberti, 2013), combinations of more than one failure, irrespective of it's individual perceived severity, can cause the overall RtL to escalate to cause harm. Thus it has been argued safety controls are essential in a resilient safety system and should be applied universally across all types of safety activity. The integration of I-LED interventions as additional safety control has also been argued to offer additional benefits in terms of reduced equipment damage and economic gains as well as intangible socio-political effects and non-technical attributes such as improved operator empowerment and job satisfaction.

Chapter 10: Conclusions and Future Work

10.1 Introduction

The aim of this thesis has been to contribute to knowledge by understanding the nature and extent of Individual Latent Error Detection (I-LED) and its benefit to safety resilience in UK naval aircraft maintenance. Research has been framed around the objectives stated in Chapter 1 along with three linked observational studies to investigate the I-LED phenomenon in naval air engineers working in their natural environment during normal operations. The findings and novel contributions of this research are reviewed in the following sections, along with an evaluation of the approach to research and directions for future work. The concluding remarks offer a final statement of how I-LED interventions should be integrated within a Total Safety Management (TSM) approach to system safety that can enhance safety resilience in naval aircraft maintenance, as well as wider safety critical organisations.

10.2 Summary of Findings

10.2.1 **Objective 1**: *Using a human-centred systems approach, develop a theoretical framework to observe the I-LED phenomenon.*

To address the first objective, an extensive review of literature surrounding the proposed I-LED phenomenon was conducted in Chapter 2. This highlighted system-induced human error effects to be the most significant factor impacting the safety success of an organisation. Human error is inevitable and occurs daily, for which undetected error becomes a latent error within the Sociotechnical System (STS) that can network with other safety failures to create causal path to an accident if not detected. Whilst system causes of human error have been researched widely, as has error avoidance and proximal detection, no specific research was found on I-LED. This confirmed the phenomenon to be a novel concept, indicating a clear gap in knowledge requiring research. In the absence of specific research, a multi-process theoretical framework was developed from existing theories on Prospective Memory (PM), Supervisory Attentional System (SAS) and schema theory. To determine whether the theoretical framework aligned with real-world evidence, thematic analysis of ASIMS data found the phenomenon existed in naval air engineers and that the multi-process framework appeared to be suitable theory, against which to conduct I-LED research.

The initial literature review also revealed some disquiet exists over the use of the term human error, as it can be used to blame individuals rather than signpost the opportunity to tackle deficiencies within the STS. Progressive safety research requires a systems view but equally must not forget that the individual human is at the frontline of the safety solution where system-induced performance variability can lead to latent errors. Multi-process theory seeks macro-ergonomic solutions to achieve I-LED thus use of the term human error was argued to be congruent with systems thinking and meaningful in progressive safety research; provided the term is used carefully from a systems perspective to describe performance variability effects caused by the full range of system influences, rather than just focusing on individual human failures.

To complete the initial theoretical review, Chapter 4 introduced an I-LED model to help understand the role of the phenomenon in system safety. Adapted from bowtie analysis, the I-LED model provides a visual representation of the transition from uncontrolled hazards to safety failures that become latent errors if undetected. As discussed in Chapter 4 rarely is an organisational accident the result of a single cause thus, in terms of undetected errors, there is often the confluence of more than one latent error and other safety failures that impact system safety. The I-LED phenomenon introduced in Chapter 2 has been argued to act as an additional safety control that supports the detection of latent errors by the individual who suffered the error using system cues to trigger recall; without which the latent error can network with other safety failures to form a causal path of escalating risk. Here the I-LED model illustrated where I-LED interventions can contribute to existing hazard controls such as process checks and independent inspections to enhance safety resilience, for which the number of controls or interlocks is a function of the level of safety required by the organisation to achieve its safety aim.

10.2.2 **Objective 2**: *Apply the theoretical framework to understand the nature and extent of I-LED events in naval air engineers working in their natural environment.*

In Chapter 5, data were collected from a cohort of naval air engineers during group interviews and analysed using multi-process theory. It was hypothesised that the I-LED phenomenon would be reported by this cohort and be prevalent based on the routine nature of human error effects. This study found the cohort had experienced I-LED events during normal aircraft maintenance operations, which appeared prevalent in the naval aircraft maintenance environment. Latent detections occurred more often At Work than Not At Work thus I-LED was found to be most successful when post-task schema housekeeping takes place in the same physical environment to that which the error occurred. This is new knowledge in the field of error detection. The concept of schema housekeeping also appears to be a new concept that contributes to schema theory, for which it was also argued that schema housekeeping is largely autonomous and persistent. Error events in the workplace were also detected away from the work environment thus this extends distributed cognition thinking beyond the need to remain proximal to the error event or physically immersed in the same system context to where the error actually occurred. Further, the argument that post-task schema housekeeping may be indiscriminate provides a new explanation for occasions of false alarms, or conversely chance detections. Notably, the very existence of I-LED indicates important cues remain available for post-task schema housekeeping to detect past errors, for which timing data from the group interviews identified a golden time window of two hours in which most I-LED events occur. The strength and distribution of system cues were also found to be important for schema triggering thus 'task-related' cues dominated At Work due to the high concentration of work related cues in the aircraft maintenance environment. The findings further authorised the theoretical framework as effective for observing the I-LED phenomenon, for which time, location and other systems cues influence I-LED. Using a systems approach combined with multi-process theory advances current safety thinking. The findings from Objective 2 also provided direction to start identifying practicable interventions in support of the next objective.

10.2.3 **Objective 3**: *Identify practicable interventions that enhance I-LED events in safety critical contexts.*

Further data were collected from a new cohort of naval air engineers during a diary study and analysed using multi-process theory linked to the Perceptual Cycle Model (PCM: Neisser, 1976). The intention was to advance knowledge of the nature and extent of I-LED events from a system perspective to identify practicable I-LED interventions. Additionally, the Cognitive Failures Questionnaire (CFQ: Broadbent et al., 1982) was administered. This simply confirmed that the sample of naval air engineers exhibited normal cognitive safety behaviours associated with skilled workers thus the findings were likely to be transferrable to other populations of skilled workers. The study found I-LED events appear to mostly occur upon the deliberate review of past tasks within a golden time window of two hours of the error event occurring; notably during periods of unfocused attention and whilst working alone in the same environment to that which the error occurred. Several sociotechnical factors associated with I-LED were studied and new practicable interventions identified. I-LED interventions were argued to be especially effective for simple everyday habitual tasks carried out alone where perhaps individual performance variability or human error effects are most likely to pass undetected if there are deficiencies in the safety system. Re-gaining Situational Awareness (SA) within the perceptual cycle through deliberate engagement with system cues supports the detection of latent errors; particularly cues involving physical objects such as equipment or written words. I-LED interventions have been shown to help trigger the recall of past errors by deliberately engaging with system cues across the entire STS during the full range of normal behaviours, and therefore aids sufficient SA re-gain to detect latent errors during the perceptual cycle.

A further review of literature found I-LED supports Safety II (Hollnagel, 2014) events by contributing to individual safety behaviour. Any I-LED intervention should be integrated within an organisation's safety system to maximise its benefit as an additional control, which also contributes to Safety I strategy. This finding supports Objective 5, which is discussed later. I-LED also contributes to knowledge of how to achieve greater safety resilience, for which it was recognised that the interventions identified in the diary study needed to be tested during normal operations in the workplace to explore their true effectiveness across everyday maintenance activities. This requirement formed the basis for the next study under Objective 4.

