HUMAN PERFORMANCE IN AIR TRAFFIC CONTROL

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Abstract

Air Traffic Controllers (ATCOs) are responsible for the safety and efficiency of all air traffic. It is essential that controllers maintain a consistently high standard of human performance in order to maintain flight safety. Knowledge of human factor influences on controller performance is critical to understand and mitigate threats to performance.

Previous research has largely focused on the association between single factors and performance, which has resulted in a comprehensive understanding of single factor influences. In current control environments however, the residual threats for incidents often result from the interaction of multiple human factors and the resulting cumulative impact on performance. This thesis describes a set of studies that investigate the relationship between multiple, co-occurring factors, and the association with human performance. Findings contribute further understanding of multifactor combinations and associations with human performance, and provide novel and practical recommendations for the mitigation of multifactor influences on controller performance.

A literature review, incident report analysis and survey of air traffic professionals confirmed that a majority of research approaches were fundamentally single-factor in nature, which is out of step with real air traffic management (ATM) contexts. In addition, findings confirmed that multiple factors co-occur in an air traffic control (ATC) environment, and are associated with controller performance. An off-line experiment using students as participants investigated the relationship between a set of human factors and the association with performance. Results indicate that several factors known to be associated with controller performance do co-vary and factors may interact to produce a cumulative influence on performance. An interview study with en-route controllers contributed to an understanding of mitigation strategies of multifactor influences.

The research presented in this thesis has contributed findings that have both theoretical and practical implications. This research has addressed long-standing gaps within human performance literature and contributed new understanding to the complex field of human performance in air traffic control. Findings suggest that factors do co-occur in ATC, and interact to negatively influence performance, pushing controllers to the edge of performance. This research argues for a more ecologically valid

investigation of real-world systems using multiple factors rather than the traditional one or two-factor paradigms. In addition, this research investigation has contributed novel understanding of mechanisms which may mitigate multifactor influences and has developed practical recommendations for aviation personnel that may be used to support performance, thereby preventing performance decline, with important implications for maintaining and improving safety within the ATC domain.

Publications

Journal papers and conference proceeding papers by the author of this thesis have been completed through the period of this PhD research. These are listed below:

Journal papers

Edwards, T., Sharples, S., Wilson, J. R., and Kirwan, B. (2012). Factor interaction influences on human performance in air traffic control: The need for a multifactorial model. *Work: A Journal of Prevention, Assessment and Rehabilitation, 41(1)*, 159-166.

Millen, L., Edwards, T., Golightly, D., Sharples, S., Wilson, J. R., and Kirwan, B. (2011). Systems change in transport control: applications of cognitive work analysis. *The International Journal of Aviation Psychology, 21(1)*, 62-84.

Conference proceedings

Edwards, T., Sharples, S., Wilson, J. R., and Kirwan, B. (2012). The need for a multi-factorial approach to safe human performance in air traffic control. *Proceedings of the 4th AHFE International Conference, 21-25th July, San Francisco: USA.*

Edwards, T., Sharples, S., Wilson, J. R., and Kirwan, B. (2010). The need for a multifactorial human performance envelope model in air traffic control. *Presented at the HCI-Aero 2010 conference, 3rd-5th November, Cape Canaveral: USA*

Edwards, T., Sharples, S., Wilson, J. R., Kirwan, B., and Shorrock, S.T. (2010). Towards a multifactorial human performance envelope model in air traffic control. *Presented at the Eurocontrol/FAA research and development conference, 19th-20th October, Brétigny-sur-Orge: France*

Sharples, S., Edwards, T., and Balfe, N. (2012). Inferring cognitive state from observed interaction. Proceedings of the 4th AHFE International Conference, 21-25th July, San Francisco: USA.

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Glossary

Air Navigation Service provider (ANSP): A body that manages flight traffic on behalf of a company, region or country

Air Traffic Control (ATC): A service operated by appropriate authority to promote the safe, orderly and expeditious flow of air traffic

Air Traffic Control Sector: A defined airspace region

Air Traffic Control Unit: Three types of air traffic control: Tower, approach and en-route

Approach Control: The unit responsible for controlling traffic departing from, or arriving to, airports

En-route control: The unit responsible for controlling traffic at cruising level.

Accept departing aircraft from approach control, and pass arriving aircraft to approach control

Incident: An occurrence, other than an accident, that affects the safety of the operation of the aircraft.

On the job training instructor (OJTI): A qualified controller who monitors and supports trainee controllers during the control task

Tower control: Responsible for aircraft on the ground, as well as arriving and departing aircraft.

Chapter 1. Introduction

1.1 Research background

Air traffic control (ATC) is a safety critical environment (Chang & Yeh, 2010). Air Traffic Controllers (ATCOs) are responsible for the safety and efficiency of all air traffic. Unlike other safety critical industries, there are no *physical* barriers or defence that protect aircraft in flight. It is therefore essential that controllers maintain a consistently high standard of human performance in order to maintain flight safety. Threats to human performance must be understood and mitigated to maintain flight safety and efficiency in an environment of growing traffic and performance demands.

With a large potential for incidents, Kirwan (2011) suggests that Air Traffic Management (ATM) is remarkably reliable. However, when aircraft have breached standard regulated minima, termed an 'incident', human error has been attributed as a primary or secondary cause in 75-90% of cases (Mackieh & Cilingir, 1998). Human factors (such as workload, fatigue, inadequate communications) are "major determiners of a human error" (Park & Jung, 1996, p330) and have been repeatedly shown to negatively affect human performance (Chang & Yeh, 2010; Park & Jung, 1996). A comprehensive and context-specific knowledge of the association between human factors and human performance is therefore critical in addressing safety incidents in air traffic control.

For more than three decades, human performance and error research has investigated the influence of single human factors (such as fatigue or mental workload) on human performance in a wide variety of settings (Loft, Sanderson, Neal & Mooij, 2007; Svensson, Angelborg-Thanderz, Sjoberg, & Olsson, 1997). For example, Schroeder, Rosa and Witt (1998) investigated the effects of fatigue on performance in air traffic controllers. Results showed that individual performance measures declined in association with increased self-reported fatigue as controllers progressed through the four day schedule. Such focused research has resulted in a body of literature and comprehensive understanding of the association between single human factors and performance. As a result of this knowledge, within the ATC context, single factor issues such as fatigue, vigilance, and situation awareness problems have now largely been designed out or sufficiently mitigated by design, operational and Human Factors and Safety expertise.

However, in current control environments factors do not occur in isolation. It is colloquially recognised that multiple human factors may be present at any one time. For example, a high workload may be experienced by a controller who is fatigued or stressed, and co-occurs with inadequate communication (e.g. incorrect phraseology) or teamwork (e.g. unexpected handovers). These co-occurring factors may interact to negatively influence controller performance differently to that of single factors alone. This is supported by the recognition that ATC incidents are often reported as being multi-causal in nature, or are seen as having no direct causes but many contributors, as highlighted by so-called 'Swiss Cheese' and Resilience Engineering models (e.g. Hollnagel, Woods & Leveson, 2006; Reason, 1990). The residual threats for incidents therefore frequently result from the interaction of multiple human factors and the resulting cumulative impact on performance.

However, relationships and interactions between co-occurring human factors, and the resulting association with human performance, have received scant attention in the literature (Glaser et al., 1999, Wilkinson 1969). In the late sixties, Wilkinson (1969) recognised this lack of focus on multiple factors, and suggested "this cannot be through ignorance of the fact that stresses do occur in combination... [there is the] impression that the combined effect of two or more can be assessed by adding their single effects. This is not so." (p266, 276). However, to date, research that has investigated human factor relationships is sporadic and findings are controversial. Even less research has been conducted that is specific to the ATC context. There is therefore a gap in understanding of the relationships and potential interaction of multiple human factors and the subsequent association with human performance.

There is a growing realization within the literature that this research gap may have limited an ecologically valid understanding of the occurrence of human factors and the association with human performance in an air traffic setting (Cox-Fuenzalida, 2007). In addition, limited knowledge of the association of multiple human factors and human performance and error has limited the study of performance decline and human error to a reactive, retrospective analysis of likely causes (Hollnagel, Kaarstad & Lee, 1999) as opposed to proactive strategies for prevention of performance decline. In turn, this affects the reliability and effectiveness of compensation strategies to protect controller performance and prevent performance decline.

It is therefore critical that the current research focus is extended from single factors to multiple factors, and contribute to this gap in understanding. Several calls for research on the interrelations between human factors that influence performance highlight the necessity and importance of addressing this research gap (Chang & Yeh, 2010; Murray, Baber, & South, 1996). Research in this thesis into multifactor relationships and associations with performance will provide value by addressing the current gap between literature and real-world concerns and furthering understanding of the occurrence of human factors in an ATC setting. In addition, understanding of the nature of human factor influences in association with performance decline will be extended, which may facilitate the development of recommendations for reducing negative influences.

This thesis is specific to en-route ATC and the focus of research is human performance.

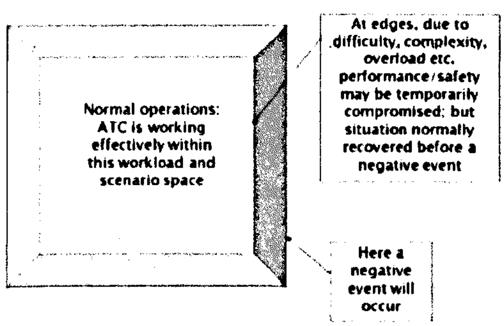
1.2 Motivation for this thesis

This PhD was sponsored by European Organisation for the Safety of Air Navigation (EUROCONTROL). The research described in this thesis was motivated by EUROCONTROL's requirement to gain further understanding of the co-occurrence of multiple factors in an ATC environment and the association of multifactor combinations with controller performance. The need for this research arose after EUROCONTROL identified that recent performance-related aviation incidents in Europe were frequently associated with multiple, co-occurring human factors. Informal discussions between aviation experts at EUROCONTROL and incident investigators revealed a colloquial belief among many aviation experts that performance-related incidents did not generally occur as a result of a single factor; instead a combination of factors were believed to most frequently influence performance-related incidents. EUROCONTROL attempted to gain information on multifactor combinations and the association with controller performance, but it was recognised that previous research was sparse in relation to these specific areas of interest.

In addition, EUROCONTROL found little relating to recommendations for mitigating multifactor influences on performance.

EUROCONTROL therefore funded this PhD research to improve understanding of the relationships that existed between co-occurring multiple factors, as well as the association between multifactor influences and performance. EUROCONTROL identified an initial set of factors to indicate the expected scope of this research. EUROCONTROL were also interested in the association between multiple factor influences and the conceptual notion of the 'edge of performance'. The 'edge of performance' is a notion that performance may reach a specific limit or boundary, after which a decline in performance may occur. The initial conceptualization of the edge of performance was provided by EUROCONTROL (Figure 1.1).

Figure 1.1. Initial representation of a the 'edge of performance'



Although basic, Figure 1.1 provides further details of the notion of a 'performance edge'. The middle of the space represents safe performance. The first edge represents the edge of performance, at which point performance may begin to degrade. Without intervention, performance may continue to degrade and reach the edge of the outer edge, at which point it is hypothesised that there is an increased likelihood of human error or even a performance-related incident. A final interest of EUROCONTROL was the recommendations for the mitigation of multifactor influences on performance.

1.3 Thesis research question and aims

The research question and associated research aims in this thesis were developed in collaboration with EUROCONTROL and in accordance with EUROCONTROL's interests. The thesis investigates the research question "Can we improve understanding of multiple factor effects on ATCO performance and provide recommendations for mitigating these influences?" To address this question, six research aims were developed:

1. **Identify a set of human factors that influence air traffic controller (ATCO) performance**

To begin the project, it was necessary to identify a set of human factors that were present in an ATC environment, and confirm the factors that were associated with controller performance. This aim was initially informed by a suggested set of nine human factors from human factors experts within EUROCONTROL. A literature review, analysis of 272 incident reports and subject matter expert opinion was used to confirm the presence of these factors within ATC settings, and the association with performance. From the results of the literature review and incident reports, nine primary factors were identified and reported to significantly affect ATCO performance.

2. **Select a sub-group of factors that may be included in further studies**

It was considered impractical to include all nine human factors in future studies of the relationships and interactions between factors. A smaller sub-group of factors were identified for inclusion in future research. The selection was based on the frequency and negative association with controller performance (the more frequently negatively influencing factors were selected), in addition to pragmatic considerations such as resources and measurement of the factors.

3. **Investigate the relationships and potential interactions between multiple, selected human factors**

The thesis aimed to investigate the relationships and potential interactions between the selected sub-group of human factors. Incident report analysis findings, findings from a survey-questionnaire with air traffic professionals and findings from an experimental study contributed to addressing this aim.

4. **Investigate the association of multiple factor relationships with human performance**

This thesis aims to investigate the link between multiple factor relationships and performance. The investigation used an experimental study in a laboratory setting to facilitate adequate control of variables and appropriate methodological design.

5. **Inform fundamental understanding of ATCO behaviour at the edge of performance**

The research aimed to describe the manifestation of the association between multiple factors and performance by investigating behaviour at the limits of performance, as it is understood by EUROCONTROL. Findings improved knowledge of behaviour at the edge of performance as well as the performance decline process, and therefore further understanding of the possibilities of protecting and supporting performance prior to a decline.

6. **Identify indicators of potential performance decline**

A final aim of the research was to identify indicators that may indicate when a controller was reaching their personal limits of performance. Indicators may be either internal, subjective experiences or overt, observable indicators. Research findings may have a practical relevance to the identification of controllers' reaching the limits of performance and the application of supportive strategies as prevention to performance decline.

1.4 Initial selection of factors for investigation

It was recognised that the focus on multiple human factor combinations in ATC could be a wide area of research. To narrow the scope of the research, EUROCONTROL provided a set of nine factors that were required to be included for consideration in the initial stages of research. These factors were: attention, communications, fatigue, mental workload (referred to throughout this thesis as 'workload') situation awareness (SA), stress, teamwork, trust and vigilance. The researcher was confident that EUROCONTROL aviation experts were familiar with the dominant factors that occurred within an ATC setting to negatively influence performance and had selected the appropriate factors for inclusion. The factor set proposed by EUROCONTROL was later refined based on study findings.

It is worth noting that attention, vigilance and SA are interrelated constructs. However, these are also noted in the literature to be distinct (e.g. Endsley, 1988; Eysenck, 2001; Mackworth, 1957) and so are initially treated as separate factors. The differentiation between these related concepts is explained further in section 2.2.2.

1.5 Overview of thesis

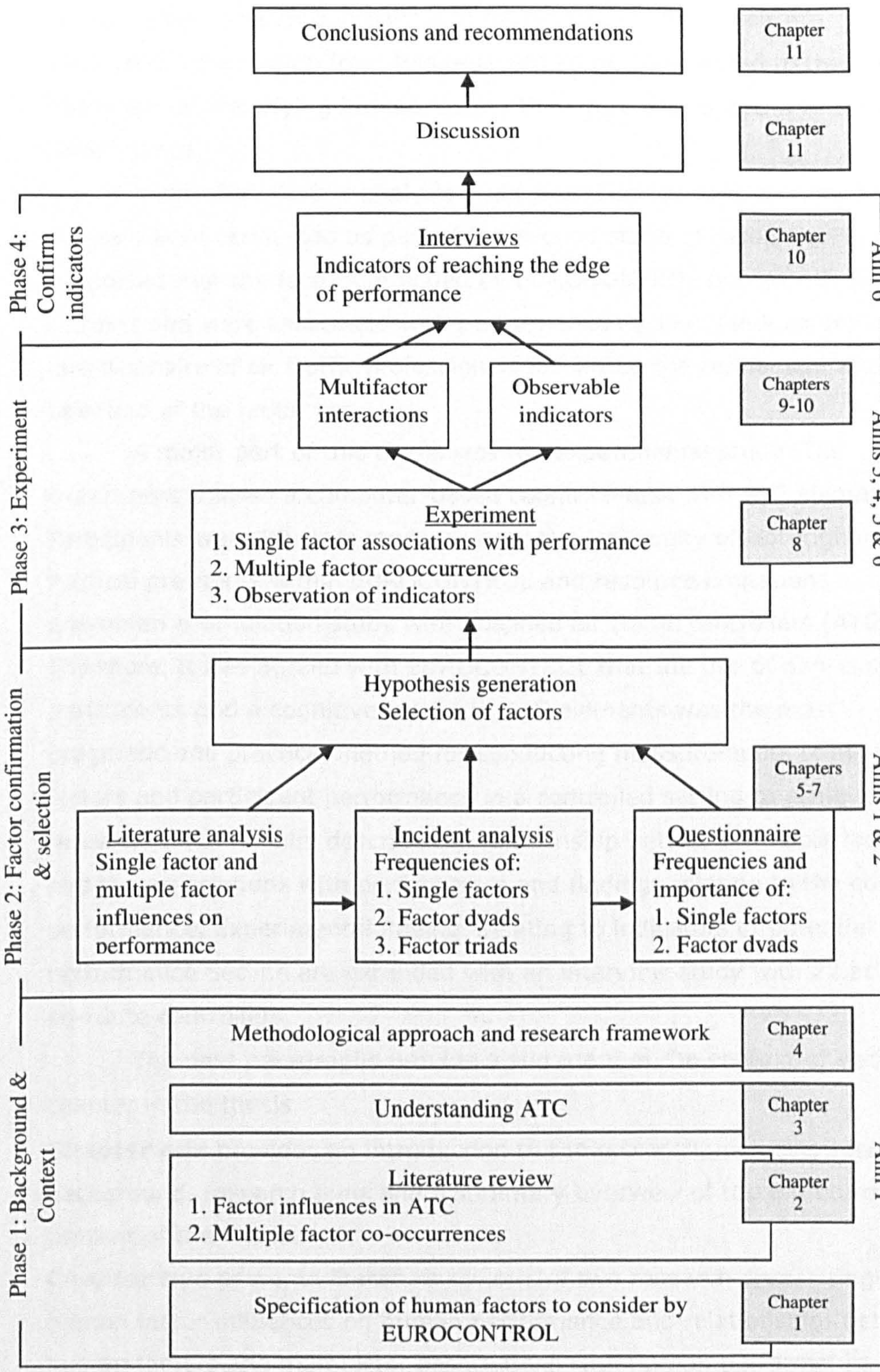
This thesis is presented in eleven chapters. Table 1.1 presents an overview of the correspondence between research aims and the thesis chapters and research activities that address each aim.

Table 1.1. Correspondence of thesis aims with thesis chapters and research activities

	1	2	3	4	5	6	7	8	9	10	11
Thesis Aim	Introduction	Literature review of human factors and human factor relationships in ATC	Understanding ATC	Methodological approach and research framework	Literature metrics and incident report analysis	Expert knowledge elicitation of human factors in relation to performance	Selection of experimental factors	Experiment method	Experiment results of multiple factor relationships and associations with performance	Indicators of potential performance decline: Results from experiment study and interview study	Discussion and conclusions
1. Identify a set of human factors that influence air traffic controller (ATCO) performance	X	X	X	X	X						
2. Select a sub-group of factors that may be included in further studies				X	X	X	X	X			
3. Investigate the relationships and potential interactions between multiple, selected human factors				X	X	X		X	X		
4. Investigate the association of multiple factor relationships with human performance				X	X	X		X	X		
5. Provide fundamental understanding of ATCO behaviour at the edge of performance				X				X	X		
6. Identify indicators of potential performance decline				X				X		X	

This table is supported by Figure 1.2 which presents an overview of the thesis structure and the progression of the thesis chapters.

Figure 1.2. Thesis structure and research framework



The thesis begins with a review of single factor influences on performance, and multifactor relationships in association with performance. An introduction to the ATC context is presented, followed by a description of the stages the researcher went through to become familiar with the ATC domain. The research approach and framework for the thesis are presented. Information from this research stage contributed to the first thesis aim of identifying human factors that were associated with human performance.

A literature review analysis and context-specific incident report analysis were conducted as part of the second stage of research. Findings supported that the factors provided by EUROCONTROL occurred in ATC settings and were associated with performance decline. Findings from a questionnaire of air traffic professionals facilitated the refinement and selection of the factor set.

A major part of this thesis was the experimental study. The experiment utilised a computer-based cognitive task with ATC elements. Participants were 29 male students from the University of Nottingham. Political pressures within EUROCONTROL and resource limitations prevented a simulation study with qualified air traffic controllers (ATCOs). Therefore, it was agreed with EUROCONTROL that the use of non-expert participants and a cognitive task with ATC elements was the most pragmatic and practical method for conducting measurements of human factors and participant performance in a controlled setting to achieve the research aims. Results describe the relationship between multiple factors and the associations with performance and findings relating to the edge of performance. Experimental findings relating to indicators of potential performance decline are extended with an interview study with 22 active en-route controllers.

The next paragraphs provide a summary of the context of each chapter in the thesis.

Chapter one provides an introduction to the research, including research background, research aims and a summary overview of the structure and content of the thesis.

Chapter two presents literature reviews of two research areas: single human factor influences on human performance and relationships between human factors and multifactor associations with human performance. The reviews were focused on human factors that were selected by EUROCONTROL for inclusion in the initial research stage.

Chapter three provides an introduction to air traffic control. A description the stages the researcher went through to familiarise herself with the air traffic control domain is described, and features of the ATC domain that are pertinent to the design of future studies are highlighted.

Chapter four presents the research approach and framework of the thesis. Together, these four chapters provide comprehensive information on the research background and context.

Chapter five provides a detailed description of a literature review analysis and analysis of European ATC incident reports.