10.2.4 **Objective 4**: *Understand the effectiveness of I-LED interventions in the workplace.*

Based upon the findings from the study conducted in Chapter 6, several I–LED interventions were designed and tested for their effectiveness using a further cohort of naval air engineers observed in their natural working environment; grouped operatives and supervisors. For the study presented in Chapter 7, it was hypothesised that the new interventions would be effective at triggering the recall of latent errors within the time window of two hours. A Stop, Look and Listen (SLL) intervention was found to be most effective at triggering recall (out of four tested). It is thought the SLL intervention maximises an individual's engagement with system cues; especially visual cues. The other three interventions were ineffective for supervisors. The SLL intervention offers a new practicable safety control, as it is a flexible technique that the air engineer can apply independently during normal maintenance activity. The tested I-LED interventions were argued to improve overall safety performance within an organisation, although it is recognised there are likely to be many more potential interventions than the four tested. This may be especially true for routine everyday maintenance operations where tasks are carried out alone or tasks are perceived to be low risk. I-LED research offers a further step-change in safety thinking by facilitating Safety II events through the application of I-LED interventions post-task completion. It was argued successful I-LED limits occasions for adverse outcomes to occur, despite the presence of existing safety controls designed to avoid or detect error effects. It is believed I-LED interventions enhance safety behaviours (or heroic recoveries) within safety critical sociotechnical contexts as the interventions help guide users to engage with system cues to achieve the timely detection of latent errors. However, this new addition to established safety systems needs to be integrated within an organisation's overall safety strategy to enhance resilience, which is discussed under Objective 5.

10.2.5 **Objective 5**: *Assess the benefit of integrating I-LED interventions with organisational safety strategies to enhance resilience.*

To address the last objective, theoretical perspectives on optimising safety resilience were considered in Chapter 8 before reviewing the benefits of integrating I-LED interventions within a safety system in Chapter 9. It has been argued that achieving resilience through a Total Safety Management (TSM) approach to system safety reflects a progressive safety strategy that optimises sociotechnical controls at the organisational level with the management and delivery of error detection skills through individual safety behaviours in the workplace. A further literature review found few models describing an agreed format for managing organisational resilience based on total safety thinking. Thus a hierarchical relationship described by a new TSM model was derived from various safety theories, including Human Factors Integration (HFI) and the 5M's concept (Harris and Harris, 2004). Theory highlighted the dichotomy between 'what should be done' and 'what can be done'. The latter could be expanded to highlight a further dichotomous relationship between safety 'as designed' by the organisation and 'as done' behaviour in the workplace (Hollnagel, 2014). It was argued the relationship between the elements shown in the model need to be optimised to achieve total safety, although it is recognised that the simplified model belies the multiple interacting sub-sets and complex communication paths within a network of systems in systems that reflects the living and ever-changing nature of a STS. Against the new TSM model, it was also argued that resilience is dependent on the system's ability to promote safe behaviours during interactions between humans and operating environments, which should be predicated on the presence of competent operators in the workplace. Reference to competence or expert operators was found throughout reviews of literature but no definitive model was found that defined competence. Therefore, a new operator competence model was also constructed to help understand human-centric factors that have the potential to impact safety performance. I-LED success is believed to be dependent upon competence, especially non-technical skills (Flin et al., 2008), and therefore forms an essential component of the TSM model. The Safety II benefit comes from effective I-LED interventions; used as an additional safety control at the local level by competent operators who are qualified, experienced, risk responsive and able to maintain required performance despite being routinely surrounded by Performance Shaping Factors (PSFs: Kirwan, 1998). To counter concerns over the term human error, it was highlighted that operator competence is dependent upon system controls. This was argued to be congruent with systems thinking and a total safety strategy as the elements comprising the TSM require system controls (as designed) that are enacted locally (as done).

Arguably, the overall benefit of I-LED interventions comes from improved operator competence that underpins I-LED success through locally enacted examples of safe behaviours. This benefit is believed to support safety resilience provided I-LED interventions are integrated within an organisation’s overall safety system and founded in demonstrable theory to form part of an enduring safety strategy. Benefits also include reduced injuries or death, avoiding equipment damage and economic gains as well as intangible socio-political effects and non-technical attributes such as improved operator empowerment and job satisfaction. However, Chapter 9 reviewed literature on the Cost versus Benefit Analysis (CBA) and Return on Investment (ROI) calculations for introducing new safety controls, which revealed detailed financial calculations were challenging due to often intangible cost data.

I-LED interventions tested in Chapter 7 do not require significant financial investment to integrate within the safety system as all were simple methods of focusing attention on system cues and therefore did not require significant investment in training, management or infrastructure. Based upon example occurrences reported in the MoD Air Safety Management System (ASIMS), representative costs for the SLL intervention were calculated using Health and Safety Executive (HSE) valuations for death and injuries. This showed that the significant CBA and ROI for High and Medium event severities with Low severity events returning some financial benefits whilst the calculation for Negligible events showed a negative return. It has been argued though that I-LED interventions are likely to benefit the recovery from all levels of maintenance error events, regardless of severity, as organisational accidents are rarely the result of a single system failure; especially for safe or ultra safe organisations where high-risk hazards (reported as a High event severity in ASIMS) are already subject to multiple system controls.

10.3 Evaluation of the Approach to Research

10.3.1 *Research strategy*

The target population existed within the context of UK naval aircraft maintenance, as this is where the researcher is employed. This facilitated open access to around 1,700 operatives and supervisors, which comprised males and females of broad ethnicity, aged 18 to 50 years. In the study of human performance variability, only the context changes, which was discussed in Chapter 5. Using the Generic Error Modelling System (GEMS) categorisation of error (Reason, 1990), data from the study presented in Chapter 5 showed the category and ratio of errors reported by naval air engineers to be broadly representative of wider maintenance error studies and the application of schema theory has been shown in previous research to be influential and effective for military applications, including aviation. This provided confidence that the target population was representative and the findings from the current research should be transferrable to other populations of skilled operators.

Having identified the target population, the challenge was to decide how to observe I-LED events in the target population; either through experiment in a controlled laboratory setting and/or natural workplace environment. It was argued in Chapter 4 that understanding error effects comes from observing safety behaviours during normal operations where real-world studies produce the necessary insight on situational error from a systems perspective. Here people create safety in the real world under resource and performance pressures at all levels within the STS, which is a view supporting both systemic and individual error contexts. Deliberately, this positioned current research within the realm of Human Factors and Ergonomics (HFE: Carayon, 2006) research rather than cognitive psychology, as it is the influence of the external environment on safety behaviour that offers the greatest safety value. Ecological experiment also brings benefit with observational studies since schema are internal representations of the world, for which measurement can only come from observed behaviour. It was recognised from the outset that research outside of a laboratory setting meant strict experimental control was not possible, although the advantage of naturalistic studies is that it avoids the bias of artificial controlled experiments that can erode the ecology of findings. Studies have also shown the nature of the operating context is not easily replicated in simulated experiments due to the complexity of sociotechnical interactions. However, the ecological benefits are recognised widely to outweigh any such concerns to deliver a meaningful contribution to safety knowledge.

A challenge to real-world research is selecting research methodologies that facilitate effective data gathering from the workplace. To help ensure quality data were captured, and to remain flexible to emergent findings, a staged approach using a mixture of methodologies was applied to a series of linked studies. This flexible approach facilitated the application of various research paradigms and data collection instruments to observe the target population over a protracted period and safeguarded against any individual study that failed. Emergent findings from each study were used to guide research, which also required continued engagement with current literature for the iterative development of hypothesis and theories. As I-LED events appeared to be an under-research field, there was little established theory to guide research and thus the linked studies proved to be an appropriate method to develop the current research thinking as findings emerged.

10.3.2 *Limitations*

The current research limited observations to naval air engineers. However, literature reviews conducted in Chapters 2 & 6 showed similar human error types and rates to that seen in other safety critical organisations whilst the CFQ scores recorded in Chapter 6 were representative of highly skilled operators, such as air engineers. This suggests that the findings from this study should be generally applicable to other military and civilian organisations.

Very few I-LED examples were available from safety reports held in ASIMS. This was not unexpected, since an individual may not see the need to report an error that has been detected and recovered successfully. If applying Bird's (1969) theoretical safety triangle, there are likely to be many thousands of unreported safety-related events that occur in a large organisations and thus many missed opportunities to analyse real world data from latent error events. The absence of safety reports also limited costs versus benefits calculations for the I-LED interventions introduced in Chapter 9.

Analysis of data from the self-report diaries described in Chapter 6 was limited to 51 usable I-LED events. Feedback from squadron engineering management highlighted that participant workload was extremely high and so they were not always able to make diary entries whilst a number of air engineers were re-employed away from the squadron, off sick or on a short notice course. The nature of the operating environment also limited the time allowed to conduct the study and the number of questions that could be asked.

These factors reiterated the challenge of observing normal operations in the workplace but the ecological data that were gained provided the necessary insight into previously unaccounted safety behaviours. Typical limitations with collecting data were also experienced when testing I-LED interventions during the study described in Chapter 7. The shortfall in data collected from the observers limited the ability to analyse latent errors detected via general Latent Error Searching (LES) as opposed to a specific cue contained in a booklet triggering a specific latent error.

10.4 Future Work

The current research has focused on individual safety behaviours since Chapter 5 found I-LED most likely to occur when alone. It is anticipated the I-LED phenomenon extends to teams though, although it is not known what the impact on PCM performance would be as the physical interaction between operators may distract individual schema housekeeping. Thus the benefit of I-LED in teams warrants study.

The low returns from the self-report diaries conducted over two months showed future research would benefit from study of a larger sample over a longer period in a cohort that is able to commit fully to making diary entries. Since the study was limited to a population of highly skilled engineers, a sample of unskilled workers should also be considered. As a new concept, it was beyond the scope of the current research to observe all the potential sociotechnical factors that might contribute to successful I-LED events involving aircraft maintenance, both At Work and Not at Work. Thus further research is needed to mature the exploratory nature of the current study to understand more about how cognition associated with the perceptual cycle is distributed across networks of sociotechnical contexts, in which I-LED events were seen to occur. It would also be advantageous to conduct I-LED research in other workplace contexts where further examples of I-LED interventions are likely to be identified. PCM performance can be influenced by the level of focal processing associated with an on-going task thus the number of separate tasks completed during maintenance activities, strength of association between tasks and the 'difficulty' of each task may be influential in latent error detection, and should also be researched further.

The PM element of multi-process theory highlights a preparation phase (encoding) when forming intention. Literature indicated that whether a PM task on the 'to do' list is recalled correctly might be influenced by the quality of the preparation phase during encoding of the task. In their discussion on reflexive-associative theory relating to spontaneous recall of a PM, Einstein et al (2005) argued that processing of external cues to recall intentions is dependent on the extent the operator encoded the task: through mental task rehearsal; importance placed on the tasks; and/or whether the task was to occur during a sequence of other tasks. Similarly, Kvavilashvili and Mandler (2004) argued association priming improved memory recall thus the quality of task encoding may also improve retrieval of information about past tasks when recall occurs. Specifically, it has been argued that operators normalise system hazards to such an extent that they are no longer cognitively prepared to detect and recover from error; effectively desensitised to risk (Reason 1990). Re-gaining SA, and therefore facilitating I-LED success, might be improved through mental rehearsal (Flin et al., 2008; Annett, 2006) and thus research is needed to explore whether I-LED performance is improved through task rehearsal. Similarly, there was a concern in Chapter 7 when testing I-LED interventions that operators would become de-sensitised to the intervention due to habit intrusion if used repeatedly over time. Further research is needed to determine whether habit intrusion through the routine everyday application of I-LED interventions counteracts its benefits over a protracted period of time. Conversely, Hutchins (1995) observed that every occasion of successful error detection provided the opportunity to develop individual error detection skills through schema development. Thus the study of I-LED interventions over time should also determine if overall error detection improves either proximal or latent error detections.

It was argued error suppression strategies might generate too many safety processes that desensitise operators to important system cues and it is likely to be difficult to control all safety situations with a process that may not reliably control all hazards impacting normative safety behaviours. Well-chosen I-LED interventions in lieu of overly prescriptive safety processes may improve overall safety performance, and is therefore a new safety approach that would also benefit from further study.

The three studies from the current research have been published in journals and the overall findings will be presented to the Royal Navy who will consider whether to adopt I-LED interventions and the TSM model as new strategies to enhance safety resilience. This will require further testing in operational squadrons so that amendments to existing safety practices can be considered for inclusion in the naval aircraft maintenance safety system. In the interim, the example SLL poster shown in Appendix N is now in use on operating squadrons.

10.5 Concluding Remarks

Informal observations made by the author during his normal employment as an AEO identified safety behaviours in naval air engineers who seemed to spontaneously self-detect their past errors at a later point in time. This I-LED phenomenon appeared to enhance their safety competence in the workplace and therefore improved system resilience. An extensive review of literature showed the phenomenon to be a novel concept, indicating a clear gap in knowledge requiring research. Thus the aim of this thesis has been to contribute to knowledge by understanding the nature and extent of I-LED and its benefit to safety resilience in UK naval aircraft maintenance.

Multi-process theory combined with systems thinking provided a theoretical framework upon which to observe the I-LED experiences of cohorts of naval air engineers. Research was structured around five objectives, which first confirmed the presence of the I-LED phenomenon. Further findings showed time, location and other system cues facilitate I-LED events, for which the deliberate review of past activity within a time window of two hours of the error occurring and whilst remaining in the same sociotechnical environment to that which the error occurred appears most effective. The detection of work-related latent errors also occurred when in non-work environments such as at home or driving a car; indicating distributed cognition extends across multiple sociotechnical networks. The nature of I-LED was also found common in simple everyday habitual tasks carried out alone where perhaps individual performance variability is most likely to pass unchecked, which gives rise to the potential for latent errord to manifest in the safety system. Testing of several practicable I-LED interventions, designed to focus operator attention on system cues such as objects or written words, showed a stop, look and listen intervention to be most effective at detecting latent errors that lie hidden in the workplace.

As described earlier, organisational accidents are rarely the result of a single system failure. This is represented by the I-LED model, which also highlighted the role of I-LED interventions as an additional safety control to counter the potential risk escalation from undetected latent error conditions. A review of CBA and ROI literature showed that it is problematical to calculate the financial benefit of safety controls such as I-LED interventions due to a lack of tangible cost data, although the application of HSE valuations for deaths and injuries to typical maintenance error events reported in ASIMS allowed representative costs to be calculated. Whilst difficult to cost in financial terms, I-LED interventions tackle latent errors that lie hidden and propagate through the entire STS, with the potential to network with other effects to create a causal path to harm or other undesirable outcome. Any safety control should be founded in theory and form part of an enduring long-term safety strategy to engender safe behaviours in the workplace to help avoid or reduce the risk of harm. The overall benefit of I-LED as an additional safety control offers physical benefits in terms of reduced injuries or death, equipment damage but also economics gains as well as socio-political effects and non-technical attributes such as improved operator situational awareness, stress and fatigue management and job satisfaction. Analysis of UK military safety data also showed safety occurrences where the perceived severity was high or medium. It was argued that use of an I-LED intervention might have prevented the occurrence and thus they are thought to offer significant ROI to safety critical organisations aiming to maximise the heroic abilities of its operators through enhanced safety competence. It has been argued the introduction of I-LED interventions, as a long-term safety strategy, does not attract significant financial costs or other resourcing implications within an organisation. I-LED interventions should also be integrated within the overall safety system to improve resilience, for which a new TSM model has been offered that describes a hierarchical relationship for total safety; predicated on the presence of competent operators with the technical and non-technical skills needed to mitigate for human error effects.