Chapter six presents an expert knowledge elicitation study that utilised a survey questionnaire of air traffic professionals. A refinement of the factor set is described based on study findings.

Chapter seven summarises the findings from the previous three research studies (literature analysis, incident report analysis and survey questionnaire). A sub-set of human factors is selected.

Together, chapters five, six and seven document the progression of the confirmation, refinement and selection of a set of human factors that is negatively associated with controller performance, to be used in the next research phase. The first two thesis aims are achieved.

Chapter eight describes the methodological development and design of an experiment study. A cognitive task with en-route air traffic control elements was utilised with students from the University of Nottingham as participants.

Chapter nine presents the results of the experimental study relating to multifactor relationships and associations with performance, as well as findings of ATCO behaviour at the edge of performance. These chapters address the third, fourth and fifth aims of the thesis.

Chapter ten presents experimental results relating to the association between observed participant behaviours as indicators of potential performance decline. The chapter then describes an interview study conducted with 22 active en-route controllers from Maastricht upper area control centre that investigates controllers' use of indicators of potential performance decline. The results address the sixth aim of the thesis.

Chapter eleven provides a discussion of the research presented in this thesis. The chapter considers findings from the relevant studies in relation to each thesis aim. Limitations of the research are described, and areas of further research are recommended. Recommendations resulting from research findings are provided. The thesis finishes with a concluding statement.

Chapter 2. Literature review of human factors in relation to performance and human factor relationships in air traffic control

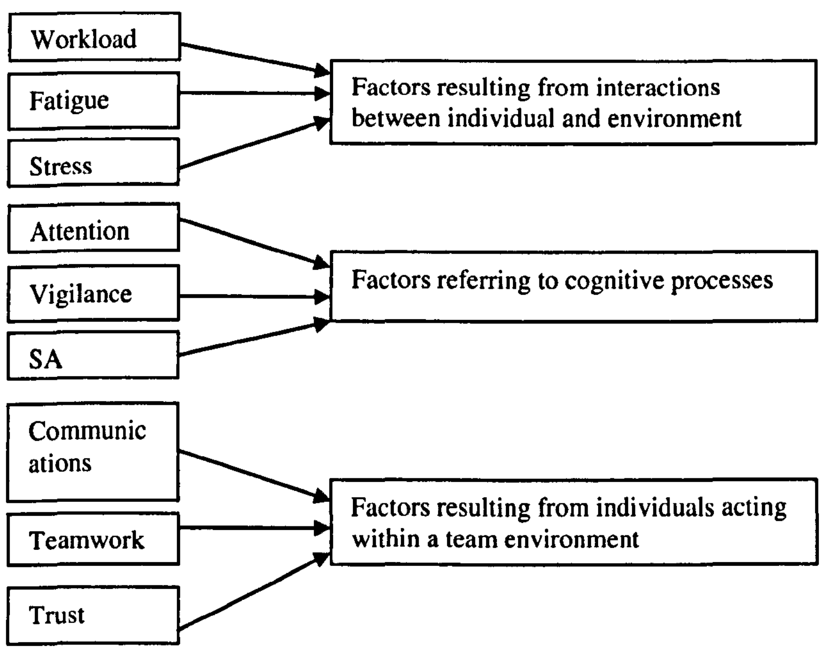
2.1 Chapter overview

This chapter summarises the literature reviewed on nine human factors (workload, fatigue, stress, attention, vigilance, SA, communication, teamwork, trust) that are proposed to occur in ATC environments. The chapter is divided into two main sections. Section 2.2 provides a review of the critical human factors within the ATC domain, and research findings relating to the association between each factor and controller performance. Research gaps are highlighted and where appropriate, suggestions of the potential contributions of future research are outlined. For each factor, the construct is presented, followed by a discussion of the role of the factor within the ATC domain. Finally, literature that has examined the relationship between the factor and controller performance within the ATC domain are considered. Section 2.3 presents a literature review of findings of the relationships between human factors and, when possible, the subsequent multifactor association with performance. A comprehensive review of human factor relationships, to the current author's knowledge, has not been previously completed; the review therefore has the benefit of identifying recurring findings as well as controversies and gaps in the literature. The review concludes that the nine pre-selected factors have been reported to be negatively associated with human performance. In addition, relationships between factors were reported, although controversy between some research findings was identified.

Each factor is defined according to an accepted, peer-reviewed definition. Although these definitions may be open to argument (e.g. Dekker & Hollnagel, 2004; Matthews, 2002), previous research is noted to have been hampered by a lack of agreement on factor definitions (Costa, Roe, & Taillieu, 2001). In order to avoid these debates, working definitions of each factor have been generated from a consideration of the theory of the factor construct, definitions in the literature, and practical application to the ATC domain. These working definitions will be utilised throughout the remainder of the research.

It was acknowledged that the factors' constructs were qualitatively different. Resulting from a pattern that emerged in the literature, the nine factors have been grouped into three categories: factors resulting from an interaction between individual and environment (workload, fatigue, stress), factors referring to cognitive processes (attention, vigilance, SA), and factors resulting from individuals acting within a team environment (communications, teamwork, trust). The categories facilitate the presentation of the relevant factors. Figure 2.1 summarises how the factors have been categorised.

Figure 2.1. Categorisation of factors based on data trends identified in the literature review



2.2 Single factors and associations with performance

2.2.1 Factors resulting from interactions between individual and environment

Three human factors were categorized as a product of the interaction between an individual and the environment: workload, stress and fatigue.

2.2.1.1 Workload

Mental workload (referred to throughout this thesis as 'workload') is a multifaceted construct (Athenes, Averty, Puechmorel, Delahaye, & Collet, 2002), dominant within human factors literature (i.e. Wickens, Mavor, & McGee, 1997). An initial distinction can be made between physical workload, associated with the physical strain placed on the human and mental workload, associated with cognitive and affective processes of the human operator (Wickens et al. 1997). As the task of an ATCO is primarily cognitive (Bonini, 2005), this review will only focus on mental workload. Although there is no universally accepted definition, mental workload is commonly described as is "an intervening construct" (Wickens et al., 1997, p114) that is a product of the interaction between objective task demands and spare cognitive resources available to an individual (Parasuraman, Sheridan & Wickens, 2008; Lamoureux, 1999). A distinction is therefore made between taskload and experienced load (Glaser et al., 1999). Taskload, refers to the actual demands of a specific task or situation. Experienced load refers to an individual's perception of the demands imposed by the objective work and the capability of the individual to meet those demands. The relationship between taskload and subjectively experienced workload is complex and can be linear or non-linear (Djokic, Lorenz, & Fricke, 2010). The relationship can also be mediated through variables including individual differences and active task management strategies (Djokic et al., 2010; Wickens et al., 1997).

Resources theories explain workload through the concepts of attentional capacity and cognitive resources (Wickens 1984; Young & Stanton, 2002). Resources theories assume that each individual has limited cognitive resources. Resources are required to be allocated to tasks in order for the operator to perform the task (Smit et al., 2004; Wickens, 1984; Wickens et al., 1997). Resource allocation is dependent on task demands; the higher complexity of the task the more resources will be required (Wickens, 1984). The allocation of resources, in relation to the resources available, contributes to the perception of subjective workload. Wickens' (1984) suggests that when tasks require less resources than the operator has available, a region of spare capacity exists – the operator has resources spare that are not being engaged by the task. A subjective perception of low workload may be experienced when a task requires few of the available attentional resources, and spare capacity is high. In comparison, high workload may be experienced when task demands require most, if not all, available resources. If task demands require more resources that the operator has available, an overload region is said to be reached; here, the attentional resources applied to the task may be insufficient to meet tasks demands, which is often associated with a negative subjective experience and resulting performance decline. Available resources can be depleted over time and influenced by external variables such as fatigue, stress and arousal. Resources theories may therefore explain changing perceptions of workload in relations to external influences.

"Workload is arguably one of the most important human factors issues" (Rantanen & Nunes, 2005). Extremes of workload may have negative implications for controller performance and subsequently safety. Workload also has economic implications in the ATC domain, being the primary limiting factor of increasing sector capacity (Djokic et al., 2010). Workload and workload regulation are therefore a dominant consideration within ATC. ATC-specific definitions of workload have been developed for operationalisation of workload in the field. For example, Djokic et al. (2010) defined ATCO workload as "a result of such a complex interaction between the task demand and the way the controller actively manages the situation", which acknowledges both external taskload as well as the importance of controlling strategy and compensation strategies in moderating perceived workload. Within the domain of ATC, workload drivers include environmental (extrinsic) demands, such as complexities resulting from the visual display (Athenes et al., 2002; Wickens et al., 1997), and task (intrinsic) demands such as the number of aircraft under control and complexity of aircraft configuration (Vogt, Hagemann, & Kastner, 2006). The controllers' selected control strategy can also be considered a workload driver, if a complex strategy is selected (Djokic et al., 2010). The selection of specific control strategies may increase or reduce complexity, influencing both task demands and workload. Controllers also utilise control strategies to regulate workload, mediating the relationship between task demands and subjective workload. For example, Sperandio (1971) identified that controllers utilised adaptive strategies to manage increases in traffic load by decreasing the amount of time processing each aircraft. This workload regulation enabled performance to be maintained in situations which may have led to an overload situation (Wickens et al. 1997).

Within ATC, Workload, "is still considered one of the most important single factors influencing operators' performance" (Di Nocera, 2006, p639). Frequently, extremes of workload such as underload (defined as a low level of objective and perceived task demands, easily met by individual resources) high workload (defined as a high level perceived or actual task demands, with a high level of operator effort) and overload (defined within ATC as a high complexity and/or volume of traffic where individual resources are insufficient to meet objective task demands, potentially impacting safety) have been demonstrated to be significantly negatively associated with human performance (Cox-Fuenzalida, 2007; Huttunen et al., 2011; Shaw & Weekley, 1985).

A large body of research from incident reports (i.e. Morrison and Wright, 1989) and ATC simulations has identified a negative association between high workload and controller performance (e.g. Shorrock, 2007; Morrison and Wright, 1989). Morrison and Wright (1989) conducted a frequency analysis of ATCO errors in reports contained in the NASA Aviation Safety Reporting System (ASRS). Errors such as monitoring failures and incorrect heading or altitude assignments were associated with increases in taskload factors such as traffic volume. These results suggest that high workloads, or possibly overloads, may negatively influence controller performance. However, workload was inferred from taskload factors such as traffic volume. Although this is correlated with controller workload the relationship is not simple or necessarily linear, and so workload cannot be inferred with confidence.

Experimental investigations have also identified an association between higher taskload, workload and performance decline. Schroeder and Nye (1993) utilised an ATC simulation study to investigate the effect of workload on controller performance. A significant, positive correlation was found between number of aircraft under control and the occurrence of ATCO errors, including incorrect use of radar information and coordination issues. Resource theories have been applied to explain this observed relationship as a result of task demands exceeding available recourses or compensation strategies, resulting in a rapid decline of performance (Huttunen, 2011). However, Endsley and Rodgers (1996) suggest that in some cases, the compensation strategies used by controllers to manage workload may instead result in reduced performance. Endsley and Rodgers (1996) found that under high taskloads, one of the strategies applied by controllers was to reduce the time attending to each aircraft, in an attempt to maintain awareness of addition duties. Although these adaptive strategies may have enabled the controller to manage the traffic under the high workload Endsley and Rodgers (1996) suggested that strategy itself may have contributed to controlling errors.

Underload has also been reported to be negatively associated with controller performance in the literature. In a review of ATCO operational errors, conducted as part of a larger task analysis, Redding (1992) found that errors occurred more frequently under low or moderate workload conditions, compared to high workload. In addition, Stager, Hameluck and Jubis (1989) conducted an analysis of 301 reports and reported that operating irregularities most frequently occurred during conditions of normal complexity and low or moderate workload, although limitations exist with using retrospective data, including reporting biases (Edwards, Sharples, Wilson, & Kirwan, 2012). Further research should focus on investigating in a controlled environment the frequency of ATCO errors in conditions of underload and overload.

There is a lack of common agreement regarding the mechanisms by which underload may impact performance depending on the theory utilised for interpretation (Wickens et al., 1997). Arousal theories suggest that underload may lead to lower arousal, which may limit attentional resources and create boredom and lack of motivation, resulting in errors of omission. Attentional resources theories however suggest that if preceded by a higher workload, lower workload periods will be utilised to replenish attentional resources, resulting in a reduction of attention on the current task. Further research may also facilitate the understanding of processes that result in the associated between underload and poorer performance (Wickens et al., 1997).

Transitions *between* workload extremes (high and low) have also been reported to be negatively associated with controller performance. Cox-Fuenzalida (2007) investigated the affect of workload transition in association with performance. A sample of 198 participants was placed in a low to high workload group or high to low workload group. Performance and error measures were recorded. A significant decrement was found in performance after a transition in both experimental conditions (Cox-

Fuenzalida, 2007). Although the study was not specific to an ATC domain, results suggest that workload transitions may be associated with a decline in controller performance. Further research is necessary to gain a comprehensive and ecologically valid understanding of this association in an ATC domain.

A working definition of workload that will be used throughout this thesis is 'perceived demand (amount and complexity) imposed by ATC tasks, demand on mental resources, and associated subjective perception of effort to meet demands'. This definition contains elements from the literature (subjective, perception, mental resources and effort) and has been adapted from the definition used in Skybrary, an aviation-specific resource. Therefore, this working definition is supported by previous research and relevant to the ATC domain.

In conclusion, workload is a dominant economic and safety-related consideration in the ATC domain. Throughout the literature, significant relationships between extremes of workload (underload, low workload, high workload, overload) and a decline in controller performance as well as increase operational errors, have been repeatedly reported. However, the relationship between task demands, workload and performance is highly complex and not monotonic. Controllers manage workload by employing control strategies which mediate the relationship between task demands and subjective workload, as well as the association of task demands with performance.

The mechanisms by which workload extremes may be associated with performance decline are not conclusive, although resource theories are commonly utilised to provide explanations. An emerging body of research findings suggest that workload transitions are also negatively associated with controller performance (Cox-Fuenzalida, 2007). However, this area of research has been relatively neglected compared to studies of overload (Wickens et al., 1997), and so further research is needed to comprehensively understand this relationship in an ATC environment.

2.2.1.2 Fatigue

Mental fatigue can be broadly described as "a transition state between alertness and somnolence" (Wickens et al., 1997, p341). It can be a product of sustained cognitive demands and high individual effort (Hockey & Earle, 2006), and have affective, psychological and physiological implications (Avers & Johnson, 2011). Fatigue has also been viewed as a hypothetical construct which is inferred by linking factors presumed to cause fatigue with measureable outcomes (Williamson et al., 2011). There is not one universally accepted definition. Rather, various definitions have been developed which describe specific elements or dimensions of fatigue, including the causes of fatigue (biological, task specific) (Williamson et al., 2011), the affective dimension (subjective experience and symptoms) and consequences of fatigue (physiological, performance-related) (Avers & Johnson, 2011).

Fatigue is multidimensional, and several distinctions between forms of fatigue have been identified. The focus of this review is mental fatigue. A broad distinction may be made between generalised fatigue (also termed cumulative fatigue) and task-specific fatigue (also termed transitory fatigue). A generalised fatigue state is believed to occur after prolonged mental effort or sleep disturbance (Isaac & Ruitenberg, 1999). Recovery can only be made through quality sleep (Caldwell, 2001). In contrast, task-specific fatigue results specifically from task characteristics or demands, and may be alleviated by doing a different activity (Matthews et al., 2000).

Focusing on mental fatigue, a common distinction is made in the literature between subjective fatigue and cognitive or performance-related fatigue. Subjective fatigue refers to the personal experience of fatigue and incorporates feelings of tiredness, distress, or difficulty in performing. Although subjective fatigue may be experienced, a reflection may not be seen in performance. Cognitive fatigue however, can be perceived in performance decrements on a task Fatigue then has both a subjective experience element and an objective element which is reflected in task performance (Mathews et al., 2000).

Caldwell (2001) suggests that there are three primary sources of fatigue frequently acknowledged in the literature: sleep disruption, homeostatic mechanisms including circadian rhythms, and time on task effects. Due to space limitations, only these three commonly identified sources have been selected for review.

Sleep disruption, typically referred to as receiving less than 7 hours sleep a night (Wickens et al., 2004) is a specific issue of concern within the air traffic control domain (Della Rocco, 1999). Air traffic controllers are required to work a rotating shift system which can result in poorer sleep, and over time, a cumulative build up of fatigue (Isaac & Ruitenberg, 1999).

Sleep disturbance has been documented to have an antagonistic effect on cognitive abilities (Baranski, Pigeau, & Angus, 1994) including visual perception and sustained attention and is associated with micro sleeps during session, making this a critical concern in ATC settings. Ribas and Martines (2009) asked a sample of 30 male ATCOs from a Brazilian ATC centre to complete the self report Epworth sleepiness scale on the second night of a set of night shifts. The results reported that 65% of ATCOs experienced excessive sleepiness. Although these results cannot be generalised to other centres, the results of the study highlight the potential for fatigue issues in an ATC centre.

A second source of fatigue frequently identified in the literature is the disruption of circadian rhythms (Gunzelmann et al., 2010). Circadian rhythms relate to an endogenous, physiological pattern of a day-night cycle (Gunzelmann et al., 2010) whereby arousal rises progressively during the day to reach a maximum in the late afternoon, prior to declining to the lowest point in the early morning. This natural pattern of arousal change can have influences on performance, with errors and incidents rising when circadian-related arousal is at the lowest point.

Time on task has been repeatedly documented to be a source of fatigue (van Dongen, Belenky, & Krueger, 2011; Isaac & Ruitenberg, 1999). This effect possibly results from "a progressive increase in the effort required to deploy cognitive resources" (van Dongen et al., 2011, p128), although the mechanisms for this effect are not exactly understood. Task characteristics and external variables may modify the time on task effect. Gilbertova & Glivicky (1967) reported that the effect is enhanced during monotonous tasks, but often suppressed during demanding or novel tasks. Homeostatic and circadian processes can interact with time on task to amplify the effect.

A large body of literature confirms a negative relationship between fatigue (or the factors that cause it) and performance (Wickens et al., 2004; Williamson et al., 2011). Fatigue has been widely reported to negatively contribute to increasing incident and accident risk (Dorrian et al., 2007; Hetherington, Flin & Mearns, 2006; Hockey & Earle, 2006). Within the air traffic domain, although fatigue has been recorded in incident reports, the frequencies are relatively low (Della Rocco ,1999; Edwards et al., 2012). An incident report analysis conducted by Della Rocco (1999), revealed that out of a total of 5773 US-based ATCO-related incidents recorded between 1988 to 1996, 153 reports, or 2.7% referenced controller-related fatigue as a contributing factor to the incident. Limitations of incident report data such as the potential for a retrospective reporting bias or the lack of personal disclosure from the controller involved may influence fatigue reporting in incident report data. In spite of these limitations, Della Rocco (1999) concluded that "fatigue was reported as a performance impairing factor affecting [ATCO] personnel" (p7).

It had been suggested in the literature that individual sources of fatigue may have source-specific implications on performance. (Wickens et al., 2004). Fatigue resulting from sleep loss is a primary concern in ATC (Wickens et al., 1997). The task of an ATCO is primarily visual and demands higher cognitions such as planning and decision making, which are reported to be negatively influenced by sleep-loss related fatigue. Schroeder, Rosa and Witt (1998) conducted a field investigation into sleep patterns and performance within an en-route ATC centre. A sample of 56 ATCOs were asked to complete a sleep diary including amount and quality ratings of sleep over three weeks. Three times a day (before, at the middle and after the working shift) controllers also completed the NIOSH test battery, which included assessments of response times to: choice reaction, mental arithmetic and grammatical reasoning. The study revealed that performance declines on each of the NIOSH fatigue battery assessments were associated with reports of less sleep. However, although the NIOSH fatigue battery is a comprehensive measure of fatigue, it does not represent an ATCO's task. Therefore, it cannot be ascertained whether these performance effects would transfer to the ATC task. In addition, self-reports in the sleep diary may lead to inaccuracies or biases.

Circadian rhythm de-synchronisation as a source of fatigue has been identified to negatively influence ATCO performance (Stager et al., 1989). Stager et al (1989) investigated the conditions associated with ATCO-related incidents. A review of 301 "operating irregularities" was conducted based on time of day of occurrence. Results indicated that ATCO-related incidents occurred more frequently during early morning hours when circadian related arousal is lowest. Further research in controlled settings is required to fully understand the influence of, or relationship between, circadian rhythm-related fatigue on performance.

The relationship between fatigue and performance is complex, and has been difficult to consistently demonstrate in the literature given the

different sources and indirect relationship (Wickens et al., 2004). Matthews et al. (2000) suggests that in general, research does not reliably show fatigue effects on performance. Moderators of the relationship between fatigue and performance may contribute to this complexity.
For example, a moderating variable that has been identified is task demands; complex tasks have been reported to be sustained at a higher level of performance even when participants report subjective fatigue, compared to monotonous or simple tasks (Desmond and Mathews, 1997). Strategy change may also moderate the relationship between fatigue and observable performance as the elected strategy may compensate for fatigue-related influences. Such moderating variables contribute to the complexity of specifying the relationship between fatigue and performance.