Overall, this thesis has contributed to knowledge on workplace safety by applying systems thinking to understand the nature and extent of the I-LED phenomenon and its benefit to UK naval aircraft maintenance. The population of naval air engineers observed in the various studies has been shown to be typical of skilled operators. Thus the findings from this research thus should translate to other populations of skilled operators where the safety critical organisation seeks to enhance system resilience through improved operator competence in the workplace.

Appendices

Appendix A: Typical maintenance environments (all pictures Crown Copyright ©).

Typical flight deck where maintenance is carried out

Maintenance hangar at sea

Maintenance hangar at a home base

Appendix A: (Continued)

Maintenance on flight deck at sea

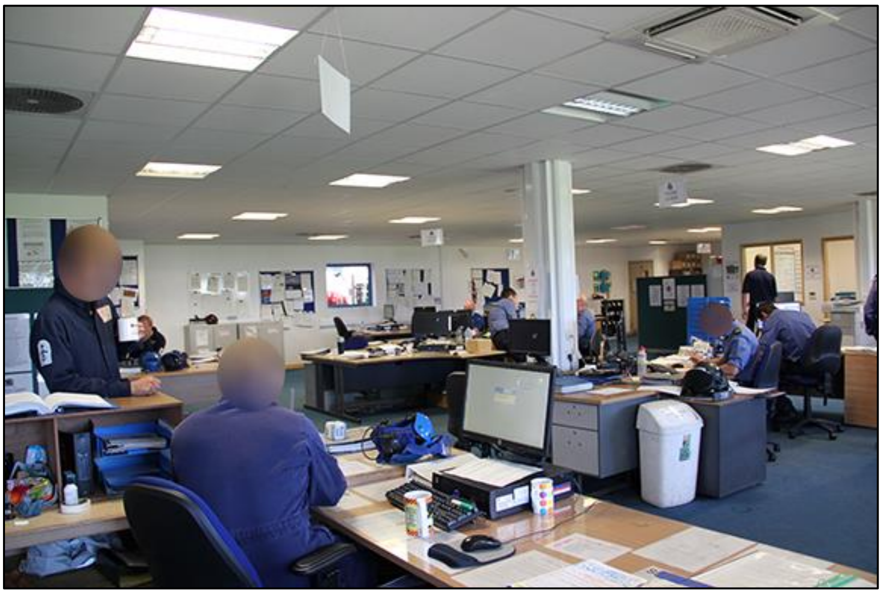
Hooking load to helicopter at sea

Maintenance on flight deck at sea in extreme weather

Appendix A: (Continued)

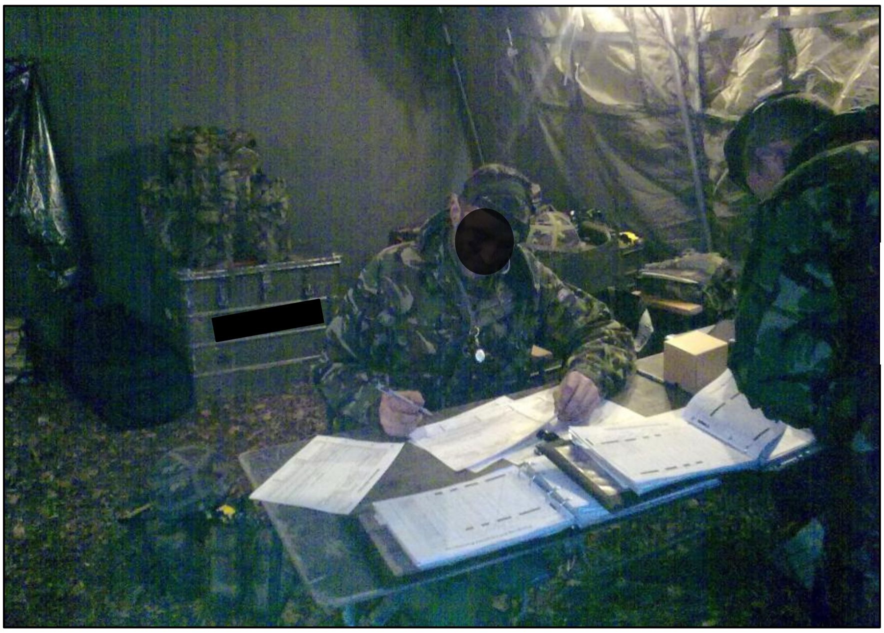
Temporary maintenance hangar deployed

Replacing an aircraft engine at sea



AMCO at a home base

Appendix A: (Continued)



Deployed AMCO in field at night

Typical squadron crew room

Engine change in Norway

Appendix B: Participant Information Sheet (Chapter 5)

Group Interviews – Participant Information Sheet

Study Title: Self Detection & Recovery from Human Error

The following Participant Information Sheet has been prepared iaw MoD Research Ethics Committee (MoDREC) guidelines. Please read the following information carefully before agreeing to take part in this research.

What is the research about?

1. PhD research has been sponsored by the Royal Navy to explore how human error is self-detected and recovered across naval aviation. Research will consider naval air engineers initially then branch out to other areas of the Fleet Air Arm.

Why have I been chosen?

2. As part of this research, you have been selected randomly from the squadron manpower list to participate in a focus group that will discuss your views on how everyday human error is self-detected and recovered amongst naval air engineers.

What will happen to me if I take part?

3. Each group interview will consist of 4 air engineers from your squadron. After a brief from the researcher, you will be asked to complete an attendance register and consent form. The register will capture the following information, which is needed to help analyse the collected data and will be kept separate from your signed consent form:

- Rank
- Trade
- Age
- Sex
- Time in Service

4. The group interview will take no longer than 30mins. It will involve a discussion on everyday human error at work. You will also be asked to write down your answers to questions on an example of human error that happened to you. For this, **you will need to come to the group with an example of everyday error that happened to you at work**. The example needs to be an error that you did not notice at the time it actually occurred but which you <u>later</u> detected after the job/task was completed. The error must be one that you self-detected and not one which was discovered by a 3rd party (i.e. a supervisor) or from following a set process. NB: For the study, error is defined simply as "not doing what the situation required."

Are there any benefits in my taking part?

5. Your participation will allow you to make an important contribution to the understanding of human error in our FAA so that <u>practical</u> interventions can be designed to help improve the self-detection of error. Updates will be published in the RN Flight Safety magazine and your contribution will be combined with other initiatives/research on error that you may have heard of.

Are there any risks involved?

6. This research has been assessed as low risk using MoD Research Ethics Committee guidelines and Southampton University has provided general ethical approval. Your involvement does not pose any physical or psychological danger and will not cause any impact on your career. As a reminder, the Royal Navy operates a Just Culture that applies equally to this research when providing essential safety-related information. **Please note that you are not to discuss any error that resulted in mandatory occurrence reporting for injury to personnel, aircraft damage or where disciplinary action was taken**.

Will my participation be confidential?

7. Information obtained from your involvement will be treated in strict confidence. Your personal details and specific contribution will not be available to Command or any other party. To preserve anonymity, your name will not be recorded with data to be analysed and all identifying information relating to organisations, squadrons, specific locations and aircraft will not be published. The researcher may need to take notes, which you are free to view. Additionally, your consent form will be held by your AEO and not by the researcher.