The working definition that was selected for further use is "a physiological state of reduced mental or physical performance capability resulting from sleep loss or extended wakefulness, circadian phase, or workload (mental and/or physical activity) that can include feelings of tiredness or weariness and impair alertness and ability to perform safety related duties" (ICAO). This definition is utilised by ICAO, and so is relevant to the ATC domain. In addition, the definition acknowledges elements of fatigue that have been indentified throughout the literature, including the biological basis of fatigue, the subjective element of fatigue, as well as a primary fatigue cause. Potential consequences of fatigue are suggested. This definition also has scope to include cumulative fatigue as well as task-related fatigue, both of which are evident in the ATC domain.

In summary, a review of research confirms that fatigue effects, resulting from a number of sources, are present in the ATC domain. Influences of fatigue on performance have also been well documented. However, the relationship between fatigue and performance is complex. Fatigue may not directly influence performance, and the relationship can be moderated by other influences such as task demands and characteristics and as well as motivational and effort/based strategy selections. Therefore, although fatigue is a constant source of concern in ATC (Wickens et al., 2004), further clearly defined and controlled research is required before the relationship between fatigue and performance can be comprehensively and accurately described.

2.2.1.3 Stress

Stress has been reported to affect other human factors and human performance. In the context of this review, stress may be described as a psycho-physiological state of tension (Congleton, Jones, Shiflett, McSweeney, & Huchingson, 1997) and a product of a substantial (actual or perceived) imbalance between environmental demands and individual resources to meet those demands (Desaulniers, 1997; Matthews, 2002). When first described by Selye (1964), the term stress was utilised to encompass two distinct constructs: eustress, or 'good stress', which can be characterised as active task engagement or even excitement, and distress, a subjectively negative experience (Le Fevre et al., 2003). These two forms are widely recognised in the literature to have differential influences on both the individual and task performance.

Individual differences in the cognitive appraisal process and the resulting perception of threat (Kalsbeek, 1981) determine the perception, and therefore impact, of stress on the individual (e.g. Lazarus & Folkman, 1984; Isaac & Ruitenberg, 1999; Wickens, 2004). Individual differences therefore mediate the perception and impact of a stressor (Karasek & Theorell, 1990).

The effects of stress on an individual can be categorised into three main groups, psychological (subjective), physiological (objective), and behavioural/emotional (Isaac & Ruitenberg, 1999). Stress will frequently be accompanied by a subjective experience, and individuals are generally able to report emotional changes in relation to the stressor, such as a change in mood (i.e. Repetti, 1993). Objective effects of stress include psychophysiological changes such as raised arousal levels (Ursin &Olff, 1993) and changes to the autonomic nervous system (ANS). Stressors and resulting subjective and objective stress effects have been documented in several safety critical domains (Leblanc, 2009; Martinussen & Richardsen, 2006) including the air traffic domain (Martinussen & Richardsen, 2006; Collet, Averty & Dittmar, 2009; Repetti, 1993; Sega et al., 1998).

Stressors exist in the ATC domain, which have been categorised into distinct groups. Organisational factors can act as stressors, such as the adoption of a blame culture, and shift-rotation patterns (Isaac & Ruitenberg, 1999). Stressors may also result from team characteristics, such as poor teamwork, communication delays, lack of cohesion, and intra-group conflict (Kontogiannis and Kossiavelou, 1999). Environmental stressors have also been identified in ATC. Kontogiannis and Kossiavelou (1999) list environmental stressors including inadequate and inconsistent temperatures (heat/cold), noise and inadequate lighting. Stressors can result from task characteristics, and have been reported to have "received more attention by researchers than any other" (Kontogiannis, 1999, p8). As the air traffic controller's task involves stressors such as high workloads, time pressure and high risk, "stress [is] inherent to the job" (Sega et al., 1998, p208).

Stressors may influence subjective and objective stress. Repetti (1993) investigated the association between work stressors and subjective experience of stress in a sample of 52 US controllers. Controllers completed a battery of measures of 'daily occupational stressors' and an 11-item checklist that measured both physical and mental well-being. Controllers completed each measure once a day for a total of three days. Results indicated that occupational stressors were significantly negatively related to reports of positive mood and physical well-being.

Objective effects of stress have also been identified within the ATC domain (Cobb & Rose, 1973; Costa, 1993). Melton et al. (1973) measured heart rate and epinephrine as psychophysiological indicators of stress in a sample of 16 US ATCOs. Findings showed that increases in both heart rate and epinephrine were associated with periods of higher task demands. Unfortunately, the variable of time of day was not controlled. As task demands tend to be higher during the day, it cannot be stated conclusively if the associated changes were influenced by time of day. Findings of objective effects of stress in the ATC domain are mixed, however. Sega et al. (1998) utilised a sample of 80 male ATCOs working at an airport in Milan and recorded heart rate and blood pressure (objective indices of the stress reaction) continuously for three days. Results were compared to an aged-matched male sample considered representative of the population. Results revealed that systolic blood pressure was significantly greater in the ATCO sample. However, changes in heart rate and diastolic blood pressure were not significant, in contrast to Melton et al. (1973). The authors concluded that on a day to day basis, controllers may be able to adapt to job stressors, due to careful selection and training, although a cumulative effect of stressors may increase the likelihood of hypertension in the ATCO population. A potential contribution to these controversial findings in the literature of the objective effects of stress on controllers is the variance in the employed psychophysiological measures (Sega et al, 1998). Without consistent measures and indices, it is not possible to comprehensively characterise the influence of stressors on psychophysiological indices in ATCOs. An additional potential reason for the controversial findings within the literature is the relative lack of differentiation between participants' experience of eustress or distress during the experimental period (e.g. Zeier, Brauchli, & Joller-Jemelka, 1996).

A relationship between stress and performance has been repeatedly identified in the literature (Lazarus, Deese, & Osler, 1952; Hockey, 1997; Wetzel et al., 2006). The relationship between stress and performance may be explained with the application of the Yerkes-Dodson law (Yerkes & Dodson, 1908). Stress and the related concept of arousal, influenced by stressors, may alter on a continuum from high to low depending on the situation. The Yerkes-Dodson law (Yerkes & Dodson, 1908) suggests that there is an inverted U relationship between arousal/stress and task performance. An optimum level of arousal is assumed to be required for successful task completion. Optimum arousal for task performance differs between individuals based on experience, adaption and task characteristics (i.e. simple tasks will generally have a higher level of optimum arousal than complex tasks.) If arousal is too low task performance may also be low. Performance is said to increase with arousal level until the optimum point is reached, hypothesised to be due to the threat of the psychological stressor providing motivation to invest further cognitive effort in the task (Wickens et al., 2004). Stress may therefore facilitate performance until this optimum, after which if arousal keeps increasing, over-arousal causes performance to decline. Here, participants may interpret task demands to be outside individual abilities (Wickens et al., 2004).

Negative influences of stress and over-arousal on task performance have been widely reported. Information processing characteristics and cognitive function, such as divided attention, working memory, retrieval of information from memory and decision making, have been reported to be negatively influenced in several high-risk domains, (LeBlanc, 2009; Delahaij et al. 2011) including aviation (Shorrock, 2007) resulting in a negative impact on task performance. Applying these results to the air traffic environment, stress may have negative influences on the ATCOs' primary cognitive task. Higher cognitive functions such as working memory and decision making are all required for a high performance, and may be affected negatively by stress (Isaac & Ruitenberg, 1999). Relatively few studies have examined the influence of stress on controller performance.

Research has found several moderators between the relationship between stress and performance. Moderation effects may explain the finding that frequently, performance declines are not observed in the presence of particular stressors (LeBlanc, 2009). One of the most frequently reported moderators of the stress-performance relationship is the active control of performance by individuals under stress by applying compensation strategies in order to maintain performance (Hockey, 1997; Matthews et al., 2000). For example, Hockey (1997) suggests that increased resource allocation may be utilised as a compensatory control mechanism to protect performance against stress affects, "but only at the expense of increased subjective effort and behavioural and physiological costs" (Hockey 1997, p73). Through this process, performance can be maintained even in the presence of stressors, until a point at which resources are not sufficient to compensate for stress effects. The stress-performance relationship may also be moderated through applying coping strategies. In a seminal investigation, Sperandio (1971) demonstrated that in an air traffic domain, controllers switch strategy to maintain performance under increasing task demands, therefore moderating the effects of a potential stressor on performance.

A working definition of stress was developed from frequently utilised definitions in the literature, and a consideration of the subjective experience and influences on the actual controller experiencing stress. In addition, two controllers were contacted for their input on the colloquial understanding of stress in ATC. The definition that will be used for stress is "pressures imposed by the situation which challenge the controller's ability to cope". This definition alludes to important elements of stress considered in the literature, including external influences, the controllers' perception of the pressures, individual ability, and the controllers' use of coping or adaptive strategies, which may protect performance.

In summary, stress may be stated to be a product of the interaction between external demands, or stressors, and an individual's perceived ability to cope with those demands. Individual differences are therefore instrumental in the perception of stressors and subjective stress experienced. Stress is documented to have both psychophysiological (objective) effects on an individual, as well and psychological (subjective) effects. These effects may be positive as well as negative, although most concerning for safety-critical environments is the negative consequences of the stress-performance relationship. Stress has been repeatedly demonstrated to negatively influence performance in several safety-critical settings, including aviation. However, relatively few studies have reported the association between stress and ATCO performance; potentially due to a variety of moderators reducing the observable influences of stress in performance. Further research should examine in a controlled setting the relationship between controller performance and subjective and objective stress to further understanding of this relationship in the ATC environment.

2.2.2 Factors referring to cognitive processes

2.2.2.1 Attention

Within the context of the human processing system attention is often referred to as the ability to attend to information in the environment (Eysenck, 2001). It is a critical element in the human processing system; attentional capture is necessary for perception and further central processing, ultimately resulting in a response to environmental information (Wickens et al., 2004). It is beyond the scope of this review to describe the full human processing system and the critical elements for information processing (please see Eysenck, 2001 for a full review). This section of the review will therefore focus on the attention construct itself, a description of the different forms of attention and a brief review of the underlying attentional process theories. The relevance of attentional mechanisms specifically within the ATC domain and implications for controllers' performance will then be summarised. Three main forms of attention have been identified in the literature (Brown & Boltz, 2002; Eysenck, 2001):

1. **Focused attention**, defined as a cognitive mechanism that facilitates an individual to selectively attend to a specific target from a range of stimuli (Behrmann and Tipper, 1999)
2. **Divided attention**, defined as a person's ability to attend to two or more stimuli at once (Eysenck, 2001)

3. **Sustained attention & vigilance**, defined as "a state of readiness to detect and respond to certain small changes occurring at random time intervals in the environment" (Mackworth, 1957, pp389-390).

Different cognitive mechanisms, and associated paradigms for assessing varying types of attention, are included in each type/construct, therefore it is important to highlight this distinction. Within this section of the review, focused attention and divided attention will be described. Due to the specific role and importance of sustained attention and vigilance in the air traffic control task sustained attention and vigilance will be considered in section 2.2.2.2 of this review.

Focused, or selective, attention can be described as a cognitive mechanism that facilitates an individual to selectively attend to a specific target from a range of stimuli (Behrmann and Tipper, 1999). "Through the operation of such a mechanism, action may be directed toward one of the many objects that potentially evoke a response" (Behrmann and Tipper, 1999, p83). The frequency of attending to specific events in the environment is modified by the value and cost of attending to specific points, as well as the cognitive effort required (Wickens et al., 2004). Selective attending occurs in separate modalities. Research on focused attention in the auditory modality has demonstrated that individuals can select specific auditory information from several present auditory sources, as demonstrated by shadowing studies (i.e. Cherry, 1953).

Early theories hypothesised that automatic attentional filters enabled the subjectively most relevant information in the external environment only to enter conscious awareness (Broadbent, 1958); individuals then consciously select the information that entered conscious awareness to process extensively. Filtration and selection are functional processes which protect overload of limited cognitive capacity.

Later theories of selection differ in regard to when the filtering is assumed to occur, early in the process (i.e. Broadbent, 1958) or later in the processing system (i.e. Treisman, 1964). However, many psychological theories of attention (Broadbent 1958; Treisman 1964) agree that the selection of information occurs sometime after the initial attending. Focused or selective attention also occurs in the visual modality. Through a series of studies with attentional- disordered patients, Posner and Peterson (1990) proposed that visual attention involves three separate components: disengagement of attention from the current focus; shifting attention to the target stimulus; engaging attention onto the new visual stimulus. Posner (1980) suggested that attention shifts can occur through an endogenous system controlled by personal intentions, or an exogenous system which automatically shifts attention, possibly due to peripheral cues. The process of selecting a target from a range of stimuli is one of the most-cited examples of focused visual attention (Eysenck, 2001).

Divided attention is a separate form of attention and refers to a person's ability to attend to two or more stimuli at once (Eysenck, 2001) and is often investigated using dual-task studies in which two, concurrent stimuli inputs are presented to participants, with the instruction to attend and respond to both inputs (Eysenck, 2001). Performance decrements on dual tasks are frequently reported (Eysenck, 2001) although findings are mixed, with some studies reporting performance maintenance. Attentional resource theories have been utilised to explain these findings (Eysenck, 2001). Resources theories assume that there is a limited capacity and limited resources available for processing information (Matthews et al., 2001). However, attentional resource theories differ in assumptions regarding capacity. Central capacity theories of attention resources (i.e. Kahneman, 1973) assume that one central store of attentional resources exists, which can become overloaded if the dual tasks sum attentional requirements over the resources available. Conversely, multiple resource models (i.e. Wickens, 1984) assume the existence of separate resource 'pools'. A prevalent multiple resources model within the literature is the multiple resource model by Wickens (1984). Wickens' (1984) multiple resources model assumes that separate pools of resources are based on distinctions between processing stages, modalities, codes and responses (see Wickens 1984). If two tasks use the same pool of resources, there is more likely to be interference, and over-demand of the resources available, potentially leading to a decline in performance. However, if two or more tasks utilise different resource pools, it is assumed that the tasks may be performed without interference or resulting performance decline.

Task characteristics also modify the relationship between multiple task demands and performance. Performance is more likely to be maintained if the tasks are dissimilar or use different modalities (Treisman & Davis, 1973), potentially due to accessing separate resource pools. In addition, performance can be maintained if the tasks are non-demanding or when responders are skilled in the task. Allport, Antonis & Reynolds

(1972) hypothesised this to be a result of automatic versus controlled processes (see Shiffrin & Schneider, 1977) which utilise less attentional resources.

Due to the primarily cognitive nature of the air traffic control task, attention in its various forms is an essential part of the information processing demanded of the controller. The ATC task will be discussed in relation to implications for performance. Within human performance literature, it is recognised that selective attention is needed for efficient performance (Eysenck, 2001). Controllers are required to selectively attend to external events using both visual and auditory channels. For example, controllers must visually search for conflicts, monitor display strips and also listen and respond to auditory input, including pilot requests and information from teammates. Information from these channels must first be attended to in order to be available for further processing (Wickens et al., 1997).

Cognitive biases may cause breakdowns in selective attention (Wickens, 1997), potentially resulting in a performance decline. One example of this is expectation-driven processing. It has been suggested in the literature that expectation driven processing allows for selectively attending and perception of expected events with reduce effort, compared to unfamiliar events. However, this can lead to perceptual errors such as incorrect read backs, and lack of detection in the hear back process. Breakdowns in the visual scanning process may also occur, potentially leading to the controller missing critical events. Stressors such as time pressure and high workload may exacerbate these affects as both filtration and selection are reported to increase (Broadbent, 1971). This is an adaptive function utilised so individuals can focus on the most important information to make a quick decision (See Maule et al., 2000). Focused attention can also maintain performance under sub-optimal conditions. Rantanen and Nunes (2005) investigated focused visual attention in controllers. The study utilised an ATC simulation conflict detection task, in which 14 controllers participated. A total of 160 short scenarios depicted two aircraft. Controllers were asked to determine if the aircraft were on a converging course, and respond as quickly and accurately as possible. Results suggested that there was a hierarchical preference of aircraft information which controllers would select progressively to assess if aircraft were on a converging course. Altitude information was first attended. If vertical separation existed no other information was attended to prior to responding. If aircraft were at the same altitude, aircraft heading information was then selected for consideration. If further information was needed, aircraft speed was then attended. Rantanen and Nunes (2009) suggested that attending to, and considering, aircraft heading and speed to assess conflicting trajectories were more cognitively demanding that the use of altitude. A limitation of this study is the generalisation of the results to the ATC domain. Although an ATC simulation was utilised, controllers are required to visually search for multiple tasks, not only conflict detections. Further research should therefore confirm these findings using ecologically valid tasks.

Divided attention is also critical for completing control task requirements. Several sources of information must be attended to simultaneously (such as visual scanning and auditory information), and control tasks are often concurrent (such as issuing instructions and annotating the flight strip) (Shorrock, 2007). This division of attention, specifically under high workloads or complex tasks, may increase the risk of perceptual errors.

A working definition of attention was selected as "the application of cognitive processes to focus on a specific environmental target necessary for further target processing". This definition was developed from the mechanics and purpose of attention, as described in the literature, and is broad to encompass the three main forms of attention, but acknowledges the role of attention as the crucial step in human information processing required for further consideration and action.

In conclusion, attention is a multidimensional construct which has three primary forms: focused attention, divided attention and sustained attention/vigilance. Each form of attention is essential for performing ATC tasks, and attentional strategies can maintain performance under separate stressors. However, breakdowns in attention, or inadequate strategies (such as incorrect distribution of attention) as well as dual-task interference may result in human errors such as perceptual errors, and resulting performance decline.

2.2.2.2 Vigilance and sustained attention

Vigilance may be described as "a state of readiness to detect and respond to certain small changes occurring at random time intervals in the environment" (Mackworth, 1957, pp389-390). Aston-Jones, Rajkowski, Kubiack and Alexinsky (1994) suggest that vigilance is synonymous with sustained attention, and occasionally used to refer to the specific detection and response element of sustained attention (Matthews et al., 2001; Wickens et al., 1997). Sustained attention is a specific type of attention (Matthews et al., 2001) which refers to the ability to maintain focused attention to a target over a period of time (Smit et al., 2004). Sustained attention may have common underlying biological processes (see Oken, Salinsky, & Elsas, 2006) and is reported to relate to arousal and alertness.

Typically, sustained attention has been studied using vigilance tasks. Cognitive vigilance tasks present alphanumeric symbols and require participants to detect and respond to a specified target (Warm, 1984; Matthews et al., 2001). Although there is great variation in vigilance task characteristics, Parasuraman (1979) suggests that vigilance tasks can be classified using a four element taxonomy:

1. Target discrimination type may be successive or simultaneous
2. Background event rate may be low or high
3. Sensory modality may be visual or auditory; and
4. Target source complexity may be single or multiple

Performance on the vigilance task is generally assessed by frequency of correct target detections, frequency of incorrect target detections and response time (Matthews et al., 2001).

A traditional view of vigilance tasks suggested these tasks were under stimulating, and any performance declines were hypothesised to result from under arousal. However, recent research has challenged this view. Several research studies suggest that maintaining vigilance on tasks is mentally demanding and associated with substantial costs in the human processing system (Warm et al., 1996; Wickens et al., 1997).

A repeated finding from vigilance task research is a progressive decline in target detection performance over time (Davies & Parasuraman, 1982). Target detection accuracy decreases whilst reaction time to targets is reported to increase over time (Wickens et al., 1997). This trend has been termed 'the vigilance decrement'.

Signal detection theory (SDT) assumes that the vigilance decrement results from two separate mechanisms. One mechanism results in the reduction of target detection accuracy. In order to detect targets, sensory information is received. A decision is then made regarding if the perceived information contains a target; to identify an element as a target, a specific criterion must be reached. SDT assumes that over time the criterion to identify an event as a target increases, so more characteristics about the target need to be matched to the internal representation before identification takes place, resulting in reduced false alarms but also an increase in missed target detections. The other mechanism accounts for the increase in response latencies. SDT suggests that over time, perceptual sensitivity decreases. This results in a longer response time for identification of targets. Conversely, response latencies for negative responses (e.g. rejection of targets) may remain stable or even decline. (Parasuraman & Davies, 1976)

Wickens' (1984) limited resources theory has also been applied to explain the vigilance decrement. Maintaining vigilance is hypothesised to deplete resources over time, resulting in the observed decrement (Fisk & Schneider, 1981). A detailed review of all vigilance theories is outside the scope of this review.

Task characteristics modify the vigilance decrement. Target conspicuosity reduces the impact of time on task on performance. SDT assumes this target intensity reduces the impact of criterion movement over time. In addition, Parasuraman and Davies (1977) identified target presentation rate and simultaneous or successive presentation of targets to influence performance through the mechanism of the sensitivity decrement; only in successive discrimination tasks with high, even, presentation rates was the sensitivity decrement found. This may result from the high cognitive demands of maintaining vigilance under monotonous tasks. Findings have implications for vigilance task designs applicable to safety-critical domains.

Vigilance is an essential requirement of the air traffic control task (Wickens et al., 1997). Controllers must maintain vigilance for events which occur in both auditory and visual modalities. Visually, en-route controllers must consistently monitor or search several displays (e.g. radar), for relevant information (e.g. flight level information, speed, conflicting trajectories) for up to two hours per session (Shorrock, 2007). This task is further complicated as "the controller must monitor aircraft at several levels, using either local or global processing" (Shorrock, 2007, p899). Auditory events can include incorrect pilot read-backs, or pilot calls and requests (Shorrock, 2007; Wickens et al., 1997).

Vigilance decrements can have potentially serious consequences for ATCO performance and system safety. The robust vigilance decrement finding has also been recorded during the control task. Thackray and Touchstone (1989) investigated vigilance in a simulated ATC task. University students served as participants. Participants monitored 16 aircraft for the following events: a change in altitude, aircraft on the same altitude moving toward each other and aircraft on the same altitude moving away from each other. A total of nine events (three of each type) were randomly presented for a total of 2 hours. Results identified a vigilance decrement. Detection accuracy declined, and response time increased with time on task. Interestingly, a vigilance decrement was only recorded for the target of aircraft on the same altitude. The findings were interpreted using the limited resource model (Wickens et al., 1997). It is hypothesised that this particular target created a successive task, which is more demanding and therefore requires more resources than simultaneous events, such as altitude change detection (Wickens et al., 1997). The higher information processing demands for this target was hypothesised to increase the likelihood of a vigilance decline (Wickens et al. 1997). Study limitations reduce the reliability of generalisation of these results to an air traffic environment. Participants were students so it cannot be assumed that the results would be replicated with trained, experienced controllers. In addition, participants were passive monitors. Active task participation also supports target detection, or vigilance, performance. Findings are therefore inconclusive regarding the specific conditions under which the vigilance decrement may occur within the air traffic domain. Pigeau et al. (1995) suggests that in operational settings, the vigilance decrement and associated performance effects may not be as pervasive as identified in laboratory studies (Wickens et al., 1997). However, "despite the importance of controller vigilance to the safety of air traffic control operations there are comparatively few studies of vigilance during simulated air traffic control" (Wickens et al., 1997, p127). Further research should be conducted with ATCOs in a high fidelity ATC simulation to investigate vigilance declines or errors specific to the air traffic domain.

Aviation incident report data also supports the importance of vigilance in ATC, and the consequences of vigilance decline or error to performance and safety. Shorrock (2007) conducted an analysis of 48 aircraft proximity reports from three UK centres. Controllers were recorded to have caused or contributed to the incident. Errors of perception and visual detection (no detection and late detection) in both visual and auditory modalities were the largest category of errors identified. These vigilance errors had serious implications for safety. An advantage of the incident report methodology is that data are generated from the field, and so may be more representative of the domain than experimental studies. Unfortunately, retrospective incident report data cannot be assessed for reliability. As Shorrock (2007) notes, the reports were not prepared for analysis which may have confounded the results due to differences in investigator training and lack of standardisation of the reporting process. However, other incident report studies utilising larger samples have reported similar results. Jones and Endsley (1996) analysed 143 performance-related incident reports. Results reported 61% of performance-related incidents included perception errors. The replication of these findings suggest that vigilance is a crucial element of the ATC task, and it can be stated with some confidence that declines of vigilance and errors of perception can occur with potentially fatal consequences. Further research is required to address the controversy between results from relatively limited experimental data and incident report analyses finding a dominance of vigilance issues in the ATC domain.

A working definition of vigilance was selected to be 'ability to pay continuous attention to an environmental field for a period of time to detect particular changes which is affected by alertness'. This is very similar to the ATM-related Skybrary definition ("ability to pay close and continuous attention to a field of stimulation for a period of time, watchful for any particular changing circumstances") but was adapted to include frequently cited elements of vigilance from the literature, such as sustained attention, target detection and the influence of alertness levels.

In conclusion, vigilance or sustained attention is a specific type of attention that is critical to the ATC task. Controllers have to maintain both visual and auditory vigilance in order to ensure the safe and expeditious flight of aircraft. Vigilance decrements can result in negative consequences to performance and safety. Through incident report analyses and simulation studies, it has been reported that declines/failures of vigilance, such as missed or late detections, occur during the ATC task, resulting in potential safety risk (i.e. Shorrock, 2007). However, further research is needed to understand the extent of the pervasiveness and implications of vigilance decline within the specialised population of air traffic controllers and the ATC domain.

2.2.2.3 Situation awareness

Despite an extensive debate in the literature concerning the definition and meaning of situation awareness (SA) (e.g. Dekker & Hollnagel, 2004; Dekker & Woods, 2002; Parasuraman et al., 2008; Sarter and Woods, 1991). Parasuraman et al., (2008) argue that a substantial body of research now supports the utility of the construct of SA. It is beyond the scope of this review to consider this debate, except to emphasise the lack of a universally accepted definition or conceptualization of SA (Salas, Prince, Baker & Shrestha, 1995). SA is recognised to be both a process and a product of that process (Dominguez, 1994; Salas et al., 1995). Endsley (1988) proposes that the process of SA is "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future" (p97). Inherent in Endsley's (1988) commonly cited definition is the assumption that situation awareness (SA) is categorized into three distinct levels. Level 1 SA begins with a situation assessment, and incorporates attending to and perceiving the surrounding environment and the techniques needed to complete this such as visual scanning. Level 2 involves understanding of the current surroundings/situation. Finally, level 3 includes the prediction of the situation or surroundings in the near future (Endsley, 1995). SA is dynamic and the repetition of the process continuously updates understanding of the environment (Parasuraman et al., 2008). SA can also describe the product of the process. SA as a product is defined as "the knowledge that results when attention is allocated to a zone of interest" (Fracker, 1988, p102). The process of developing and maintaining SA, and the resulting SA product may have a bi-directional relationship. Sarter and Woods (1991) suggest that situation assessments result in perception which informs the SA product. This mental representation subsequently primes the individual to attend to specific information in the environment.

A distinction can be made between the concepts of individual SA and team SA. Team SA refers to a shared or distributed awareness or mental representation of the environment between team members (Salas et al., 1995). However, as this research focuses on individuals' human performance, individual SA only will be reviewed in this section and for the remainder of the research.

Within ATC, ATCOs must continually assess dynamic information sources to develop a mental representation of aircraft in 3D space and projected future aircraft locations. Simultaneously, other relevant information such as speed, destination, and size are assessed and integrated into the representation. Controllers call this 'the picture' (Endsley & Rodgers, 1994). Whitfield (1979) investigated the concept of 'the picture' through verbal data from controllers. Results suggested that controllers reported the picture to be a geographical representation. Whitfield (1979) concluded that the picture supplies information to the controller, from which to plan and project situations. Both static (e.g. knowledge about airspace structure) and dynamic (e.g. aircraft information) data were represented in the picture. Both controllers (Mogford, 1997) and researchers (Endsley & Rodgers, 1994) have stated that the picture is essential for effective air traffic control.

Endsley (1995a) suggests that a number of task and system factors influence an operator's achievement of SA, including task complexity, workload, and active control vs. passive monitoring. It is therefore important to consider the development of SA in the context of the situation.

Situation awareness (SA) is important for successful performance in ATC (Endsley & Rodgers, 1994). A large body of research has found that adequate SA supports correct decision making (Mogford, 1997) and SA has therefore been recognised to be necessary for the controller to select appropriate action (Rognin & Blanquart, 2001). It is important to note that although SA supports selection of an appropriate response, additional processes mediate this relationship. Inadequate or complete loss of SA may negatively influence performance. 'Losing the picture' is a colloquial term for the controllers' temporary loss of the 3-dimensional mental representation. This loss makes it hard to control traffic safely. Simulation studies have reported findings of a relationship between SA and controller performance. Mogford (1997) investigated the relationship between SA and performance in an ATC simulation study with 37 ATCO students as participants. The simulation was frozen after 20 minutes; eight aircraft were active on screen. Participants were not aware when the simulation would be frozen. Participants were given a paper map of the sector, and asked to write aircraft positions and relevant aircraft data of the aircraft under control at the time the simulation was frozen. Results indicated that students prioritised aircraft information. On average, aircraft position (86%), heading (82%) and altitude (73%) were recalled most frequently. Only 55% of students accurately recalled 2 or more figures from the aircraft identifier, and 53% accurately recalled speed. However, trainees who had recalled aircraft altitude as well as heading were found to be scored higher overall on performance. Mogford (1997) hypothesised that these were salient components of SA. Trainees could retain a minimum but adequate set of data to assist in the comprehension and projection of aircraft, therefore contributing to identification of conflicting trajectories. Mogford (1997) concluded that "insufficient work has been done to demonstrate the importance of SA for successful task performance" (p331). Unfortunately, due to the study design, levels of SA could not be linked with separate performance elements. Further research is therefore required to link SA levels with task performance.

Data from incident report analyses have also documented associations between inadequate SA and performance decline or performance-related incidents (Rodgers & Nye, 1993). Rodgers and Nye (1993) conducted an analysis of ATCO operational errors. SA was reported to be a key contributor, with 57% directly attributed to problems involving the radar display. Findings therefore suggest that inadequate SA may be negatively associated with ATCO performance. It was speculated that different levels of SA may lead to different errors and severities of consequences; further research may investigate this hypothesis in a controlled, experimental environment.

Controllers may lose part of the picture, such as a single aircraft, which is negatively associated with performance. Kirwan (2011) reports an investigation into a series of similar ATCO-related loss of separation incidents. After a full investigation, Kirwan (2011) suggested that the incidents were occurring through a form of mental filtration, via 'layered situation awareness'. This concept relates to the demands on the controller; to facilitate performance, controllers may selectively focus on particular aircraft of immediate importance. Therefore, other aircraft not demanding action may become filtered out (Kirwan, 2011). Although this is an adaptive strategy to manage task demands, the strategy itself resulted in a partial loss of SA.

Other hypotheses suggest the decline of SA may result from higher workloads placing competing demands on spatial working memory, required for level 3 SA (Wickens et al., 1997). However, causes for inadequate SA are likely to be different depending on the level of SA that is affected. Separate levels of SA and associations with human performance and error should therefore receive further attention in the literature.

The working definition of SA "maintenance of a coherent mental picture for current and future events based on continuous extraction of environmental information, which includes controller performance" was adapted from the ATC-specific Skybrary definition. This definition acknowledges the three levels of SA as defined by Endsley (1998), as well as the continuous and cyclical SA process. The inclusion of a mental picture recognises SA as a product as well as a process, and the importance of this mental picture in the controllers' performance. As controllers colloquially refer to SA as 'the picture' this definitions also incorporates natural language of an ATC environment.

In conclusion, SA has been repeatedly shown to be essential for the work of the ATCO. Both systems and task factors can contribute to the operator's ability to achieve SA (Endsley, 1995a), with a dominant research finding of a negative relationship between taskload or workload and SA. Adequate SA can support performance, whereas both simulation studies and incident report analyses have revealed that inadequate, or loss of SA, can result in declines in performance and safety-related consequences.

2.2.3 Factors resulting from individuals acting within a team environment

2.2.3.1 Communications

Communication has commonly been investigated in relation to team environments (Kanki, Folk, & Irwin, 1991; McKinney, Barker, Smith, & Davies, 2004). Specific to the ATC domain, most research on ATC communications has focused "less on the interpersonal component of communications than on its content and form" (Wickens et al., 1997, p140). Therefore, this review will consider the communications construct and its application to the ATC domain. Teamwork will be reviewed separately in section 2.2.3.2.

Communication may be defined as the "transfer of meaningful information from one person to another" (Hogg & Vaughan, 2002, p568) and involves both the production and the reception of messages, although communication is independent from (but related to) the concepts of speech and language (Hogg & Vaughan, 2002; Huttunen et al., 2011). The basic model of communication requires a sender; a message or information; a receiver; and a channel of communication (Hogg & Vaughan, 2002). Isaac & Ruitenberg (1999) suggests that communication starts when a sender encodes an idea or message. The message is sent through one or more channels that are either verbal or non-verbal. Different channels have different processing implications for the receiver. The receiver must attend to and decode the message, drawing on long term memory to apply meaning to the symbolised message. Receivers differ in personal characteristics such as experience, culture and expectations which may influence the decoding and interpretation of the message.

A distinction is made between separate forms of communication, including verbal and nonverbal (Isaac & Ruitenberg, 1999). Verbal forms of communication include speech and written communications (Hogg & Vaughan, 2002), as well as para-verbal signs accompanying speech. Huttunen et al. (2011) suggest that speech prosody elements such as pitch, tone and rhythm have an important role in communicating, supporting and contributing to the message, and the interpretation of the message by the receiver.

"Speech rarely occurs in isolation from non-verbal cues" (Hogg & Vaughan, 2002, p582). Non-verbal communication includes communication forms such as gaze, gesturing and facial expression. This can occur independently or in conjunction with other forms of communications. Communications can also be differentiated on other dimensions, including direct (message stated explicitly) or indirect (not intended for the individual who gains information) communication, as well as addressed (message sent intentionally) or non-addressed (messages sent without the intention of the sender) communication. Although it is beyond the scope of this review to examine each one it detail, it should be noted that each element of communication can influence the likelihood of receipt and of correct interpretation by the receiver, and therefore the efficiency of the communication.

Task- related communication "is the foundation of ATC" (Huttunen et al., 2011) and is critical to the control task. Communications occur between several aviation professionals working in a form of distributed team (Rognin & Blanquart, 2001). Verbal communications and para-verbal signs (see Huttunen et al., 2011) are the primary means of communication between ATCOs and aircraft pilots (although communications through written data link is contemporarily also used in specific circumstances) to issue instructions and provide information (Wickens et al., 1997). In addition, communications between controllers in adjacent sectors are critical to the ATC task in order to coordinate aircraft movements between sectors. Task-related communications between an executive and coordinating controller on the same sector also support the control task. When possible, verbal communications are also used for explicit discussion. However, due to the proximity of the two controllers, non-verbal communication such as gestures can be utilised effectively to send information (Rognin & Blanquart, 2001). To facilitate safe and efficient communication between various aviation professionals, task-related communications are regulated by a set of established communication standards. "The need for clear and unambiguous communication between pilots and Air Traffic Control (ATC) is vital in assisting the safe and expeditious operation of aircraft" (EUROCONTROL, ICAO Phraseology reference guide, p2). English is used as the standardised language. In addition a standardised phraseology is used in all communications which has been designed for maximal clarity and to protect against ambiguity. Research findings have indicated that regulation and standardisation of communication supports efficient communications (Kanki et al, 1991; McKinney et al., 2004; Rognin & Blanquart, 2001).

Communications may influence performance both positively and negatively. Effective communication supports individuals in developing a shared awareness of the situation or system, supports teamwork and therefore results in a maintenance or increase of performance (Rognin & Blanquart, 2001; Kanki et al., 1991). A large body of work exists exploring the qualities of effective communications, such as increased planning statements, structure and predictability (Kanki et al., 1991).

Errors of communication have been repeatedly found to influence performance negatively, occasionally with severe consequences. Findings generally suggest that verbal and written communication errors have been a "critical contributor to risk in a variety of industries" (Gibson, Megaw, Young, & Lowe, 2006, p57). General figures suggest 40% - 80% of incidents in safety-critical domains may result from communication errors (Sexton & Helmreich, 1999; Tajima, 2004).

A number of taxonomies exist for classifying communication errors (e.g. Corradini & Cacciari, 2002; Skantze, 2005). Gibson et al. (2006) suggest that failures of communication may be defined by three primary criteria: the adequacy of the transfer of communication goals, deviations from accepted or regulated grammar, and errors of commission or omission when compared to contextual objectives or requirements. The factor of communication not only influences overall performance, but communication error may be therefore classified as a measure of performance.

Incident report analyses have reported an association between errors of communication as a contributor to performance related incidents and performance decline (Isaac & Ruitenberg, 1999; Rantanen, McCarley, & Xu, 2009). Shorrock (2007) conducted an analysis of 48 performance-related incident reports, recorded from UK centres between 1995-1997. A frequency analysis revealed, that the largest group of perception errors were associated with failures of communication, specifically, failures to recognise pilots errors in the read back/hear back loop. Cardosi, Falzarano and Han (1998) contributes further detail to this finding. A review of 386 incident reports from the aviation safety reporting system (ASRS) was conducted. It was found that pilot-controller communication errors were categorised into three main forms: the actual read back/hear back error in which the pilot reads back the instruction incorrectly and the controller does not correct the error, the absence of a pilot read back, and hear back errors in which the controller does not correct a pilot read back containing the controller's own error from the original instruction. Such communication errors within the controller-pilot read back-hear back closed loop were concluded to be contributors to aircraft breaches of separation minima. Cardosi et al. (1998) conclude that implementation of supports to reduce the number of communication errors between pilot and controller should be a priority. A separate study utilised error reports from a US control centre to investigate the frequency of communications error content. The Seattle centre (as reported in Isaac & Ruitenberg, 1999) conducted an analysis of 389 hear back/read back errors recorded during one month in 1995. Errors consisting of incorrect altitude read backs (31% of errors), incorrect radio frequency changes (24% of errors) and addressing the wrong aircraft (10%) accounted for the majority of errors. Although the errors did not necessarily contribute to an incident, the error of communications in one month (389) suggests the pervasiveness of the communication issues and potential implications on performance. An advantage of an analysis of error reports as opposed to incident reports is that the data are more inclusive. Incident reports will only be created with the occurrence of a breach of separation minima, and so error data provides a more comprehensive/inclusive overview of key communications errors. This study was based on one US centre. Therefore, it is necessary to conduct similar studies in other centres to determine the extent of generalisation of the results.

Several types of miscommunication are documented in literature from the aviation domain. Miscommunications can include ambiguity through word choices or distortions of meaning (Isaac & Ruitenberg, 1999). This is more likely if standard phraseology is not used. Slips are also frequent forms of miscommunication, which result in verbally communicating information that was not intended (e.g. saying flight level 210 instead of 220). Of course, if this is not detected in the read back, the pilot may then follow the instruction. Miscommunications can result from a number of physical and psychological causes or contributing factors. Physically, the intelligibility of speech may be affected by the physical systems (Isaac & Ruitenberg, 1999) such as the radiotelephony system blocking calls or distorting communications. Ill-fitting headphones may also create distortion to verbal messages potentially resulting in mis-hearing, as can a high level of ambient noise in the operations room. One of the more frequently reported psychological contributors to communication errors or miscommunication is the expectation bias. Expectation bias is thought to result from top-down information processing, as opposed to the more intensive bottom-up processing. Expectation about what the receiver is going to hear may override direct perception (Shorrock, 2007), potentially contributing to non-identification of errors in hear backs. The frequency and potential severity of consequences of communications errors have resulted in crew resource management for pilots and team resource management for controllers including training for standardised and effective communications (Leonard et al., 2004). These initiatives have been shown to positively influence communications and resulting team performance (Leonard et al., 2004).

A working definition of communications tailored to the ATC environment is 'the exchange of information, including timeliness, accuracy, clarity and receptiveness'. Elements found to influence the effective transfer of information in the literature (section 2.2.3.1) are explicitly acknowledged, although the definition is broad enough to encompass the many and distributed forms of communication which occur in ATC operations.

In conclusion, communications are essential within ATC and the wider aviation domain. Separate forms of communications including verbal, para-verbal speech features, written and non-verbal are essential for the safe and efficient flow of traffic, through communication between controllers and pilots as well as between teams of controllers. Communication errors and miscommunications have been associated with performance decline and performance-related incidents. Training programs are in place for aviation professionals that raise awareness of communication issues and the potential consequences of communication errors.

2.2.3.2 Teamwork

Teamwork is commonly referred to as the organized, collective working methods between an established group of people (Bailey & Thompson, 2000; Erdem & Ozen, 2003; Rasmussen & Jeppesen, 2006). The related concept of a team can be described as a distinguishable set of two or more people who interact dynamically, interdependently, and adaptively toward a common and valued goal/object/mission (Salas, et al., 1995, p4). Although the concepts of teamwork and teams are closely related, the focus of this review is on human factors that may affect performance in an ATC domain. Therefore, the focus of this review article will be the factor of teamwork, and specifically, teamwork in ATC. Teams and team effectiveness will be discussed only when it is deemed to facilitate the further review of the teamwork factor.

Teamwork theory development has focused on understanding variables affecting teamwork effectiveness, such as task properties and work environment (Morey et al., 2002). Coordination is also recognised to be a "central feature of effective teamwork" for joint task such air traffic control (Svensson & Andersson, 2006, p1227).

Teamwork is a critical component in ATC, and "the work of the individual controller is very much dependent on teamwork, reflected in communicating and coordination with other operational staff such as flight crews" (Woldring, 1999, p81). Rognin & Blanquart (2001) suggest that teamwork interactions occur between different individuals or teams within en-route ATC. One form of teamwork occurs between the executive controller and coordinating controller, who are responsible for different tasks on the same sector. The coordinator, as the "radar's assistant" (Rognin & Blanquart, 2001, p329) will facilitate the executive controller by coordinating aircraft and providing information when required.

The shared physical workspace and control tools facilitate teamwork. Each controller has a radar screen depicting the same sector. Each can make changes on the radar screen which can be seen by the other, assisting in the development of shared awareness (Rognin & Blanquart, 2001; Wickens et al., 1997). Teamwork also occurs between controllers responsible for adjacent sectors. When necessary, controllers in adjacent sectors will explicitly discuss and agree the coordination of aircraft between sectors, for example, by confirming the flight level which the aircraft should exit one sector and enter another. An additional, but relatively less investigated form of teamwork occurs during shift-change between controllers, known as a hand-over. ATCOs are permitted to control for a maximum of 2 hours without a break and so changes are frequent. The outgoing controller must provide a comprehensive briefing of the current situation, control strategies and any upcoming issues on the sector to the incoming controller. Standard operating procedures define the information that should be included in a handover in an attempt to reduce omissions that may lead to human error. Each controller will take responsibility to facilitate the handover (Durso et al., 2007). Durso et al. (2007) suggest that the outgoing controller will often change the style of controlling, delaying instructions if possible, or switching to a more tactical control strategy that may be more easily explained. In addition, the incoming controller will often scan multiple sources of information to gain a mental picture prior to taking control of the sector. When it is safe to do so, a verbal briefing of the situation will take place. The briefing time varies depending on the traffic situation, although a naturalistic observation study of 89 cooperative shift changes from three en-route control centres indicated that the range was 10 seconds to three minutes, with an average briefing time of one minute (Durso et al., 1997). Teamwork between various sub-teams is therefore pervasive in the ATC domain and critical to successful completion of the control task.