What happens if I choose not to participate?

8. You do not have to participate in this research if you do not want, for which you do not need to give a reason why.

Where can I get more information?

9. Your AEO has been briefed on the purpose of this research and the scope of the focus group. The researcher can be contacted as follows:

Appendix C: Group interviews - themes derived from Question 9 (Chapter 5).

Narrative Response (n=48)	**Themes** (n=48)
Reviewing task in head / doubt	Reflection/review
Just thinking / disbelief in work	Self doubt/suspicion
Self doubt / unsure	Self doubt/suspicion
Came to mind watching TV	Came to mind
Occurred something not correct	Came to mind
Questioned in mind after work	Reflection/review
Just came to my head	Came to mind
Feeling something amiss after secure	Self doubt/suspicion
Came to mind at lunch	Came to mind
Recalled when completing paperwork	Task-related cue
Noticed associated tool then realised	Task-related cue
When discussing work with colleague	Discussing work
Triggered using similar equipment	Task-related cue
Noticed HUMS computer and realised	Task-related cue
Realised when reviewing work (in head)	Reflection/review
Niggling feeling	Self doubt/suspicion
Suspicious signing paperwork	Task-related cue
Realisation just hit me	Came to mind
Niggling feeling not replaced all plugs	Self doubt/suspicion
Uneasy feeling after work	Self doubt/suspicion
During handover discussion occurred to me	Discussing work
Triggered by similar task on other aircraft	Task-related cue
Knew something wrong so checked	Self doubt/suspicion
Came to mind seeing hydraulic rig	Task-related cue
Triggered by incident on another aircraft	Task-related cue
Came to mind when partner asked about day. Initial suspicion only	Self doubt/suspicion
Came to mind	Came to mind
Thinking about day	Reflection/review

Niggling feeling something not right	Self doubt/suspicion
Reviewed tasks in head after work	Reflection/review
Felt uneasy when watching TV	Self doubt/suspicion
Remembered when doing next stage	Task-related cue
Uneasy feeling clearing away	Self doubt/suspicion
Was discussing job at stand easy	Discussing work
Remembered walking to AMCO to sign	Came to mind
Flash mental image of ac jacks that led to thinking of adapters	Came to mind
Remembered looking out window	Came to mind
Visualised job and remembered error	Reflection/review
Mental review during pause in operations	Reflection/review
Thinking about job before sleeping	Reflection/review
Remembered check by chance	Came to mind
Reflecting on work, came to mind	Reflection/review
Thinking about task then unsure checked / became suspicious	Reflection/review
Saw Sea King on news winching and came to mind high lines not packed	Task-related cue
Entering numbers in 700C made me question if ac number correct	Task-related cue
When competing same task on other ac caused to question	Task-related cue
Nagging feeling forgotten something then came to mind	Self doubt/suspicion
Came to mind on when catching up on paperwork	Came to mind

Appendix D: Group interviews - themes derived from Question 13 (Chapter 5).

Narrative Response (n=42)	**Themes** (n=55)
Trying to minimise interruptions. Potentially having a break between tasks to allow reflection on tasks completed	Avoid interruptions/distractions Rest/break needed between tasks
Stop doubting yourself. Check things more than once	Check work
Q&A before finishing of work by Supervisor to detect error prior to leaving	Check work
Having a checklist for each task to run through after completion	Use checklist/process
I am not sure – its human nature to make errors. Processes are in place to minimise the risk of this	Use checklist/process
To quickly double check the process carried out	Check work
Avoid feeling rushed at work, although I feel this is mostly my perception and not the intention	Avoid rushing
More hands-on training instead of so much classroom work	Training must be fit for purpose
Double check work before signing for it. Taking your time with your tasks	Check work Avoid rushing
By constant practice. However, due to broadening of responsibility by covering a wide range of different systems, skill fade and a lack of depth of knowledge will mean that self-detection suffers	Experience/skill needed
Run a task through your head on completion	Check work
By more careful self-assessment	Check work
Greater depth of training for Phase 2Bs (air engineer training)	Training must be fit for purpose
Don't be complacent or over-confident and be conscious of how others perceive your work output	Error awareness
By reading through instructions as you work, rather than before a long task then afterwards, just to be sure nothing was missed	Use checklist/process
A list of common errors to check for on the work cards	Use checklist/process
Encouraging people to check their work until they are absolutely certain that it has been carried out correctly	Check work
I believe self-detection is a personality thing. It is how fastidious a person is at that particular moment. I am unsure how it could be improved	Influence of personality
Possibly some kind of system to enable each person on the job to go through all the jobs for the shift	Check work
Possibly having a short break (5 or 10 minutes) between jobs/tasks to give time to think and not get clustered/confused in your head if you are carrying out the same task one after the other repeatedly	Rest/break needed between tasks
Maybe notifications or bold parts in Topics to jog your memory of what	Use warnings

should be done/should have been done	
We could be made more aware that we are prone to errors	Error awareness
I think experience plays a big part of self-detection and the ability to openly admit or discuss potential errors without the fear of reprisals or punishment for making an error or openly admitting it	Experience/skill needed Just Culture
Spending a period of time at the end of each working day reflecting on how day went	Check work
If a task seems repetitive perhaps take extra care as it can be the simple tasks that cause more issues	Check work
Going over the task before, during and after helps	Check work
Details on paperwork should be thorough and emphasis on paperwork should be a training factor on all career courses	Processes must be fit for purpose Training must be fit for purpose
Employ better engineers or improve perks. People don't care about an employer that doesn't care genuinely	Experience/skill needed Reward/incentives Employer responsibility
By removing some of the pressure to make slots and rushing jobs allowing for time to check twice and allowing for personnel to take breaks (quick 5mins breather) without being made to feel lazy	Avoid task pressure Check work Rest/break needed between tasks
Not really sure as everyone is different and some remember and others do not	Influence of human performance
By making sure you understand fully what job/task you're undertaking and by conducting it straight away	Experience/skill needed Avoid delays
One-man one-job. Avoid overloading tasks/people. Culture change on Watch to work a set time, not work towards early 'chop'	Avoid tasks in parallel Avoid task pressure Avoid interruptions/distractions
Having time post task to reflect on it	Rest/break needed between tasks
Constantly check periodically what you have done by referring to publications. Have tick sheets to confirm task had been complete	Use checklist/process
Try to avoid distractions during jobs. One job at a time until its completion	Avoid tasks in parallel Avoid interruptions/distractions
Responsibility and empowerment should be pushed/delegated to the lowest level possible in order to give people ownership of the task. If they feel they own the task they will be more likely to do it properly and reflect on their own work	Individual responsibility
Less pressure to achieve tasks in busy periods	Avoid task pressure
Reduce perceived pressure supervisors think they are under	Avoid task pressure
Know that you are capable of error and regularly self check even minor tasks to eliminate grey outs	Error awareness Check work

Allowing more time to complete tasks	Avoid task pressure
Self discipline & don't get side tracked	Avoid interruptions/distractions
Very difficult. If the job was important you naturally check and check again to ensure it is completed correctly. Emphasising the importance of tasks may help however if we over emphasise everything you would lose the effect (i.e. making everything important)	Emphasise task importance Check work

Appendix E: Cognitive Failures Questionnaire (Chapter 6)

Diary Study – Cognitive Questionnaire

Participant Number: ______________

The following questions are about minor errors that everyone makes from time to time, but some of which happen more often than others. Please circle one of the numbers (0-4) for each question, which should cover the last 6 months (Answer questions 1-25):