Teamwork has been repeatedly found to influence human performance in the literature (Erdem & Ozen, 2003; Glaser et al., 1999; Rasmussen & Jeppesen, 2006). Specifically within the ATC domain, Malakis, Kontogiannis, and Kirwan (2010b) suggest "teamwork appears to be associated with air traffic control performance" (p628) and provide several examples of teamwork problems that have been implicated in several high profile aviation accidents (Malakis et al., 2010b).

Seamster et al. (1993) conducted an ATC simulation study to investigate the elements of effective teamwork and associations with performance. Scenarios depicting operational problems that could occur whilst controlling aircraft were presented to pairs of controllers, representing the executive and coordinating controllers. Controllers were asked to collaborate to solve the issue as they would normally. Scenarios varied by traffic load. High traffic loads could prevent verbal communications at selected points due to the volume and frequency of communications. Findings showed that the controller pairs who engaged in specific team processes such as situational enquiries, maintaining awareness through monitoring and statements of intent maintained effective teamwork and a high level of performance and were most efficient at controlling high volumes of traffic. Controllers who had highest performance also engaged in preplanning, and selection of control strategies during the lower taskloads before higher volumes of traffic. Without engaging in these mechanisms, or the effective application of team strategies, performance was not maintained to a high level suggesting the importance of effective teamwork to maintain efficient and safe performance. However, the artificial problem scenarios may limit the generalisation of the findings to the operations room.

Analyses of incident reports also support an association between teamwork and performance. In an analysis of operational errors from 1988-1991, Rodgers and Nye (1993) found that inadequate teamwork and coordination was reported to be a casual factor in 15% of the operational errors reviewed. Adequate and effective teamwork is therefore essential to

maintain and support performance in an ATC setting. Wickens et al. (1997) suggest that findings in the literature regarding the association between teamwork and performance are robust, and imply that teamwork is a critical element in the safe and efficient control of air traffic.
Further research specific to the ATC domain should be conducted to explore elements of effective teamwork and the relationship between teamwork and performance.

The selected working definition describes teamwork as 'collective and mutual interaction with humans in the system for performance'. The definition is designed to incorporate the multiple forms of teamwork within the ATC system, from teamwork between controllers on the same sector to larger distributed teamwork, for example, between controller and supervisors or pilots. In addition, the definition also acknowledges the research findings of the influence of teamwork on ATCO performance and the ability to provide a safe and efficient service.

In summary, teamwork "is likely to be a critical component of ATC for the foreseeable future" (Wickens et al., 1997, p150). Various forms of teamwork are evident in the distributed ATC team, and are essential to the achievement of the ATC task. Teamwork has been repeatedly found to influence human performance. Performance may be enhanced with specific effective teamwork elements. Conversely, inadequate teamwork has been associated with performance declines and human errors.

2.2.3.3 Trust

Trust is a multidimensional construct (Costa et al., 2001). Several trust taxonomies exist in the literature (Erdem and Ozen, 2003; Kiffin-Peterson & Cordery, 2003). However, there is not a universally accepted definition or even taxonomy of trust (Bonini, 2005). One taxonomy of trust widely cited in the literature differentiates between dispositional and situational trust (Kiffin-Peterson & Cordery, 2003). Dispositional trust refers to an individual's propensity to trust, based on both predispositions to trust, and subsequent environmental influences. Situational trust is context specific, arising from the perception of an individual's (or machines) trustworthiness (for a full review see Kiffin-Peterson & Cordery, 2003).

A second distinction is made between interpersonal trust and trust in technology. Interpersonal trust may be broadly described as the willingness to be vulnerable "to another party based on the belief that the latter party is competent, open, concerned and reliable" (Mishra, 1996, p265). A distinction can be made between cognitive trust, defined as a logical belief that an individual is trustworthy, and affective trust, defined as a product of an emotion or feeling that an individual is trustworthy (Erdem and Ozen, 2003). Erdem and Ozen (2003) suggest that cognitive trust is most important at the beginning of an interpersonal relationship, whereas affective trust becomes increasingly important for the development of a long-term relationship. Trust in technology has been defined as an intervening variable that mediates between the system and an operator's interaction strategy with the system (Muir, 1994). Research findings suggest that if an operator does not trust the system, it will not be used (Muir & Moray, 1996). Lee & Moray (1992) and Muir and Moray (1996) developed a dynamic model of human-machine trust. The model assumes that trust is continuously updated based on previous levels of trust and current experience of the system. The development of trust in systems may therefore be an interactive process and can be considered as both an effect and a cause.

In the air traffic domain, both interpersonal trust and trust in technology are essential for the system to function correctly (Bonini, Jackson & McDonald, 2001). ATCOs have been recorded to consider trust "as important in their work in terms of their relations with colleagues, pilots and management; as well as with regard to their attitude towards technology" (Bonini, 2001, p450). Specific to the ATC context, trust has therefore been defined as belief in others' ability and confidence in the system (Bonini et al., 2001). Interpersonal trust is recognised to have an important role in ATC. Controllers must rely on other controllers, pilots and other aviation professionals to effectively achieve the control task. For example, controllers trust that pilots will respond to instructions; controllers are also dependent on relevant information provided by colleagues. Throughout these multiple relationships, trust in the individual is critical to cooperation, and ultimately, adequate teamwork (Bonini 2005). Colleagues' characteristics have been found to influence the development of interpersonal trust (Bonini et al., 2001). Bonini et al. (2001) conducted a questionnaire study with 52 en-route ATCOs. Questions related to interpersonal trust, as well as related concepts such as belief and mistrust. Findings revealed that colleagues who appeared confident were more likely to be trusted. In addition, perception of competence influenced the development of trust. Experience was found to moderate trust. Controllers reported that experience enabled them to know when to trust and when to distrust. Overall, "competence and personality were the variables that were considered t influence most whether they trusted fellow controllers or not" (Bonini et al., 2001, p107). An advantage of a questionnaire study is that the data is generated from experts in the field and so has ecological validity. However, the actual relationship between these influences and the development of trust cannot be further explored. Further research in controlled experimental settings would enable tighter control over the documented influences of trust development, and could extend findings through examining this relationship.

Trust in technology is essential to system performance in ATC (Bonini, 2001). In this context, trust refers to confidence in the equipment and the dependability of information. Rising air traffic has resulted in frequent system modifications and additions within control centres. In order to be effective, it is essential that new technology and tools are accepted and used by controllers. Both acceptance and use of technology have been repeatedly found to be related to trust in the technology (Eidelkind & Papantonopoulos, 1997; Muir, 1988). Trust is therefore critical to facilitate the use of technology. Factors influencing the development of trust in technology have been reported to include ease of use as well as proof of reliability and usefulness (Bonini et al., 2001). The influence of the proof of reliability is believed to influence the development of trust in systems over time, with controllers reporting more trust in the technology that has been in use for longer, such as radar (Bonini, 2001; Lee 1992).

Trust (both interpersonal and trust in technology) has been frequently reported to influence human performance (Bonini, 2005, p13; Costa et al., 2001). More specifically, the decision of whether to trust an individual or system, and the appropriateness of that decision in the given context, influences the resulting influence on performance. Research is limited regarding the association between trust and performance (Costa et al., 2001), especially research within the ATC domain. This section will therefore review trust and performance related to the ATC domain but will supplement findings where appropriate with research from other safety critical domains. Findings from the psychological literature on interpersonal trust record a robust positive correlation between interpersonal trust and team working. As an extension of this, trust and teamwork influence overall performance. The relationship between these two factors is discussed in detail in 2.3.3.3. Research findings suggest that interpersonal trust may also lead to a reduction in human error (e.g. Erdem and Ozen, 2003). Trust in technology is believed to influence performance through 'miscalibration' (Wickens, 2002; Wickens et al., 1997). When an unfamiliar technology is used, calibration is said to occur between operators and the system. This process incorporates the operator understanding when it is appropriate to trust or not trust the technology (Bonini et al., 2001; Wickens et al., 1997). A miscalibration between the operator and technology can result in mistrust or over-trust (leading to complacency), each with specific implications for performance. Inappropriate mistrust may result in an inappropriate lack of technology use, potentially resulting in reduced efficiency or even a reduction in safe performance (Wickens et al., 1997).

The concept of over-trust in aviation has been more frequently investigated, dominantly in relation to automation. Over-trust of technology can result in complacency or overreliance on the technology which has been shown to be negatively related to vigilance and monitoring behaviour (Muir & Moray, 1996). Muir and Moray (1996) investigated operators' perception of trust in the technology, and the performance of the operator when using the system. A strong negative correlation was reported between trust in the machine and monitoring. Muir and Moray (1996) concluded that over-trust had influenced the control strategy selected by the operator, which minimised monitoring. Overreliance on technology may be used as a heuristic replacement for vigilance information seeking and processing. Data from incident reports also suggest an association between over-trust and overreliance in technology and performance decline or performance-related incidents. In an analysis of ASRS incident reports, monitoring failures were associated with overreliance on automation (Mosier, Skitka, & Korte, 1994). Although a direct relationship cannot be determined from incident report data, the pattern of over-trust and performance decline is consistently reported in the literature (Wickens et al., 1997). The relationship between trust and performance outcome appears to be indirect. Inappropriate trust (mistrust or over-trust) in colleagues may result in a lack of checking behaviour or insufficient teamwork. This reduction of monitoring may then result in performance decline. Similarly, inappropriate mistrust in systems may result in a lack of facilitation of performance, whereas over-trust in technologies may result in a reduction in monitoring, leading to a vigilance decline. These outcomes may then negatively influence controller performance.

A working definition of trust specific to ATC is suggested to be 'the level of confidence in events, people, equipment or circumstances'. This definition is based on the definition of trust developed for Skybrary, and so is relevant to the ATC domain. In addition, the definition focuses on the confidence element of trust, shown to be accepted by controllers (Bonini, 2005), and encompasses a broad range of elements that controllers are required to trust in ATC.

In summary, trust influences interactions with colleagues and technology use (Bonini, 2005). Operators experience a period of a calibration of trust when interacting with an unfamiliar colleague or technology (i.e. learning when it is appropriate to trust or not trust). An incorrect calibration can create mismatches between trust and competence, resulting in potential negative influences on performance effects. Unfortunately, research which investigates trust and the association with performance specifically within an ATC environment is limited (Wickens et al. 1997). Further research within safety critical domains, and in particular, ATC, is needed to further inform the relationship between interpersonal trust, trust in technology and performance.

2.2.4 Implications of literature review findings relating to human factor associations with performance

A review of literature supported that the nine human factors occur in an ATC environment. In addition, the review supports that each factor is associated, positively and/or negatively, with controller performance. Incident data was frequently utilised to support the association between the human factors and performance. However, due to the nature of the data no causal relationship can be confirmed. Further field studies or controlled experimental studies are required to further inform the occurrence of these factors in ATC and any direct or indirect influences on ATCO performance.

2.3 Human factor interactions: A review of human factor relationships and associations with performance

The following sections present a review of the literature of the relationships between the selected nine human factors (workload, fatigue, stress, attention, vigilance, SA, communications, teamwork, trust). For consistency, the review is again organised according to the three novel categories applied in section 2.2. In addition, the factors are considered in the same order as the previous review. For each factor, the relationship with other human factors is discussed, and the association of combined, multiple factors with performance is explored where possible. Controversies are reviewed, and gaps in research are highlighted.

2.3.1 Factors resulting from interactions between individual and environment

2.3.1.1 Mental workload

The relationship between workload and fatigue is a common area of research. Bystrom, Hanse and Kjellberg (2004) investigated the affects of workload on musculoskeletal symptoms and fatigue. Employees in an assembly plant completed questionnaires measuring subjective workload, fatigue and musculo-skeletal complaints. Results revealed that workload positively related to musculo-skeletal complaints, and significantly, positively correlated to subjective fatigue (Bystrom et al., 2004). Unfortunately, this study did not examine the impact of the workload - fatigue relationship on human performance. Corrandini and Cacciari (2002) extended these results by addressing this limitation. Workload, fatigue and communication errors were investigated in a field study of air traffic controllers. Radio communications were recorded throughout the investigation period. Subjective workload measures and objective vigilance measures were also utilised. Communications were analysed in relation to vigilance performance, workload, and shift position (morning, afternoon, night). Results revealed that performance decrements, operationally defined by increased errors in communication and decreased vigilance, were observed during periods of lowest workload and highest fatigue. Workload may therefore impact vigilance. Corrandini and Cacciari (2002) concluded that the interaction of these factors potentially affected performance to a greater extent that the presence of one factor.

Unfortunately, it is not possible from this study to determine causality of the relationship between workload and fatigue. A complex interaction between workload, fatigue and communications, impacting vigilance and performance was found, although not further explored. Further research should therefore aim to establish a causal path for these factor interactions.

Smit et al. (2004) isolated the impact of workload on vigilance. Participants were asked to complete either a low workload or a high workload vigilance task. The low workload task consisted of a simple target detection lasting forty minutes. When the letter 'a' was seen, participants were required to push a button. In the high workload condition, the stimulus presentation was identical to the low workload condition, but in this case, participants were told only to push a button on seeing the letter 'a' when preceded by an 'x'. Results revealed a greater decline in vigilance performance during the high workload task than in the low workload task. The authors concluded that vigilance decreases as a function of mental workload (Smit et al., 2004). The authors explained the results in terms of attentional resource theory (Wickens, 1984). Attentional resource theory suggests that each individual has limited cognitive resources that are depleted by information processing demands. Smit et al. (2004) suggested that cognitive resources were depleted faster in the high workload condition, resulting in a more significant negative impact on performance than the low workload condition.

The effect of workload on situation awareness (SA) is less researched. Wickens (2002) reviewed the "intertwining of situation awareness and workload" (p129), and concluded that individuals who experience high workload engage in one of many cognitive strategies to reduce workload, such as task shedding. Consequently, SA cannot be maintained. It is interesting to note that the engaged cognitive strategies may therefore act as a moderator of the impact of workload on SA. However, Wickens (2002) does not cite empirical research to support this view, or further expand this hypothesis, resulting in little empirical support for this proposition. The relationship between these factors is not well understood in the literature. This is an important gap in current research; SA is argued to be a contributor to human error-based incidents across several domains including driving (Matthews, 2002) and aviation (Wickens, 2002). The impact of workload on SA, and subsequently human performance, is therefore an important area of further study.

The relationship between workload and stress has received more attention in the literature. Psychological stress does not have a universally accepted definition. However, it may generally be described as an individual response to the perception of environmental demands and the perceived and actual ability to of the individual to meet those demands (Biers, 1984). Glaser et al. (1999) investigated the impact of workload on stress and performance. Participants were placed in a high or low workload condition to complete a work simulation task. Participants completed tasks of a data entry operator, such as reviewing paperwork and entering data into a computer system. Causal Path analysis results revealed a significant affect of workload on stress – increased subjective workload resulted in increases in self-reported stress. An interesting finding was that workload did not have a direct effect on performance. Glaser et al. (1999) concluded that stress mediated the workload-performance relationship. A significant strength of this study was the application of path analysis. This analysis enabled inferences of causality, which is very limited in the literature (Glaser et al., 1999). Further research should examine the relationships between factors utilising such methods (Glaser et al., 1999).

Mental workload (referred to as 'workload' throughout this thesis) is often studied in relation to communications. Two primary lines of research are evident throughout the literature: affects of workload on communication errors, and affects of workload on speech characteristics (pitch, loudness, rate). Prinzo (1998) examined workload and communication accuracy in an air traffic control (ATC) simulation study. Participants were placed in a high workload or low workload condition. Workload was generated by traffic density. Communications were recorded and analysed in terms of deviations from ATC regulation phrases. The results showed that in high workload situations, irregular and abbreviated communications increased. Prinzo (1998) concluded the increase in irregularities and abbreviations may result from employed cognitive strategies that reduced workload by decreasing phrase length. The study did not investigate these results in relation to error. However, communication irregularities have been found to contribute to error (Gibson et al., 2006), and so it may be hypothesized that the communication changes may increase error likelihood.

The second strand of workload-communication research focuses on the impact of workload on speech characteristics. Brenner, Doherty and

Shipp (1994) utilised a visual tracking task to investigate speech characteristics under conditions of high and low workload. Brenner et al. (1994) observed that frequency, rate, and vocal intensity of speech all increased with workload demands. It was concluded that workload significantly affected speech characteristics. Rantanen, Maynard and Ozhan (2005) suggested that speech characteristics may therefore be used as an online measure of workload. However, research in this area is limited. Further research should examine the reliability of this measure and assess the potential for online measurement of workload.

The relationship between workload and communications is not uni-directional. Casali and Wierwille (1983) used a simulated air traffic control task to investigate the impact of communications on workload. Casali and Wierwille (1983) found that as the number of communication phrases rose, both subjective and objective measures of workload increased. Therefore, a two-way relationship between communications and workload was identified: communications are drivers of workload, and workload is a driver of communication errors and speech characteristic changes. There may therefore be the potential for more errors as workload and communication frequency raises.

In summary, mental workload does significantly interact with other human factors to produce performance decrements. However, although many investigations explore factor relationships, there is a general lack of research establishing the causal directions of those interactions, and impact of factor interactions on human performance. This knowledge is important for the potential future prediction of human performance and error, compared to the current focus on retrospective analysis of error. Additionally, few studies focus on more than two-factor relationships. This inhibits the exploration of potential moderator/mediator relationships. Future research should focus on these elements and address these research gaps.

2.3.1.2 Fatigue

The interaction of fatigue on vigilance has received attention in the literature. Matthews (2002) investigated the interaction of fatigue, vigilance and workload in a simulated driving task. Participants were required to complete a driving task and concurrently respond to intermittently presented stimuli representing pedestrians. Participants were allocated to one of two conditions – a control condition in which participants were required to complete the driving task as normal, or a fatigue condition. Fatigue was induced by participants engaging in a cognitively demanding secondary task whilst driving. Driving performance was recorded and compared between conditions. Results showed that participants in the control condition responded to more target stimuli than fatigued participants. Matthews (2002) inferred that fatigue negatively impacted vigilance. Interestingly, fatigue affects were only observed when drivers were on straight roads rather than curved roads. It was concluded that fatigued drivers experienced a loss of motivation to engage sufficient effort to maintain performance (Matthews, 2002). It may be possible to explain these results using the attentional resource theory (Wickens, 1984). This theory suggests that when environmental demands are perceived to be low, cognitions will be limited so that depleted cognitive resources will replenish with rest. It may be that at times of low workload, the automatic recovery of cognitive resources resulted in impaired performance. Further research is required to examine this hypothesis. Future research is additionally required to confirm and extend the results of this study. It cannot be ascertained from this investigation if fatigue directly impacted vigilance. Fatigue was created artificially, and influencing factors such as workload and stress which may have impacted on the relationship between fatigue and vigilance were not controlled. Controlled, empirical investigation is needed to confirm the inferred relationship between fatigue and vigilance.

The possibility of a bi-directional relationship between fatigue and vigilance has been proposed. Galinsky, Rosa, Warm and Dember (1993) researched the effects of fatigue and stress on vigilance. A vigilance task required participants to detect auditory and visual targets. Participants provided subjective ratings of fatigue and stress pre- and post- vigilance task. Fatigue and stress ratings rose after vigilance task completion. The authors concluded that maintaining vigilance induced both fatigue and stress (Galinsky et al., 1993). As measures were used concurrently, it is not clear from these results whether increases in fatigue and stress were independent products of the vigilance task, or if, for example, stress was a product of fatigue alone. Additionally, factor interaction effects on performance were not explored. It is therefore not possible from this study to infer if performance was differentially impacted by an interaction of the three factors of fatigue, stress and vigilance, compared to a single factor. Future research should expand these results through empirical investigation of the causal nature of these factors, and the resulting impact on human performance.

A relationship between fatigue and stress has been identified in the literature. Shiftwork investigations have repeatedly found an association between increases in fatigue and stress increases (Park, Ha, Yi & Kim, 2006). Park et al. (2006) used an applied field study to investigate the relationship between subjective fatigue and stress hormone levels of employees in a manufacturing plant. Most employees worked a backward, rapidly rotating 3-shift (morning, afternoon, evening) pattern. Participants were required to complete a demographic questionnaire prior to the study. Fatigue questionnaires were completed on the second or third day of each shift, and urine samples were collected for stress hormone analysis. Results found that a positive correlation between stress hormone secretion and subjective fatigue existed only for employees with less than 5 years shiftwork experience. No relationship was found between subjective fatigue and stress hormone secretion for employees with more than 5 years shiftwork experience. Park et al. (2006) concluded there was a mediating affect of experience between fatigue and stress (Park et al., 2006). The correlational design of this study unfortunately prevents an elaboration of any causal relationship between these factors. Therefore, it may not be established if fatigue did generate stress, or if these factors simply covary. Additionally, the impact of fatigue and stress affects on performance was not measured. Future research should attempt to define the relationship between fatigue and stress, and extend Park et al.'s (2006) findings by investigating the impact of the factor interaction on performance.

In summary, the interaction between fatigue and other human factors appears to have received limited attention in the literature in comparison to the factors of workload and stress. Very few studies, to the current author's knowledge, have investigated a causal relationship between fatigue and other human factors, and subsequent effects of factor interactions on performance and error. In industrial settings, it may not be possible to remove employee fatigue and the effects of fatigue on performance. This has resulted in a complex issue for human performance research. However, if knowledge of the interrelations between fatigue and other human factors, and the subsequent effect on performance was enhanced by future research, the effects of fatigue on performance may not necessarily need to be removed, but instead predicted and mitigated, potentially preventing human error.

2.3.1.3 Stress

Stress has been repeatedly reported to affect the human factor of attention through selection and filtration of information processing. Mann and Tan (1993) investigated the consequences of selection and filtration in a decision making task. Mann and Tan (1993) presented participants with dilemmas concerning employment and selection procedures, decisions that are frequently presented to managers in natural settings. Participants were then given a list of eight writing tasks regarding the dilemmas, and participants' selection decision was recorded. Participants either had unlimited time or worked to a time-pressured deadline (Mann & Tan, 1993). The results demonstrated that participants making decisions under time pressure considered fewer alternatives and evaluated fewer consequences relative to the control group. Mann and Tan (1993) concluded that filtration and selection increases were evident when making decisions under time pressured conditions. This study did not discuss the impact of this interaction on the quality of the decisions, however, and so it may not be inferred how these changes affected performance. Further research should review these interaction affects and the precise impact on performance in more applied settings.

Stress may also significantly impact vigilance. Ozel (2001) notes that vigilance is determined by the degree of stress currently experienced by an individual. Although this interaction has been colloquially highlighted, few investigations have comprehensively studied this relationship (Hancock & Warm, 1989). Research that has explored the interaction between stress and vigilance has primarily focused on the impact of environmental stressors (Hancock & Warm, 1989). For example, Wyon, Wyon and Norin (1996) investigated the effect of a thermal stressor on driver vigilance. Participants drove four laps of a predetermined circuit on public roads with varying traffic regulations and speed limits, and were asked to respond to computer initiated signals by pressing a foot switch and verbal reporting. Participants were randomly assigned to one of two thermal conditions – an acceptable 21°C or warm 27°C. Results showed a negative effect of heat stress on vigilance. In the thermal stressor condition, the numbers of missed signals were 50% higher than in the 21°C condition. Response times were also significantly longer in the thermal condition. Wyon et al. (1996) concluded that the thermal stressor may have increased arousal, therefore resulting in a narrowing of attention and consequently an increase in error. This study demonstrates the affect of stress on vigilance and attention, resulting in a significant performance decrement. However, this affect on performance may also have been due to fatigue, which heat may induce (González-Alonso et al., 1999). Therefore, future research should examine the isolated impact of psychological stress on vigilance if the interaction between stress, vigilance and performance is to be comprehensively understood.

The interaction between stress and vigilance may be bi-directional. Lundberg and Frankenhaeuser (1980) monitored physiological stress responses during a vigilance task. Catecholamine and cortisol increased throughout the vigil. It was concluded that vigilance tasks elicit a stress response. Gluckman et al. (1988) extended Lundberg and Frankenhaeuser's (1980) study by investigating subjective stress responses pre and post completion of a vigilance task. Results found that participant stress ratings increased after completion of the task, supporting Lundberg and Frankenhaeuser's (1980) previous findings. The association between vigilance and objective and subjective measures of stress has been repeatedly reported in the literature. However, again, most studies are correlational in design. Although the wealth of evidence suggests a significant causal impact of vigilance on stress, further research should empirically investigate a causal link between the factors. Additionally, the impact of the combined association of vigilance and stress on performance has received comparatively less attention. It is therefore difficult to determine if the association of stress and vigilance affects performance to a greater extent than a single factor. Finally, the previously discussed association between workload and stress may suggest that stress arises from workload of the vigilance task. To the author's knowledge, research has not generally considered the interaction of more than two factors. Primarily, dyadic relationships are reported within the literature. If such factor interactions were addressed in future research, a more comprehensive understanding of the interaction of vigilance, stress and human performance would be achieved (Nickerson, 1992).

A note may be made here regarding the relationship between stress and situation awareness (SA). Endsley (1995a) hypothesized that stress would impact SA, due to attention narrowing and decreases in working memory capacity. Endsley (1995a) postulated that the resultant decrease in SA would negatively impact performance. No empirical investigation was conducted to support these colloquial hypotheses, and this area has been largely under-researched (Perry, Sheik-Nainar, Segall, Ma & Kaber, 2008). Further empirical research is needed to explore this interaction between stress and SA, and the resulting impact on performance.

The relationship between stress and communication has been examined primarily through two primary streams of research. One research stream focuses on the impact of stress on communication error. Bellorini (1996) examined this relationship in a field study in an air traffic control (ATC) centre. Communications were recorded and controllers completed self-report stress measures. It was found that communication omissions were more frequent when controllers were experiencing high stress. Results also revealed that a high density of communications resulted in stress increases. This may indicate a bi-directional relationship between stress and communications, or workload and stress effects. Workload was not reviewed, so it is not possible to infer if a three way interaction was evident in these findings. As the relationship between stress and communication may be bi-directional in nature, it is important for future studies to examine this relationship in controlled experimental settings to confirm the causal directions of the relationship. Additionally, future research should examine the triadic interaction between workload, communication and stress. These gaps in knowledge must be addressed for progression in error prediction and prevention.

The second strand of research focuses on the impact of stress on speech characteristics. Changes in speech characteristics have been attributed to the physiological impact of stress on the vocal tract and surrounding muscles (Womack & Hansen, 1996). Ruiz, Absil, Harmegnies, Legros and Poch (1996) explored the effects of stress on communications in both laboratory and field settings. Within the laboratory study, participants were asked to engage in a stroop task. Participants named the colour of a word which was congruent to the actual word (for example, the word 'red' was presented in the colour red). Participants then named words presented in incongruent colours (for example, the word 'red' was presented in green). This incongruence is postulated to be stressful (Ruiz et al., 1996). In the field setting, communications from an aircraft accident were analysed. Both studies found pitch and intensity changes as a result of stress increases. In the laboratory condition, it was possible to distinguish between low, medium and high stress through speech characteristic analysis (Ruiz et al., 1996). It may therefore be suggested that speech characteristics are significantly affected by stress, and may be a useful online indicator of individual levels of stress. However, variations in speech are difficult to quantify. Although most studies report stress-related *changes* in speech characteristics, the specific changes between individuals are largely inconsistent (Womack & Hansen, 1996). These challenges must be addressed if communications are to be utilized as an overt indictor for psychological stress.

In summary, further research is required to establish the nature of the factor interactions briefly discussed above, and the subsequent effects on performance. As knowledge of the factor relationships grows, the ability to predict complex interactions improves. With this improvement, it may be possible to prevent performance degradation prior to human error through human error prediction. This would be a critical advancement for safety-critical domains.

2.3.2 Factors referring to cognitive processes

2.3.2.1 Attention

Endsley and Rodgers (1996) investigated attention distribution and situation awareness in an air traffic control (ATC) simulation. Qualified air traffic controllers (ATCOs) were presented with fifteen visual radar-screen scenarios involving operational errors that had previously occurred. The scenarios started from ten minutes prior to the operational error. A 'freezing' technique was used to measure SA. During each scenario, the recreation was frozen twice and participants were asked to complete a series of questions about the developing situation. Results showed that ATCOs strategically distributed attention to process critical information on the radar screen, including the aircraft's control level and initial alphabetical part of the aircraft's call sign. Significantly less recall was found for non-prioritised information, such as aircraft groundspeed, altitude and numerical part of aircraft call sign, potentially indicating that attention had not been focused on these factors (Endsley & Rodgers, 1996). The authors concluded that strategic attention allocation is needed in such dynamic environments due to the high frequency of stimuli, and that such strategies are effective in the majority of ATC tasks. However, Endsley and Rodgers (1996) suggest the relative lack of attention to the numerical aspect of the call sign may negatively impact performance, and account for a high number of read back errors usually seen in ATC (Rodgers & Nye, 1993). Endsley and Rodgers (1996) also concluded that the attention distribution strategies exhibited may sometimes lead to a reduction of SA. If attention is not directed to certain key information in the environment, SA cannot be maintained. Subsequently, the reduction in SA is likely to lead to a decline in human performance. The impact of the attention distribution strategies on performance was not investigated. Future research may expand Endsley and Rodger's (1996) research by investigating the hypothesis that attention distribution strategies may negatively impact both SA and human performance.

Many other research strands have investigated the impact of other human factors on attention. The impact of stress on attention, and subsequently performance, has previously been discussed and will not be repeated.

Fatigue is also a human factor that has been found to affect attention. Stern, Boyer, Schroeder, Touchstone, & Stoliarov (1994) investigated the relationship between fatigue and attention using an ATC simulation task. Participants engaged in ATC simulation tasks for two hours per day for three days. ATCOs' gaze targets and gaze control measures were recorded at varying points throughout the tasks as an indicator of periods of impaired attention. Results revealed significant fatigue and time on task effects for 13 gaze control measures including fixation duration and blink rate. Stern et al. (1994) concluded that the changes in gaze control reflected a breakdown of inhibitory control as fatigue rose, resulting in an inferred impact on attention. However, attention may not be conclusively inferred from gaze control. The definition of attention suggests a focused perception of a target in the environment. By measuring gaze, it cannot be established if an individual was attending to a target, or simply looking at a target, without perception. Therefore, future studies should examine the relationship between fatigue and attention using a more direct measure of attention. Stern et al. (1994) did extend previous research by suggesting a physiological measure that may be sensitive to fatigue, however. Measures of gaze control may potentially provide an overt measure of fatigue if further developed.

A point of comparison of the differential effects of stress and fatigue on attention may be noted. As previously discussed, stress primarily affects a psychological attention function, eliciting cognitive strategies which reduce the attentional field and the number of targets processed (Ozel, 2001). Comparably, Stern et al. (1994) has demonstrated that fatigue may affect the physiological mechanism of orienting and attending, required prior to cognitive processing. This may suggest that specific human factors impact other factors on differing levels of physiological mechanisms and psychological mechanisms.

In summary, attention has been primarily investigated in terms of the impact from other human factors. Further research should therefore expand previous knowledge by investigating the combined interaction effects of attention and other human factors on performance. This would not only further knowledge of factor interactions with attention, but also provide an ecologically valid representation of the likely interactions and effects on human performance and error.

2.3.2.2 Vigilance

The relationship between vigilance and other human factors has been considered in the literature, although notably less than the effect of vigilance on human performance. The impact of mental workload on vigilance has been discussed previously; however research also suggests that vigilance influences workload. Warm, Dember and Hancock (1996) investigated the impact of vigilance on workload using a target detection task. Target detection frequency was used as a measure of performance, and a NASA-TLX subjective workload questionnaire was used to measure participant workload. The vigilance decrement correlated with an increase in subjective workload (Warm et al., 1996). This study supports an association between vigilance and workload. However, the investigation unfortunately does not permit a causal relationship between workload and vigilance to be inferred as a correlational design was used. Further empirical research should therefore investigate the causal nature of the relationship between vigilance and workload. In a real-world setting, it is likely workload and vigilance would interact dynamically in a bi-directional relationship. It may therefore also be of benefit for further research to investigate the nature of this bi-direction interaction, and the combined effect of this relationship on human performance.

The relationship between vigilance and stress has previously been explored. Therefore, this relationship will not be again reviewed. Stress is an additional a human factor which has been reported to be associated with vigilance.

The impact of vigilance on attention has been explored to a limited extent in the literature. Attention may be defined as the cognitive act of orienting and perceiving specific items in the environment (Eysenck, 2001). Vigilance and attention are argued to be independent constructs, although significantly related, as attention is required for vigilance tasks. Deaton and Parasuraman (1993) have hypothesised that vigilance would deplete cognitive resources, resulting in decreased attention. As attention resources are depleted, the vigilance decrement may occur, as suggested by the attention resource theory (Wickens, 1984). However, limited empirical research has investigated this hypothesis, and future research is needed to address this potential interaction.

Further research is also needed to explore the bi-directional interactions between vigilance and other human factors. With increased knowledge of factor interactions and subsequent impacts on human performance, the potential to predict when human error is likely to occur is achievable (Hollenbeck et al., 1995). This would have significant implications for safety critical industries which depend on human operators monitoring automated systems.

2.3.2.3 Situation awareness

The relationships between SA and other human factors are primarily reported to be uni-directional. Most human factors impact SA, and SA may then affect human performance. This proposition is implicitly supported by Endsley's (1995a) hypotheses that a number of human factors would impact SA. For example, Endsley (1995a) suggested that the known consequences of mental workload and stress (narrowing of the attentional field, decreases in working memory capacity) may result in an incorrect understanding of the surrounding environment, leading to a reduction in SA and therefore performance. These hypotheses were not empirically investigated however, and the causal analysis of factor impacts on SA remains under-researched (Perry et al., 2008).

Hancock, Simmons, Hashemi, Howarth, & Ranney (1999) used a driving task to investigate the effects of mental workload (workload) on task performance. Participants were asked to complete 60 circuits of a test track, stopping at red lights as appropriate. A telephone was utilised as an in-car distracter. Results revealed that braking response times and driving manoeuvre errors increased with the presence of the distracter, demonstrating a performance decrease with increased workload (Hancock et al., 1999). Ma and Kaber (2005) suggested that high mental workload negatively impacted SA by resulting in a drop in driver awareness. Subsequently, performance was negatively impacted. However, SA was not directly measured in Hancock et al.'s (1999) investigation, and so Ma and Kaber's (2005) hypothesis could not be confirmed. Additionally, a subjective measure of workload was not used. Therefore, it cannot be determined if the drop in performance resulted from the interaction of workload and SA or simply from distraction. To address these limitations, Ma and Kaber (2005) used a simulated driving task to investigate the relationship between workload and SA. At periodic points in the task, participants engaged in a telephone conversation. Ma and Kaber (2005) used a simulation freeze technique to measure SA. The task was temporarily suspended, and participants were asked a series of questions on their current driving situation. Subjective workload was measured using a workload scale. Task performance was measured in terms of lane deviations and speed control. Results showed a marked decrease in performance during the telephone conversation. Additionally, workload ratings increased, and SA performance dropped. The authors concluded that the telephone conversation placed an extra cognitive load on participants, leading to less resource capacity. The ability to maintain attention decreased, which resulted in a negative impact on SA (Ma & Kaber, 2005). It should be noted that these results were generated in a medium fidelity driving simulator (Ma & Kaber, 2005) which may limit the generalisation of the results to real world environments. Additionally, the precise nature of the relationship between workload, SA and performance may not be confirmed from the results of this investigation. Although a relationship between workload and SA can be inferred, the results cannot suggest a causal link as factors which may moderate or mediate the relationship were not controlled. Therefore, further research in a controlled laboratory setting may be needed to address these limitations and confirm Ma and Kaber's (2005) results. The relationship between workload and stress (previously discussed), may also be relevant to the interaction of SA and workload. Further research is required on this potential three factor interaction, and resultant effect on performance.

Communication is a prominent factor that impacts SA. Koester (2003) investigated SA through observations of 8 maritime voyages. Bridge communications were recorded at predefined time intervals and analysed for evidence of levels 1 and 2 SA. Koester (2003) therefore used communications to infer SA. Communications were categorised as general, or relevant. Results showed that at potentially critical situations, relevant communication types increased and general communications dropped. Koester (2003) concluded that the rise in relevant communications indicated the attempt to share information and maintain situation awareness. Unfortunately, as this study used an observation design, no independent measure of SA was used. A relationship between communications and SA cannot therefore be conclusively supported from this study. Additionally, the direction of this relationship cannot be established. It may be that communication results in the maintenance and support of SA, and therefore, the maintenance of human performance, as suggested (Koester, 2003). However, communication may also have risen due to a rise in individual SA, resulting in the use of communications to raise Team SA. In this case, SA would have initially affected the increase in communications. This possibility of a bi-directional relationship cannot be explored from the findings of this study. The utility of the results is therefore limited. Further research must explore multiple factor interactions, and the direction and nature of those interactions to address this significant gap in knowledge. Once factor interactions have been researched, the likelihood of a human error resulting from SA losses may be predicted. This is a critical progression for safety research.

2.3.3 Factors resulting from individuals acting within a team environment

2.3.3.1 Communications

The relationships between communication and mental workload, communications and stress and communication and situation awareness (SA) have all been previously discussed, and so a review of these areas is not again necessary.

The intuitive relationship between communications and teamwork is experimentally supported (Sexton & Helmreich, 1999). Ruffell-Smith (1979) investigated the impact of communications on teamwork in an aviation simulator study. Pilot crews were asked to work together as they would in real life. Communications were recorded and analysed in terms of quality and quantity. Team performance was assessed by effectiveness in fulfilling objectives, and human errors were recorded throughout the study. Findings showed that the quality of crew communication was more closely associated with crew performance than the technical proficiency of individual pilots, inferring a significant impact of communications on teamwork. A comparison of teams rated as 'effective' and 'ineffective' did not reveal any significant differences between the frequency or severity of errors. However, Ruffell-Smith (1979) concluded that effective teams had higher quality and more effective communications. Communication was therefore inferred to increase team working effectiveness, and to moderate the impact of error on team performance. Further research is needed to determine if a causal relationship exists between communications and teamwork. The interaction between teamwork and communication has been comparatively under-researched, although often the relationship between communications and teamwork is colloquially recognized (Sexton & Helmreich, 1999). Communications and teamwork are critical constructs in most industries, and a comprehensive understanding of this relationship, and its impact on performance, would have significant implications for education and training in safety critical environments.

Communication has also been colloquially recognised to impact trust (Willemyns, Gallois & Callan, 2003) as communications are the main channel of social interaction (Hogg & Vaughan, 2002). Willemyns et al. (2003) empirically investigated the impact of communication on perceptions of trust. Employees working in a variety of organizational sectors completed two questionnaires requiring written descriptions of a satisfactory and unsatisfactory interaction with a supervisor or manager. Participants were asked to describe the conversation in as much detail as possible, including any recalled specific statements. Several closed-response questions measured participants' perception of this interaction. Content analysis revealed that communications classified as 'in-group' communications, such as non-dominating communications, small talk, significantly increased the level of trust in a supervisor. 'Out-group' communications, such as dominating styles, lack of support, critical messages, led to a lack of trust. The authors concluded that the investigation provided evidence that "certain communication characteristics can result in greater trust in manager-employee relationships" (Willemyns et al., 2003, p117). As this investigation was focused on organizational and retail setting communication, it may be suggested that results may be limited in generalisation.

Further research of the relationship between communications and trust in a setting with regulated communications, such as ATC, may further knowledge of the interaction between communication and trust. In aviation, communications are strictly regulated in an attempt to reduce error potential (Tajima, 2004). With these strict regulations for communication, and the level of dependence between controllers and pilots for effective role completion, research may establish whether trust would be a crucial component for the effective communication between these interdependent groups. It may also be investigated if 'in-group' and 'out-group' communications would affect trust in this type of environment.

2.3.3.2 Teamwork

The relationship between teamwork and stress is one of the more researched human factor interactions (e.g. Kontogiannis & Kossiavelou, 1999). Kontogiannis and Kossiavelou (1999) suggest that several teamwork components could act either as stressors or stress-moderators. Teamwork may therefore either exacerbate or alleviate stress, subsequently impacting human performance. However, Glaser et al. (1999) argue that the relationship between teamwork and stress is relatively weak. Glaser et al. (1999) used a work simulation study to investigate the impact of workload on stress and performance. This study has previously been discussed. However, Glaser et al. (1999) extended this investigation to examine the relationship between teamwork, stress and workload. The authors utilised the same experimental design, which required participants to complete data entry tasks on a computer database. Participants were placed in either a high workload or low workload condition. Subjective measures of workload, stress and perceptions of social support were recorded throughout the investigation. Results demonstrated that in the low workload condition, perceived stress was low regardless of participants' perceptions of high or low social support. However, in the high workload condition, a reverse buffering effect of teamwork was found, wherein high social support resulted in significantly higher stress levels. Towards the end of the study, subjective ratings of both teamwork and stress declined, regardless of workload (Glaser et al., 1999). Unfortunately, the data for social support and stress were collected concurrently, and it is therefore not possible to infer the causal relationship between the three factors. In an attempt to explain the reverse-buffering effect, Glaser et al. (1999) suggested that, if negative feelings about the task were discussed between team members at the beginning of the experimental period, high social support may have resulted in increased stress. Glaser et al. (1999) also suggests that the decline in stress may have resulted from previous perceptions of high social support. As causal relationships cannot be inferred from this investigation, it is not possible to confirm this hypothesis from the study's findings. An alternative explanation may be that the perceived decline in teamwork and social support led to a reduction in stress. Further research is therefore needed to address the causal relationship between teamwork, stress and workload. Further understanding of the conditions under which teamwork elicits a buffer effect, or reverse buffer effect, should also be developed. If these relationships are understood, it may be possible to predict when teamwork may support performance, or when teamwork would result in a negative performance impact. This may have implications for guiding the select use of team working in safety-critical industries.

Kontogiannis & Kossiavelou (1999) suggest that a bi-directional relationship exists between teamwork and stress. In an investigation of the effect of stress on teamwork, Serfaty, Entin, & Volpe (1993) used teams of military commanders to investigate if performance was maintained under time pressure stress. Results showed that efficient teams were able to maintain the same level of performance with one-third of time available to make decisions. Serfaty et al. (1993) suggested that under high time pressure, subordinates changed communication strategies towards their commander. Instead of waiting to report based on commander requests, information was provided to commanders on what the subordinates considered would be useful. The authors concluded high stress had impacted on team working strategy, and an adaptive shift in communication patterns maintained team performance (Serfaty et al., 1993). The specificity of the environment may limit the generalisation of these findings. Strict hierarchical regulations regarding team working and communication are not necessarily existent in less safety critical environments, such as business organizations, and the effects of teamwork on stress produce differing results. Further research may therefore attempt to replicate these findings in different domains.