		Very often	Quite often	Occasionally	Very rarely	Never
1.	Do you read something and find you haven't been thinking about it so must read it again?	4	3	2	1	0
2.	Do you find you forget why you went from one part of the house to the other?	4	3	2	1	0
3.	Do you fail to notice signposts on the road?	4	3	2	1	0
4.	Do you find you confuse right and left when giving directions?	4	3	2	1	0
5.	Do you bump into people?	4	3	2	1	0
6.	Do you find you forget whether you've turned off a light or a fire or locked the door?	4	3	2	1	0
7.	Do you fail to listen to people's names when you are meeting them?	4	3	2	1	0
8.	Do you say something and realize afterwards that it might be taken as insulting?	4	3	2	1	0
9.	Do you fail to hear people speaking to you when you are doing something else?	4	3	2	1	0
10.	Do you lose your temper and regret it?	4	3	2	1	0
11.	Do you leave important letters unanswered for days?	4	3	2	1	0
12.	Do you find you forget which way to turn on a road you know well but rarely use?	4	3	2	1	0
13.	Do you fail to see what you want in a supermarket (although it's there)?	4	3	2	1	0
14.	Do you find yourself suddenly wondering whether you've used a word correctly?	4	3	2	1	0
15.	Do you have trouble making up your mind?	4	3	2	1	0
16.	Do you find you forget appointments?	4	3	2	1	0
17.	Do you forget where you put something like a newspaper or a book?	4	3	2	1	0
18.	Do you find you accidentally throw away the thing you want and keep what you meant to throw away – such as throwing away the contents of a package you wanted but keeping the packaging?	4	3	2	1	0
19.	Do you daydream when you ought to be listening to something?	4	3	2	1	0
20.	Do you find you forget people's names?	4	3	2	1	0
21.	Do you start doing one thing at home and get distracted into doing something else (unintentionally)?	4	3	2	1	0
22.	Do you find you can't quite remember something although it's 'on the tip of your tongue'?	4	3	2	1	0
23.	Do you find you forget what you went to the shops to buy?	4	3	2	1	0
24.	Do you accidentally drop things?	4	3	2	1	0
25.	Do you ever find you can't think of anything to say?	4	3	2	1	0

Appendix F: Self-report Diary (Chapter 6)

POST TASK ERROR DETECTION EVENT: 1	**DATE:** ______________________

Q1. Please give a brief description of the error event:

Q2. At what time did the error event occur? ____________ (Exact time or within nearest 30mins)

Q3. What type of task was it? Complex ☐ Simple ☐ NK ☐

Q4. What was the cue to do this task? Event ☐ Time ☐ Both ☐

Q5. What was the error type? Slip ☐ Lapse ☐ Mistake ☐ NK ☐

Q6. Where were you when the error occurred?

- AMCO ☐
- Hangar ☐
- Line ☐
- Maintenance office ☐
- Issue centre ☐
- Storeroom ☐
- In aircraft ☐
- Workshop ☐
- Flight deck ☐
- Other (please specify) ☐

Q7. At what time did you recall the error (post task completion)? ____________ (Exact time or within nearest 30mins)

Q8. Where were you when you recalled the error?

- AMCO ☐
- Hangar ☐
- Line ☐
- Maintenance office ☐
- Crew room ☐
- Issue centre ☐
- Storeroom ☐
- In aircraft ☐
- Workshop ☐
- Flight deck ☐
- Home/Mess ☐
- In bed ☐
- In a vehicle ☐
- Gym ☐
- Other (please specify) ☐

Q9. What were you doing when you recalled the error?

- Planning/preparing maintenance activity ☐
- Conducting similar maintenance activity ☐
- Conducting dissimilar maintenance activity ☐
- Walking ☐
- Driving a vehicle ☐
- Exercising (i.e. cycling, running, etc) ☐
- Showering ☐
- Eating ☐
- Socialising (i.e. in a pub) ☐
- Discussing work (not formal handover/brief) ☐
- Daydreaming ☐
- Resting ☐
- Entertainment (i.e. reading, TV, internet, etc) ☐
- Sleeping ☐
- Other (please specify) ☐

Q10. Did you intentionally review your past tasks/activities? Yes ☐(Go to Q11) No ☐(Go to Q12)

Q11. Was this part of your personal routine? Yes ☐ No ☐

Q12. On checking your work, was the error: Real ☐ False Alarm ☐

Q13. Did anything in your immediate location appear to trigger the error recall?

- Sound ☐
- Equipment ☐
- Document ☐
- Smell ☐
- Taste ☐
- General vista ☐
- Other ☐

Please describe:

Appendix F: (Continued)

<table>
<tr><td colspan="6">Q14. What were you thinking about at the time of the error recall? (Answer either 14a or 14b)</td></tr>
<tr><td>Q14a. Work-related thoughts:
• Past task / event ☐
• Task in-hand ☐
• Future task / event ☐
Please describe:</td><td colspan="5">Q14b. Non work-related thoughts:
• Past activity / event ☐
• The ‘moment’ ☐
• Future activity / event ☐
Please describe:</td></tr>
<tr><td colspan="6">Q15. Were you alone when the error was recalled? Yes ☐ No ☐</td></tr>
<tr><td></td><td>Strongly disagree
5</td><td>Disagree
4</td><td>Uncertain
3</td><td>Agree
2</td><td>Strongly agree
1</td></tr>
<tr><td>Q16. The specific error was very clear to me.</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Q17. I was very confident that my past task was in error.</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Q18. The error recall occurred when I was highly focused on the activity at Q9.</td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

Please use for making notes or to add any additional information:

Appendix G: Participant Information Sheet (Chapter 6)

Diary Study – Participant Information Sheet

Study Title: Post-Task Latent Error Detection in UK Naval Aircraft Maintenance

The following Participant Information Sheet has been prepared iaw MoD Research Ethics Committee (MoDREC) guidelines. Please read the following information carefully before agreeing to take part in this research.

What is the purpose of the research?
Human error is inevitable and a daily occurrence, and is the most significant factor in aircraft safety-related occurrences. This is well known in the Fleet Air Arm, for which we are very proactive in removing error (or reducing the likelihood) through the competency of our people and via careful adherence to rules and procedures. A task carried out in error inadvertently creates a latent error that can result in a future undesirable outcome if the error is not detected later. Detection of typical latent errors, post-task completion, has been observed amongst UK naval air engineers and is reported to be a result of some seemingly spontaneous recollection of past activity. This diary study is trying to understand the nature and extent of latent errors that are detected post-task completion so that interventions can be designed to help enhance their detection.

Who is doing this research?
The researcher is a serving Air Engineer Officer who is sponsored by the Royal Navy.

Why have I been invited to take part?
Research is looking at naval air engineers initially but will branch-out to other areas of the Fleet Air Arm. As part of this research, you have been selected randomly from the squadron manpower list to participate in an anonymous diary study that will record the self-detection of latent errors.

Do I have to take part?
You do not have to participate in this research if you do not want to.

What will I be asked to do?
You will be briefed on the purpose of the research and how your data will be used before starting the study. The researcher will give the brief. After the brief, you will be asked to complete a simple questionnaire to baseline the study, a participant register and consent form. The register will capture the following information, which is needed to help analyse the collected data: rank; trade; age; and sex.

The register will be kept separate from your signed consent form. You will be given an anonymous participant number to write on a diary booklet that you will be given. It should take no longer than 2 minutes to complete the questions in the diary for each occasion you experience a post-task latent error detection event. The study will take place in your normal work environment and will continue until you have recorded 5-10 latent error examples, or a maximum of 2 months has passed. There are no additional time or travel commitments and no errors that result in injury to personnel or damage to equipment are to be recorded in the diary. **NB: Normal occurrence reporting procedures remain extant throughout.**

When you have completed 5-10 error examples, you will mail your diary direct to the researcher in the supplied pre-paid envelope.