The affect of teamwork on communications has been explored in the literature. This review has previously explored the impact of communication on teamwork, but there is evidence to suggest a possible bi-direction relationship. Cannon-Bowers, Salas, and Converse (1993) reviewed the cognitive process of 'shared mental models' associated with teamwork. Such models may be defined as "organized bodies of knowledge that are shared across team members (Salas et al., 1995, p127). Cannon-Bowers et al. (1993) hypothesized that shared models improve performance by enhancing team coordination, and enables a greater understanding of other team members. As a result, communication may fall. A review of the literature within this area has revealed limited experimental support for this concept, however. Future research is needed to investigate this relationship.

Limited research on the interactions between teamwork and other human factors has previously been noted (Rasmussen & Jeppesen, 2006). Many safety critical environments involve teamwork, and so further research in this area is critical to develop an understanding of the relationships between teamwork and other human factors. This understanding may result in the ability to predict declines in team or individual performance, which may then be prevented or mitigated before the occurrence of human error. These developments in knowledge are critical for focus to shift to error prediction and prevention, rather than the current retrospective approach to human error.

2.3.3.3 Trust

Although research of the relationships between trust and other human factors is limited, the interaction of trust and teamwork is most often investigated. Three decades prior, Golembiewski and McConkie, (1975, p131) suggested "there is no single variable which so thoroughly influences interpersonal and group behaviour as does trust". The impact of trust on teamwork has also been noted in more recent years, with the acknowledgement that trust is needed for effective teamwork (Costa et al., 2001; Erdem and Ozen, 2003). Kiffin-Peterson and Cordery (2003) investigated the relationship between trust and attitudes towards teamwork. Over two hundred employees from forty work teams were surveyed on trust and teamwork related concepts, such as attitudes towards teamwork, trust in colleagues and trust in managers. The results indicated that two forms of situational trust (trust in co-workers and trust in managers) were stronger predictors of preference and positive attitudes to teamwork than dispositional trust. Additionally, situational trust was found to partially mediate the relationships between disposition or trait related trust and preference for teamwork (Kiffin-Peterson & Cordery, 2003). Unfortunately, this study did not investigate the impact of these attitudes on team or individual performance, instead simply affirming the impact of trust on teamwork preference.

Erdem and Ozen (2003) addressed this limitation, and extended Kiffin-Peterson and Cordery's (2003) study by investigating the relationship between trust and team performance. Fifty work teams from ten organizations completed a questionnaire which incorporated questions of cognitive and affective trust of team members, and self rated team performance. Results demonstrated that team members who rated their teams highly on both affective and cognitive dimensions of trust also reported more signs of effective performance, such as planning, solving problems and continuous improvement (Erdem & Ozen, 2003). Additionally, a negative correlation between both dimensions of trust and error was identified. As team performance was self-rated, the results may be influenced by response bias. Therefore, further research which uses objective measures of performance should confirm these findings. In summary, these findings have important implications for many domains, including team-focused, safety critical domains such as ATC. Erdem and

Ozen (2003) conclude that behaviour promoting trust in teams should be encouraged by organizations to support high performance, and potentially reduce error.

The impact of trust on the factor of stress has also been reviewed in the literature. Costa et al. (2001) developed a model of trust, stress and perceived task performance using structural equation modeling (SEM). Initially, data was collected from 144 teams in three social care institutions. Employees were asked to complete questionnaires consisting of Likert scale measurements of perceptions of team trust, perceived task performance and stress. SEM was used to analyse and structure the data. Results suggested that trust is positively related with perceived task performance, and negatively related with stress. Unfortunately the potential dyadic and triadic factor interactions were not examined. The reliability of the findings may be also be questioned. SEM, although a detailed and accepted analysis methodology, represents a theoretical model that best fits the data. Therefore, empirical validation of this model should be conducted to confirm these results. Additionally, the authors themselves note that it is not possible from the findings of this study to assess the actual contribution of trust in positively impacting performance and reducing stress (Costa et al., 2001). Further research should therefore validate and extend this model, and investigate these factors in controlled experimental studies in which causality between trust, stress and performance can be separated and identified. This research would further develop understanding of the interaction between trust, stress and human performance.

2.3.4 Implications of literature review findings relating to multifactor influences

To date, research that investigates multifactor associations with performance, particularly within ATC settings, are infrequent. By moving attention to investigating factor interactions and performance impacts, investigation of the error likelihood resulting from such relationships would be possible. This presents the possibility of preventative or supportive measures being implemented when error is known to be likely, potentially preventing human error which may have resulted in an incident. This goal is especially relevant to safety critical environments such as air traffic control, in which human error could result in injuries or lives lost.

2.3.5 Summary of working definitions of factors

The definitions of each factor are as follows:

1. Workload: Perceived demand (amount and complexity) imposed by ATC tasks, demand on mental resources, and associated subjective perception of effort to meet demands.
2. Fatigue: A physiological state of reduced mental or physical performance capability resulting from sleep loss or extended wakefulness, circadian phase, or workload (mental and/or physical activity) that can include feelings of tiredness or weariness and impair alertness and ability to perform safety related duties
3. Stress: Pressures imposed by the situation which challenge the controller's ability to cope
4. Attention: The application of cognitive processes to focus on a specific environmental target necessary for further target processing
5. Vigilance: The ability to pay continuous attention to an environmental field for a period of time to detect particular changes which is affected by alertness
6. SA: Maintenance of a coherent mental picture for current and future events based on continuous extraction of environmental information, which includes controller performance
7. Communications: The exchange of information, including timeliness, accuracy, clarity and receptiveness
8. Teamwork: Collective and mutual interaction with humans in the system for performance
9. Trust: The level of confidence in events, people, equipment or circumstances

2.4 Conclusion

This review of human factor relationships and factor associations with human performance, spanning the past three decades, has presented and discussed nine of the primary human factors known to have a significant impact on performance and error. Complex, often bi-directional and sometimes controversial, relationships were found in the literature. This review suggests that investigations have primarily focused on relationships between factor dyads only, limiting knowledge of ecologically valid factor co-occurrences and relationships. In addition, few studies continue to investigate the association between multiple factors and performance. Finally, as most studies investigating factor relationships apply a correlation design, resulting in limited research on the causal relationships between human factors. Future research should address the significant gaps in literature, including developing understanding of human factor interactions, and the combined effect of these interactions on human performance and error. Future research can address a research gap by establish an understanding of the causal relationships between factors.

2.5 Chapter summary

The literature presented in Chapter 2 summarised research spanning several decades on relating to a specific set of nine human factors (workload, fatigue, stress, attention, vigilance, SA, communications, teamwork, trust) and performance. The chapter was divided into two sections. Within each section the nine human factors were grouped into three novel categories for consideration: factors resulting from an interaction between individual and environment, factors referring to of cognitive processes, and factors resulting from individuals acting within a team environment. Categorisation resulted from recurrent patterns in the literature of the consideration of factors.

The first section presented an overview of each of the nine factors and considered the association between each factor and human performance. The review supported that each human factor had been reported to influence human performance, and specifically, human performance within an ATC setting. This information contributed background information to the thesis and to the project aim of identifying a set of factors that have been found to influence controller performance. The second section reviewed research investigating relationships between the nine human factors and the association between combined multiple factors and performance. The review provided support for the occurrence of relationships between factors, although some controversies and conflicting findings were identified. Gaps in research were identified. Few studies investigated the relationships between three or more factors, or associated multiple related factors with performance. In addition, correlation research designs were primarily utilised to investigate factor relationships and so causality was not established. It is subsequently suggested that further research is conducted to address these research gaps. This section of the review contributed to the current research by providing background information regarding previous findings, and provided initial information for later hypothesis generation of the relationships between factors.

The review concludes with a suggestion that, in order to progress in the area of human performance, and human error prediction, it is necessary to focus future work on exploring the relationships between human factors, and the combined, subsequent association on human performance and error, in both laboratory and applied settings. This may serve to reduce the current controversies in this field, and lead to further understanding and progression in the area of human performance.

Chapter 3. Understanding air traffic control

3.1 Chapter overview

This chapter describes the stages the researcher went through to become familiar with the air traffic control (ATC) domain. Background information on the air traffic management (ATM) and ATC systems is first described, followed by a description of the further insight gained from the researcher's visits to air navigation service providers (ANSPs) and ATC operations rooms. Experiences and insights into the ATC domain that are pertinent to future research considerations are presented.

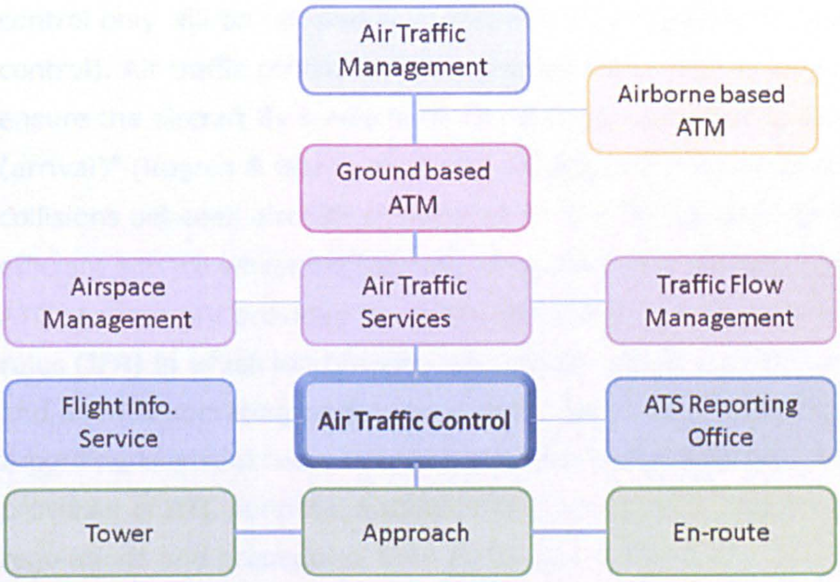
3.2 Air traffic control in context

Air traffic control is a safety critical domain that relies on air traffic controllers to maintain a safe distance between aircraft. Unlike other high risk industries (e.g. nuclear industry) controllers orchestrate the traffic live, and there are few safety mechanisms and no physical barriers to defend against accidents. Air traffic control is therefore highly dependent on the maintenance of exceptional human performance. In a context of growing demands for air travel, it is essential that human performance is supported and maintained.

3.3 Air traffic management (ATM) system

Air traffic control is a ground based service provided as part of the air traffic management (ATM) system (Figure 3.1). Air traffic management (ATM) is made up of several systems and incorporates the planning, organisation and control of all air traffic movements (ICAO, 2007). ATM provides a service to airspace users (pilots, airlines), with the objective to ensure the safe, orderly and expeditious flow of air traffic (ICAO, 2005). ATM follows consistent and internationally agreed procedures and regulations, as set out by ICAO legislation. This standardisation facilitates efficient transitions between airspace regions, or sectors, both nationally and internationally, for aircraft. Figure 3.1 (adapted from Malakis, 2008) presents the structure of the ATM system.

Figure 3.1. The hierarhcial structure of air traffic management elements, including air traffic control



ATM consists of airborne systems, primarily on aircraft's on-board systems such as communications, navigations and surveillance (CNS) technologies, and ground-based systems which incorporate all components conducted on the ground that facilitate air travel. A distinction can be made between three broad services (Figure 3.1). Airspace management is a continuous function which aims to provide the most efficient flight routes for aircraft. Traffic flow management provides efficient routes through sectors and distributes aircraft so controllers will not be overloaded. These components are responsible for the organisation and planning of airspace. As such they do not interact with aircraft directly, but facilitate the efficient and safe flow of traffic through the airspace. The third component, Air traffic services (ATS) is responsible for the control of aircraft through the airspace. Three distinct services achieve this function (ICAO, 2007). The flight information service is available to any aircraft within a flight information region (FIR) (as agreed by ICAO), and includes information that is relevant to the safe and efficient flight of the aircraft. The specific services provided by ATS to aircraft are determined according to the classification of the specific airspace. The reporting office classifies reported aviation issues.

3.4 Air traffic control

The foundation of the ATS function is the air traffic control service. Civilian control only will be referred to in this thesis (as opposed to military control). Air traffic control (ATC) is a service provided to airspace users "to ensure the aircraft fly safely from one place (departure) to another one (arrival)" (Rognin & Blanquart, 2001, p329). ATC objectives are to prevent collisions between aircraft and aircraft and obstacles, and provide an efficient service whilst maintaining an orderly flow of traffic (ICAO, 2007). ATC services are provided to all aircraft operating under instrumental flight rules (IFR) in which instruments are primarily used for flight by the pilot, and aircraft operating under visual flight rules where pilots fly the aircraft according to visual cues, in selected sections of controlled airspace. The provision of ATC services is standardised across ICAO member states by regulations and procedures from ICAO (i.e. ICAO, 2007, doc 4444), to which all member states are expected to adhere. The service is provided by ground based air traffic controllers (ATCOs) who instruct aircraft movements, primarily through verbal communication, for efficiency or safety purposes. ATCOs are responsible for aircraft safety, and are required to maintain the legal minimum separation between aircraft of 1000 vertical feet and 3-5 nautical miles, depending on the airspace. Aircraft operate 24 hours a day. As such, ATC services are required 24 hours a day. ATCOs work shifts to meet this demand (Della Rocco, 1999). Shift schedules and lengths vary by ATC centre.

3.4.1 Air traffic control and airspace design

Within each country, controllers guide aircraft through regulated airspace. The airspace is theoretically divided into distinct, adjacent regions known as sectors. Sectors vary in size, both laterally and vertically, and have been described as creating a three-dimensional jigsaw (Bonini, 2005). Typically, two controllers will be in control of one sector at any one time; depending on the country and airspace, this varies between one – three controllers per sector. Once the aircraft has reached the edge of the airspace, the controller is required to hand off the aircraft to a controller in the adjacent sector. Sector dimensions can be changed to accommodate changes in traffic levels as well as other constraints such as military activity (Bonini, 2005). Each sector has a pre-determined capacity limit to prevent operator overload. Capacity limitations are the primary limiting factor on increasing traffic levels (Huttunen et al., 2011). Changes and advancements to the airspace or ATC system are therefore generally focused on increased safety and/or increased throughput of traffic. The ATC demands of each sector are different and so controllers must complete a period of supervision on each sector group before controlling alone (Bonini, 2005; Kirwan et al., 1997).

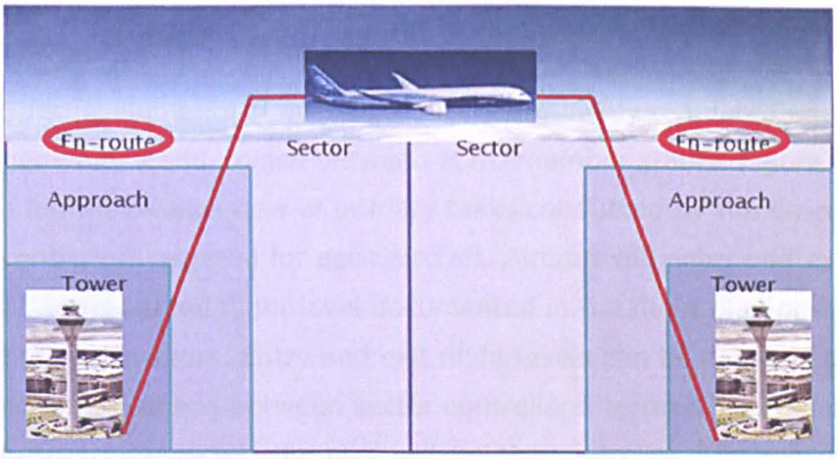
3.4.2 Types of air traffic control

Three separate ATC units provide services to aircraft: tower control, approach control and en-route control. Each unit has distinct responsibilities and tasks, although all provide ATC services within the prescribed function of ensuring safe and expeditious flight (ICAO, 2001). The unit that provides the ATC service to the aircraft depends on the phase of flight of the aircraft (Figure 3.2). The complete flight process may be divided into 12 sections, each associated with a unit of ATC (Malakis, 2008) Table 3.1 presents ten flight stages and associated ATC.

Table 3.1. Phases of flight and associated ATC unit control

Phase of flight	**Associated ATC unit**
Engine start & taxi	Tower control
Take off	Tower control
Initial climb	Approach control
En-route climb	En-route control
Cruise	En-route control
Initial descent	En-route control
Descent	Approach control
Approach	Approach control
Landing	Tower control
Taxi & parking	Tower control

Figure 3.2. Process of aircraft flight phases



Tower control is responsible for the initial engine start up, taxiing and take off of the aircraft. Tower controllers sequence ground traffic to and from the gate. Tower controllers will hand over or receive aircraft from approach controllers. Tower control is performed at the airport or aerodrome, and controllers visually monitor the aircraft. Depending on the size of the airport and traffic density, the taxi management duty may be conducted independently by a ground controller whilst takeoff and landings responsibilities may be conducted by a local tower controller. Approach control manages the safe and efficient initial climb from, or descent to, an airport (Figure 3.2) and sequence aircraft based on efficiency and safety considerations. Approach control is radar based, and many approach control units will be based at the airport or aerodrome (Wickens et al., 1997). En-route control provide ATC services (e.g. issuing clearances, maintaining separation and efficiency) for all aircraft in the final ascent from the aerodrome and beginning descent into the aerodrome, in additional to all aircraft who are in the cruising phase. Flights are directed along pre-established routes through the airspace. Instructions are issued to maintain separation or for expeditiousness and efficiency (ICAO, 2005). En-route controllers use radar information to provide guidance for aircraft. The only exception to this is during oceanic flight where controllers rely on verbal contact from the aircraft at specific times, also known as procedural control. En-route control is the focus of this PhD and will be discussed in detail in the following sections.

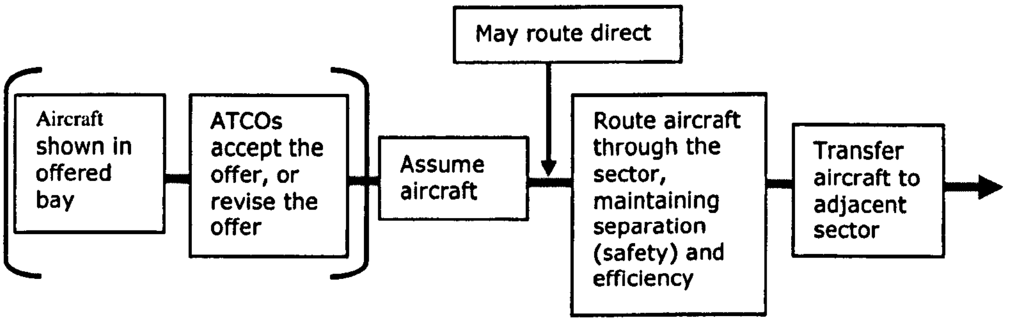
3.5 En-route control task

3.5.1 Standardised/regulated tasks

Specific elements of en-route control are highly regulated and therefore generally standardised between ICAO member states. Figure 3.3 presents a high-level overview of primary tasks conducted by the en-route controller, required for each aircraft. Aircraft will enter and exit the sector at a pre-agreed flight level documented in the flight plan or agreements between sectors. Entry and exit flight levels can be changed through communications between sector controllers, termed 'coordination'. On entry to the sector, the pilot will call the controller. The controller responds and formally takes control of the aircraft. The controller manages the aircraft through the sector via verbal or written instructions (data-link). The aircraft will exit the sector at the agreed flight level, or be re-coordinated to a different flight level as necessary. Once the aircraft is close to the sector boundary, the controller will instruct the aircraft to change radio frequency and make contact with the adjacent sector controller.

Due to the demands placed on controllers, session time is limited to a maximum of 2 hours with a minimum of a 30 minute rest break between sessions. Shift time is also strictly regulated to combat fatigue and the effects of other stressors on ATCO performance.

Figure 3.3. High level en-route ATC tasks for each aircraft



3.5.2 Cognitive elements of an en-route control task

ATC is a highly cognitive task (Eurocontrol, 2007). Controllers engage in a repeated process of distinct cognitive tasks to manage traffic (Djokic et al., 2010). Controllers monitor aircraft, including speed, flight level and route.

Vigilance is therefore a critical element of the control task. Controllers then evaluate the information to identify any potential conflicts or opportunities to improve efficiency. Decision making is integral to the control task (Bonini, 2005). Controllers then make a plan and prioritise actions for the efficient and/or safe management of the traffic. To plan efficiently, controllers must be able to anticipate future events, such as aircraft trajectories and pilot intentions, which is an essential cognitive skill (Niessen et al., 1999). Anecdotally, en-route controllers report developing plans for the projected situation two or three minutes ahead of the present time. Controllers usually develop several backup plans which can be applied if the situation changes. This flexibility is critical to control traffic in a dynamic environment. Controllers therefore assess and prioritise plans (Lenorovitz & Phillipp, 1987) to determine the most appropriate strategy for the situation at the present time. Controllers implement the preferred plan through verbal instructions to pilots. The plan must be executed at the correct time and in an appropriate sequence. Controllers have to divide attention between multiple tasks and aircraft.

Situation awareness is a critical element in controlling aircraft and anticipating future events. Controllers maintain SA through a mental representation. The mental representation is updated by consistently rescanning radar. Degradation of picture, and therefore situation awareness, can have severe negative consequences. Controllers may not be aware of all aircraft, or know the intentions of the perceived aircraft, and so cannot plan or prioritise actions.