What is the device or procedure that is being tested?
There are no devices or procedures under test other than those already available in your normal workplace environment.

What are the benefits of taking part?
The aim of this research is to help enhance the self-detection of latent errors that could otherwise pass undetected. Your participation will make an important contribution to the understanding of how latent errors are detected.

What are the possible disadvantages and risks of taking part?
This research has been assessed as low risk using the MoD Research Ethics Committee guidelines and Southampton University has provided ethical approval. Your involvement does not pose any danger and will not cause any impact on your Service career. As a reminder, the Royal Navy operates a Just Culture that applies equally to this research when providing essential safety-related information.

Can I withdraw from the research and what will happen if I don't want to carry on?
You are free to withdraw from the diary study at any time and you are not required to give a reason.

Are there any expenses and payments that I will get?
The diary study is voluntary and thus no additional incentives are available.

Whom do I contact if I have any questions or a complaint?
The researcher can be contacted directly if you have any questions. In the case of a complaint or other concern, please contact your AEO in the first instance.

What happens if I suffer any harm?
This research has been assessed as low risk. You should not be exposed to any physical harm through this diary study and you are not to record any latent error examples that may cause you stress.

What will happen to any samples I give?
You are not required to provide samples.

Will my records be kept confidential?
All information provided will be treated in strict confidence. To preserve anonymity, your name will not be recorded with the collected data and any identifying information relating to organisations, squadrons, specific locations and aircraft will not be published.

Who is organising and funding the research?
Research is organised by the researcher who is a serving AEO. The Royal Navy has funded this research.

Who has reviewed the study?
Southampton University Ethics Committee, Navy Command HQ and the RNFSC have reviewed this study.

Where can I get further information and contact details?
Your AEO has been briefed on the purpose of this research and scope of the diary study. The researcher can be contacted as follows:

Appendix H: Participant Information Sheet (Chapter 7)

Intervention Study – Participant Information Sheet (PIS)

Study Title: Individual Latent Error Detection in Naval Aircraft Maintenance

The following Participant Information Sheet (PIS) has been prepared iaw MoD Research Ethics Committee (MoDREC) guidelines. Please read the following information carefully before taking part in this research.

What is the purpose of the research?
Human error is inevitable and the most significant factor in aircraft related safety occurrences. We all suffer errors and this is a daily occurrence, for which a maintenance task that is inadvertently carried out in error creates a latent error that can result in a future safety issue if the error is not detected later. Air engineers have been shown to self-detect their latent errors through the recall of past activity. This happens post-task completion and can appear to be completely spontaneous. The self-detection of latent errors post-task completion is completely separate to detecting errors by following a process, mandatory checklist or via a supervisory check. This study is testing several intervention techniques designed to help promote the recall of latent errors, which may be present in completed maintenance activities.

Who is doing this research?
The researcher is a serving AEO who is sponsored by the Royal Navy through their elective studies programme with Southampton University.

Why have I been invited to take part?
The RNAESS is being used to test several intervention techniques using students attending career courses. This is so that the interventions can be tested in a controlled and safe environment prior to use in operating squadrons.

What will I be asked to do?
The study will take place at 760 and 764 Squadrons where training will be carried as normal. After completing a practical task, you may be asked to try an intervention technique. Your instructor will explain the intervention to you, which will be separate to the rules and procedures you have already been taught as part of your course. You must be alone when you try the technique to avoid distraction, after which you report back to your instructor who will ask you a series of short questions to gauge how useful you found the technique. Each technique is very simply, quick and will not impact any part of your course assessment. Your data will then be used to determine which technique is most effective and could be used in operating squadrons.

You will be briefed on the purpose of the research and how your data will be used. After the brief, you will be asked to complete a simple questionnaire to baseline this study against other studies that have analysed human error. Southampton University and MoD ethics committees require a consent form to be completed, which simply records that you agreed to participate in this study and so it will not be linked to your data, as there is no requirement to do this. Your course officer will also complete a register of participants to record the course number, rate, sex and age of participants, which is needed to analyse collected data. As your data is anonymous, your course officer will issue you a participant number, which you need to include with your feedback to your instructor.

What is the device or procedure that is being tested?
There are no devices or procedures under test other than those already available in your normal workplace environment.
What are the benefits of taking part?
The aim of this study is to help enhance individual detection of latent errors that could otherwise pass undetected in routine everyday maintenance-related tasks, despite doing your best to avoid an error. Your feedback on the intervention techniques will help decide which one(s) should be used in live squadrons

What are the possible disadvantages and risks of taking part?
This research has been assessed as low risk using the MoD Research Ethics Committee guidelines and Southampton University has provided ethical approval. Your involvement does not pose any danger and will not cause any impact on your training or practical assessments.

Can I withdraw from the research and what will happen if I don't want to carry on?
You do not have to participate in this research if you do not want to and you are free to withdraw from the study at any time.

Are there any expenses and payments that I will get?
The study is voluntary and within the scope of your career course thus no additional incentives are available.

Whom do I contact if I have any questions or a complaint?
The researcher can be contacted directly if you have any questions. In the case of a complaint or other concern, please contact your course officer in the first instance.

What happens if I suffer any harm?
This research has been assessed as low risk. You should not be exposed to any physical harm or stress through this study.

What will happen to any samples I give?
You are not required to provide samples.

Will my records be kept confidential?
All information provided will be treated in strict confidence. To preserve anonymity, your name will not be recorded with your data and any identifying information will be removed.

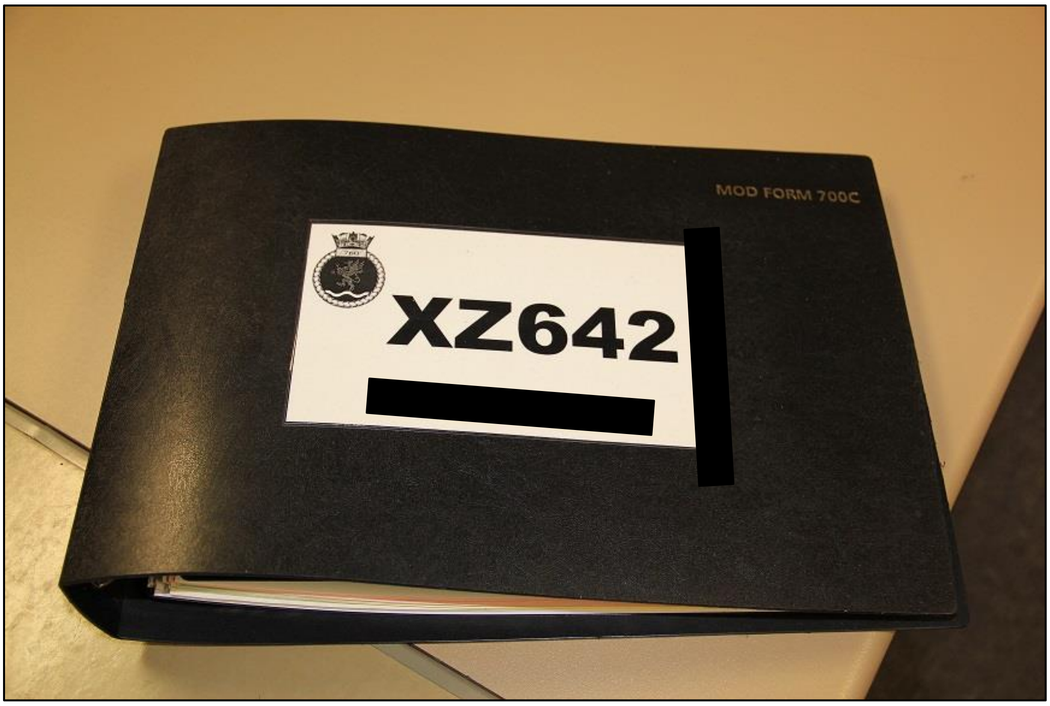
Who is organising and funding the research?
Research is organised by the researcher who is a serving AEO. The Royal Navy has funded this research under its elective studies programme.

Who has reviewed the study?
Southampton University Ethics Committee, RNAESS MAT Hd and RNAESS CO have reviewed this study.

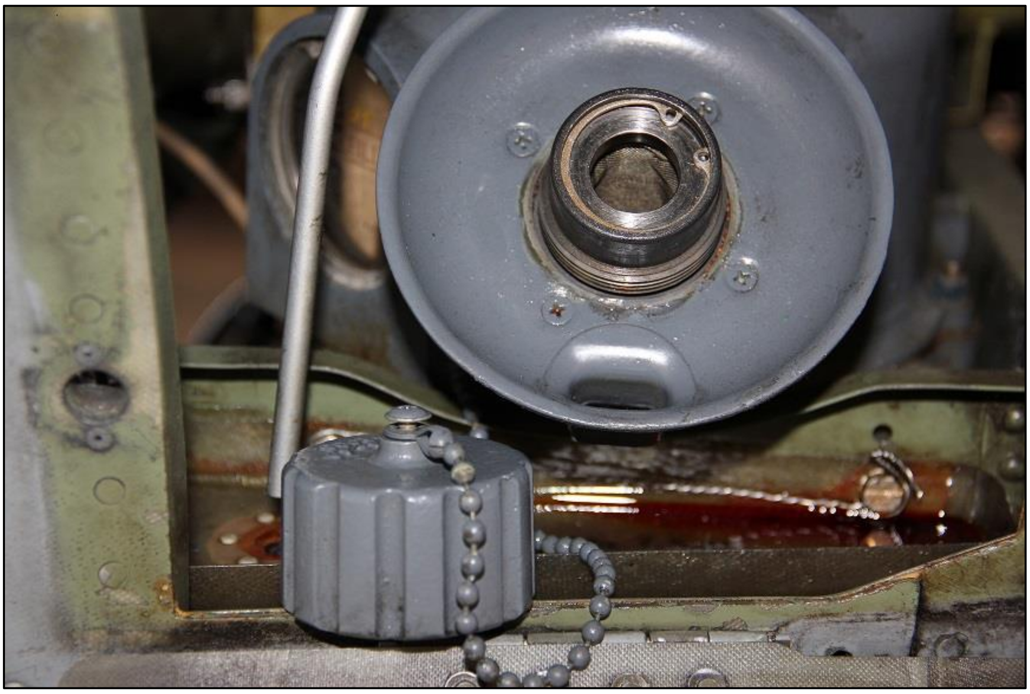
Where can I get further information and contact details?
Your course officer has been briefed on the purpose of this research and scope of the study. The researcher can be contacted as follows:

Appendix I: Example picture flash card for an operative (Chapter 7)

Appendix J: Example picture flash card for a supervisor (Chapter 7)

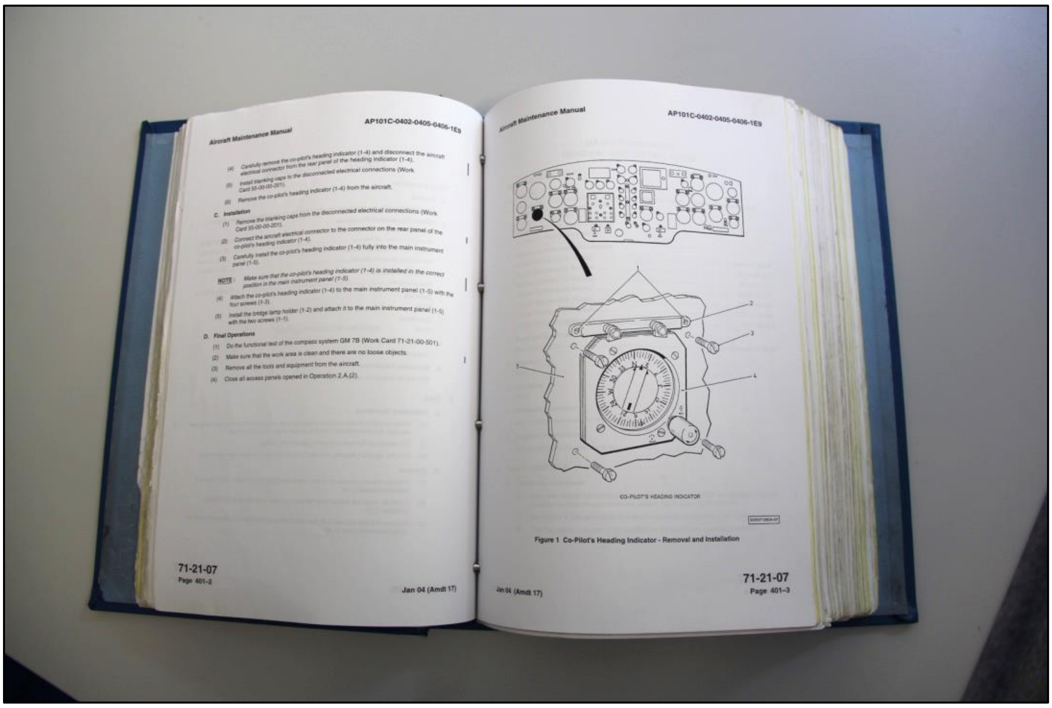


Appendix K: Example word & picture flash card for an operative (Chapter 7)



Filler cap

Appendix L: Example word & picture flash card for a supervisor (Chapter 7)



Maintenance checks

Appendix M: I-LED Study – Observer Form (Chapter 7).

SQUADRON:	**COURSE NO:**
PARTICIPANT NO:	**DATE:**
TASK:	**NO. OF PREDICTED ERRORS:**
INTERVENTION USED:	**BOOKLET NO. (if applicable):**

Please check the participant took their time with the intervention and were alone.

Q1. Number of participant errors observed by instructor:

Q2. Number of latent errors detected by the participant using the intervention:

Q3. For each detected latent error, please record the specific cue (contained within the intervention technique) that triggered the latent error recall. Specific cues are 'stop', 'look', 'listen', a particular word or picture:

Cue	Latent Error Detected	Cue	Latent Error Detected
E.g. Filler cap	Oil filler cap left off	3.	
1.		4.	
2.		5.	

Q4. Time lapse between task completion and intervention technique? ___________ (Exact time or within nearest 5 mins)

Q5. Where did the participant try the intervention?

- AMCO ☐
- Hangar ☐
- Line ☐
- Maintenance office ☐
- Crew room ☐
- Issue centre ☐
- Storeroom ☐
- In aircraft ☐
- Workshop ☐
- Passageway ☐
- Classroom ☐
- Other (please specify) ☐

Q6. On checking their work, was the latent error:

Error 1: Real ☐ False Alarm ☐
Error 2: Real ☐ False Alarm ☐
Error 3: Real ☐ False Alarm ☐
Error 4: Real ☐ False Alarm ☐
Error 5: Real ☐ False Alarm ☐

Q7. Participant alone when using the intervention? Yes ☐ No ☐

Q8. The intervention was effective: Yes ☐ No ☐

Please use for any additional information:

Appendix N: Example SLL poster in use on aircraft squadrons.

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