3.5.3 Orchestration of traffic: personal control styles conducted within strict regulations

The orchestration of the traffic through the sector is dependent on the controller's choice of management strategy, conducted within strict regulations and procedures. Controlling aircraft is a creative process, and controllers differ on styles of control strategy. Learning to control has therefore been associated with learning a craft, with skills and strategies passed from instructor to trainee. Controllers actively interact with the traffic and by applying specific strategies, controllers regulate and manage their own workload (Sperandio, 1971).

3.6 Selection and training of en-route controllers

The selection and training of controllers is rigorous. Selection may incorporate a battery of cognitive ability tests and occasionally personality and biographical assessments (Wickens et al., 1997). Over 114 weeks, training progresses through lectures, simulations and on the job training with an increasing emphasis on independent control of aircraft in Europe. Controllers initially qualify on one sector group. Qualification on other sectors groups is possible after a period of supervised on the job training.

3.7 En-route control operations environment

ATCOs provide ATC services under dynamic and often challenging conditions (Huttunen et al., 2011). Numerous variables can influence the control situation, such as weather conditions or military activity, which will affect the management of traffic through the sector. Unexpected or emergency situations contribute to the complexity. Time pressure is an inherent characteristic of ATC (Rantanen & Nunes, 2005), which may act as a stressor (Wickens et al., 1997). Extremes of traffic frequency and complexity, resulting in high or low taskload, are each associated with separate challenges for the controller. It may be challenging to remain vigilant during periods of very low traffic. In periods of high traffic, controllers must divide attention between aircraft and complete multiple tasks, whilst making decisions and under time pressure and high taskloads.

Controllers also frequently transition between taskloads, and must rapidly transition state to the associated traffic demands contributing further to challenging conditions. Control systems and tools can also change relatively frequently. Controllers must therefore also adapt to frequent changes in the operations room.

3.7.1 Teams and coordination within air traffic control

The ATC service is achieved through the coordination and interaction of teams. In its broadest sense, each aviation professional contributing to the ATC service may be considered as part of the same team. Controllers' cooperation with other teams can be divided into intra-cooperation and inter-cooperation.

3.7.2 Intra-cooperation between controllers

3.7.2.1 Cooperation between controllers working on the same sector

"The control of aircraft is considered a combined team effort" (Rognin & Blanquart, 2001, p329). Each en-route sector, in general, will be controlled by two ATCOs working jointly on the same airspace, an executive controller (EC) and a coordinating controller (CC). All controllers can be an EC or CC during each session, planned via a roster. To facilitate cooperation, controllers are co-located on operational work stations. The EC and CC work as a team to provide a safe and efficient ATC service although each controller has separate responsibilities. The EC controls the aircraft and is responsible for managing aircraft through the sector and issuing clearances. The CC is often described as the EC's assistant (Rognin & Blanquart, 2001). Tasks include coordinating aircraft sector entries and exits with CC's on adjacent sectors, as well as supporting the EC as appropriate by highlighting conflicts, discussing plans or managing the number of aircraft in the sector to prevent overload. The supporting role of the CC reduces the EC's workload (Stager & Hameluck, 1990) and provides redundancy in the system by providing an additional pair of eyes and ears for monitoring traffic. The EC and CC must maintain a shared awareness of the traffic situation (Rognin & Blanquart, 2001) to work together by maintaining their own internal representation. In addition, the CC will observe non-verbal cues such as controller-pilot communications, speed of instructions, traffic situations on the radar (Rognin & Blanquart, 2001), to appropriately support the EC.

3.7.2.2 Cooperation between controllers during handovers

Cooperation between controllers on the same sector also occurs during hand-over of the control session. Once the ATCO (EC or CC) has worked the 90 or 120 minutes on session, control will be handed over to another ATCO. Frequently, an incoming ATCO will observe the traffic situation to build a mental picture. At an appropriate time, the outgoing ATCO will provide a verbal summary of relevant traffic information. Once the incoming ATCO feels comfortable, control will be handed over.

3.7.3 Inter-cooperation between controllers

Inter-cooperation occurs between controllers on adjacent sectors to maintain a smooth and integrated service. Aircraft will pass through several sectors from take-off to landing. Each aircraft must be coordinated to fly through each sector at specific entry and exit flight levels. Coordination is frequently implicit and potentially automatic depending on available systems. Coordination can be explicit through verbal communications if a change to entry or exit flight levels or routes is required.

3.8 Communication as an essential element of the air traffic control system

Both verbal and non-verbal communications are essential in the ATC system. ATCOs control aircraft by issuing verbal instructions to pilots using radio telephony (R/T), or written instructions using a data-link system. Verbal communications between controller and pilot also permit the exchange of relevant information such as location of weather and associated turbulence and position of other aircraft (Wickens et al., 1997). Air-ground communications, including phraseology, language and procedures are highly regulated and standardised which ensures comprehension between individuals (controllers, pilots) of different nationalities and native languages, and reduces errors in the communication process.

The readback-hearback process is an example of a communication procedure which reduces error. Once a controller communicates an instruction to the pilot, the pilot must 'read back' the message to the controller. The controller actively listens to this read back (known as the 'hear back') for inaccuracies. This creates redundancy in the system, and an opportunity for controllers to identify and correct errors.

Communication between the EC and CC on the same sector is essential for the transfer of information. As the ATCOs are co-located, communications may be verbal or non-verbal (Rognin & Blanquart, 2001). For example, a controller could point at the radar screen to inform the other of a particular situation. Verbal communication is still used, when possible, to transfer information, including reminders and discussing strategies and priorities. Verbal communications are also necessary for handovers between a controller incoming to the position and the outgoing controllers (section 3.7.2.2) and explicit coordination between adjacent sectors (section 3.7.3).

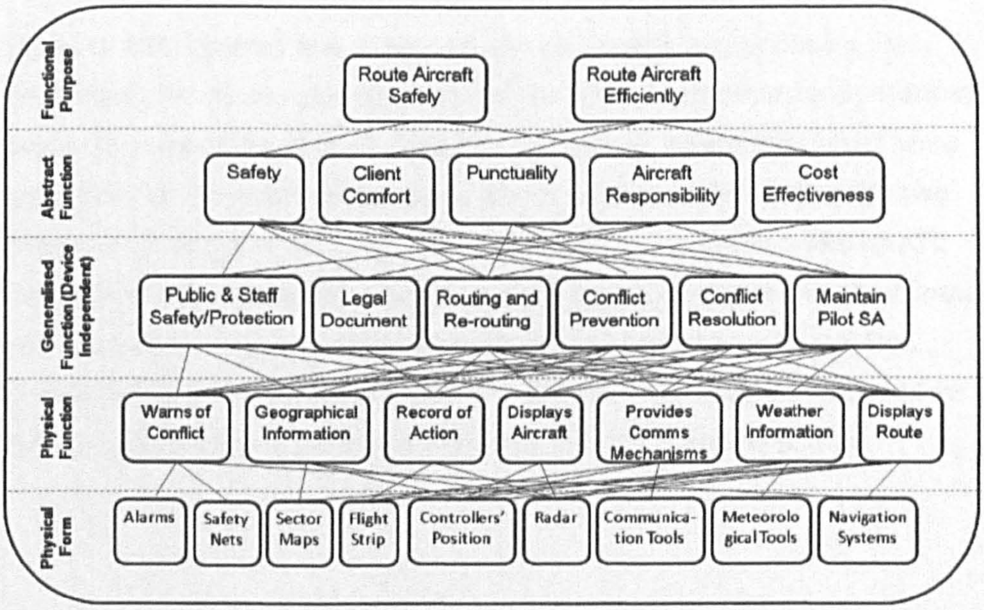
3.9 Physical systems used in the air traffic control task

A controller's work position (CWP) incorporates the physical systems and tools for controlling traffic. Although systems and technology can vary between centres, several technologies are standard. Each CWP will have a radar screen, electronic data display, keyboard, mouse, and trackballs. Radar is essential for monitoring aircraft, and displays information including sector boundaries, aircraft in and around the sector and aircraft information such as call sign, current and planned flight level, trajectory, speed and heading. Figure 3.4 presents a typical layout of an en-route ATC centre. Two controllers work together on one sector. Each ATCO has one radar monitor and several input devices to support the control of the aircraft.

Figure 3.4. En-route control room

Paper or electronic flight strips are also a controlling tool. Flight strips document the estimated time each aircraft should be entering the controllers' sector and facilitate traffic planning. For centres that use paper strips, a strip-board will be included in the CWP to organise the information of the upcoming traffic. For centres using electronic flight strips, this information will be presented on the controllers' computer display. To facilitate communications, each CWP is equipped with a telephone with direct lines to adjacent sectors for rapid coordinations. Verbal communication with pilots utilises Very High Frequency (VHF), or High Frequency (HF) or Ultra-High Frequency (UHF) radio. Controllers often wear headsets for communication which facilitates communication whilst leaving hands free for other tasks. A limitation of RTF communication is that the frequency cannot be utilised simultaneously which limits the number of aircraft a controller can manage. Some centres also have data-link systems for the controller to control aircraft with written instructions to the pilot; this system is dependent on the aircraft also being equipped with data-link. ATC systems and tools are designed to support efficiency and/or safety. Frequent additions of new tools, or system modifications, are also conducted to further support the controller in providing a safe and efficient service. Please see Millen, Edwards, Golightly, Sharples, Wilson and Kirwan (2011) for more detail on physical systems identified through the application of a work domain analysis using an abstraction hierarchy. The final abstraction hierarchy is presented in Figure 3.5

Figure 3.5. An abstraction hierarchy of the ATC domain



3.10 Familiarisation with the air traffic control domain

3.10.1 The need for familiarisation with the ATC domain

Air traffic control is a unique safety critical industry which is highly dependent on human performance. Several other safety critical industries, such as the nuclear industry, have highly regulated procedures for each task element. In addition, many task analyses are available which comprehensively summarise the operator task and environment. In contrast, controllers orchestrate traffic according to several variables, including the airspace design, current situation and own controlling style. Many more degrees of freedom exist in ATC. To comprehensively understand the domain and how to conduct research in the domain, familiarity with the ATC environment was needed (Kirwan, Kaarstad, Hauland, & Follesoe, 1995). A series of visits to ATC centres allowed the researcher to become involved in the ATC environment, and learn about the domain from aviation professionals and through informal observations. The experience informed the study approach and design of future investigations to ensure information was captured using the appropriate methods and analysis approach within this unique environment.

3.10.2 Generation of visits to control centres

Visits to ATC centres and meetings with air traffic professionals were organised. Practical considerations of visiting a high security environment (such as availability of host, security clearance) meant that visits were organised on an opportunity basis. Visits were generated through two avenues. EUROCONTROL, as the project client, arranged visits to ATC centres on the researchers' behalf. The researcher continued the contact with personnel and arranged future visits or meetings with aviation professionals as necessary. Table 3.2 summarises visits to ATC centres and aviation professional groups and the associated learning points.

Table 3.2. Operations rooms visited and resulting knowledge points

Organisation visited	Unit of ATC	Date attended	Knowledge points
Nottingham Tower ATC	Tower and approach control operations room	April 2009	Tower and approach operations room layout, environment, knowledge of different ATC units
EUROCONTROL experimental centre (GENSPACE Scheme)	Practiced en-route control in a full scale simulation	May 2009	Knowledge of ATC task, task processes, cognitive task, dynamic environment
National Air Traffic Service (NATS)	En-route control operations room	January 2010	Layout, environment, culture, systems, increased practical knowledge of sectors and control strategies
NATS	En-route control operations room	February 2010	
NATS	Meeting with incident investigators of en-route loss of separation incidents	April 2010	Incident investigation process, perspectives on controller performance and influences on performance, on ATC culture, interests in research outcomes
Safety-Improvement Sub-Group (SISG)	Meeting with European incident investigators and ATCOs	May 2010	Wider ATM context, interests and concerns of different groups
Belgocontrol (Belgium ANSP)	Approach and en-route operations room	July 2010	Systems and operations rooms organisation, management perspectives on performance and safety
Maastricht upper area control centre (MUAC)	En-route ATC operations room	April 2012	Organisation of operations rooms, systems, rostering process, supervisor responsibilities and task elements, organisation of several upper area en-route sectors
MUAC	En-route ATC operations room	June 2012	Controller experiences in relation to high and low workload, teamwork, communications, fatigue, stress

3.10.3 Summary of ATC-related information pertinent to future research

3.10.3.1 Culture of ATC professionals

Wider ATM contextual knowledge was provided by aviation professionals. Depending on role, such as centre manager, incident investigator, ATC supervisor, individuals had different perspectives of the ATM system and different interests and expectations of research designs and the practical application of research findings. This discrepancy was important to acknowledge, so that future meetings and suggestions for research were meaningful to the specific expert group. Overall, all aviation professionals were positive towards supporting research investigations, provided that research outcomes were relevant to the ATC environment, and could be practically applied to achieve a positive influence on safety and/or efficiency.

3.10.3.2 Experience of the different types of air traffic control

Experience of tower, approach and en-route operations rooms enabled an appreciation of the range of ATC tasks and contexts. Controllers in all units had similar skills (e.g. representation of the picture, planning and orchestrating traffic) although the tasks were disparate. Differences were especially apparent between tower control and en-route control in terms of systems, tools and task requirements. Approach control and en-route control were both conducted through the use of radar, but the sectors managed by approach control resulted in much more vertical orchestration of traffic compared to en-route control. These differences suggested that research findings specific to en-route control may not be automatically directly generalised to other ATC units.

3.10.3.3 Experience of the en-route air traffic control operations room

Physical qualities of en-route operations rooms

Physical layouts of operations rooms differed between centres. Common elements included an open room with a supervisor position, usually located centrally, with views around the control centre, and Controllers' Working Positions (CWPs) which were co-located depending on sector. There were two CWPs per sector. Systems and tools described in section 3.10 were observed in use. It became apparent how each tool facilitated or supported the control task. The open space meant that controllers were able to see and communicate with colleagues across the room, and listen to colleagues' discussions and clearances. The open layout also meant that visitors walking around the room needed to be cognizant not to distract controllers. Visitors sat with controllers with permission, and spare seats and headsets were made available. When possible, controllers provided information about airspace characteristics, systems and tools as well as the traffic situation.

Environment and culture of en-route operations rooms

The en-route operations room provided an insight into the less tangible atmosphere of operations rooms, and culture between controllers, as well as environmental influences under which the control task is performed. The atmosphere in the operations room was variable depending on traffic flow. During peak traffic, the room was busy and loud, with supervisors moving around the room and controllers consistently talking on radios and phones. When traffic was considered low, the operations room had a relatively relaxed atmosphere, with controllers sitting back in chairs and chatting to colleagues in between periods of traffic. During these times, controllers spoke to visitors at length and provided information about the traffic situation. When traffic was building from low to high, it became apparent that controllers had to change state and would change controlling style in preparation for the traffic. Taskload variations appeared to be integral to the task.

It was observed that several simultaneous demands are placed on controllers, including simultaneous task demands as well as demands by colleagues. ECs will often be approached by supervisors or teammates for discussion, especially when traffic is building. In addition, frequent visitors to the operations room may result in distraction to controllers. The environment was therefore demanding, especially during high traffic periods, and it was essential that controllers were not interrupted. It was identified that research could not be conducted in an operations room, unless a method such as a non-intrusive observation was applied with sensitivity.

On initial visits, occasionally controllers voiced concerns that information they shared may be repeated to teammates, supervisors or even centre management. It became apparent that in order to gain open and honest responses from controllers, even during informal visits, that anonymity and confidentiality must be explicitly stated during any conversations or future studies.

Controllers used language and terms which were specific to the ATC domain. Phraseology, such as 'the picture' for SA and understanding of factors such as fatigue and workload, will be necessary to take into account in future research in order to communicate effectively with controllers.

It was apparent through observations that there was a team culture in the operations room. Teamwork was observed between EC and CC who would work together to deliver services to the same sector, through discussions, the CC facilitating the task of the EC and acting as a second monitor of the traffic situation. Especially in high traffic, the coordinator appeared to change control strategy to support the executive without verbal discussion. It was also frequently observed that supervisors would offer extra support to controllers if it was necessary, usually in unexpected or emergency situations, and consult with the controllers before collapsing or separating sectors. It appeared necessary for controllers to trust one another to make the appropriate decisions and control traffic with a consistently high performance. Controllers also needed to trust colleagues to provide support if needed, such as swapping positions if the EC had been controlling busy traffic for a length of time and felt fatigued. Although this was not observed, controllers spoke of this as a critical option for managing their own performance.

3.10.3.4 Developing understanding of the En-route task

The ATC task was experienced first-hand by the researcher during a two-day high fidelity simulation event hosted by EUROCONTROL. Basics of ATC were taught and then practiced under varying air traffic conditions (such as sector size, traffic density, traffic complexity and unexpected situations). The physical systems and ATC tools were used, which provided insight into the functions and the way in which it supported the ATC task. Regulated procedures, such as phraseology, airspace characteristics and basic required control processes were experienced. Aviation phraseology was learned so that the 'pilot' could be spoken to during the simulation. As control of aircraft is primarily verbal, it was identified if future studies were conducting when ATCOs were on position, measures requiring verbal responses could not be utilised.

In addition, the cognitive nature of the task became apparent. Remaining vigilant was essential. A large number of variables needed to be assessed in order to select the most appropriate traffic management strategy. Rescanning was also integral to maintaining the mental representation in order to monitor that the selected strategy was still appropriate to the changing situation. Occasionally, unexpected issues would occur, such as non-response from a pilot, unexpected aircraft in the sector, an aircraft coming into the sector at an unexpected flight level or even a breakdown of communication technologies. Controllers need to be flexible enough to be able to incorporate these issues into the traffic management strategy and still maintain safe control of traffic. This suggests that it is necessary in future studies to utilise measures of subjectively experienced variables. Performance level was based on efficiency and safety. If the situation was safe, strategies which were more efficient were expected.

Controllers perform simultaneous tasks, whilst maintaining performance in a demanding environment. It is important to note that it was not only periods of high traffic that were found to be challenging. During extended periods of low traffic, occasionally vigilance and scanning periodicity may fall which can influence performance. It is therefore essential to consider both extremes of taskload and workload if considering workload in future investigations. Controllers had regular rest intervals to use as they saw fit, including taking a nap, reading a magazine or eating and drinking.

Visits to three European centres showed that there were differences in the systems and tools utilised by controllers. It is important for future studies to include controllers from different centres to gain representative results. If this is not possible, caution will be suggested regarding generalisation of results.

3.10.3.5 Implications of an understanding of the ATC domain for future phases of research

Experience of the ATC task and operations room, in addition to information captured in books and journal papers, provided insights into the ATC domain as well as information that facilitates the design and method selection for future studies. The learning points that will be acknowledged in future studies include:

1. Tailoring of different information to meet the interests of different aviation groups
2. Any research outputs should be practical and relevant to the ATC domain
3. Caution with generalisation of results between different forms of control

4. Distraction of controlling on position could have severe negative consequences. Investigations are therefore not recommended to take place in the operations room
5. Anonymity and confidentiality concepts will be explicitly stated to future aviation professional participants to encourage open and honest feedback.
6. Controllers use specific terms that relate to ATC elements. To communicate effectively, this natural language can be incorporated into future studies with ATCOs as participants
7. Subjective measures or methods may be prioritised due to the cognitive nature of the control task

3.11 Chapter summary

A review of the key features of ATM and ATC was provided. The separate forms of ATC were described, and the task elements of ATC were presented. It was emphasised that the task was primarily cognitive and research study designs and measures must acknowledge this task feature. The ATC working environment was described, and the importance of teamwork, intra and inter cooperation and communications is emphasised. The researchers' familiarisation with the ATC field is subsequently justified and described. The generation of visits is described, and visits to control centres are documented. Topics pertinent to considerations of future research are presented, including physical layout of the ATC operations rooms, environment and culture of the ATC operations room and the en-route task. The chapter concludes with a summary list of information topics, established from the visits and naturalistic observations of the operation room, which must be acknowledged in the design of future research in order to be relevant and appropriate to the ATC setting.

Chapter 4. Methodological approach and research framework

4.1 Chapter overview

This chapter describes the research approach and research framework of the thesis. The research approach incorporates elements of the action research approach, and the strategic combination of multiple methods and sources of data. The framework presents an overview of the integration of methods used to address the thesis aims. Each method is then described in order of application and linked to the research aims.

4.2 Overall research approach

4.2.1 Research studies built upon previous findings

Research studies built upon previous findings, incorporating some properties of the action research approach (see Reason & Bradbury, 2006). Findings from previous studies contributed to the method selection and research questions of the subsequent study that were most appropriate to address the overall aims of the thesis. The aims of the thesis remained the same throughout the project, although the research progression was flexible.

4.2.2 Multiple sources of data addressed research aims

A strategic combination of methods was applied to address the aims of the thesis. Table 4.1 summarises the methods used to address the thesis aims. The strength of this approach is that a comprehensive understanding of the data from varying perspectives, is generated.

Research took place in both field and experimental settings. Data specific to the ATC environment (incident reports, questionnaire of air traffic professionals) was used to gain a representation of human factors occurring in the field. An experimental study then facilitated the measurement of factor relationships and associations with performance in a controlled setting. Finally, a return to the field facilitated the confirmation and extension of specific findings from the experiment, through an interview study with active controllers. Robson (2002) lists four key benefits of applying multiple methods:

- Quantitatively confirming qualitative findings
- Contributing to experimental results
- Establishing statistical tests
- Integrating small scale studies with a large scale perspective.

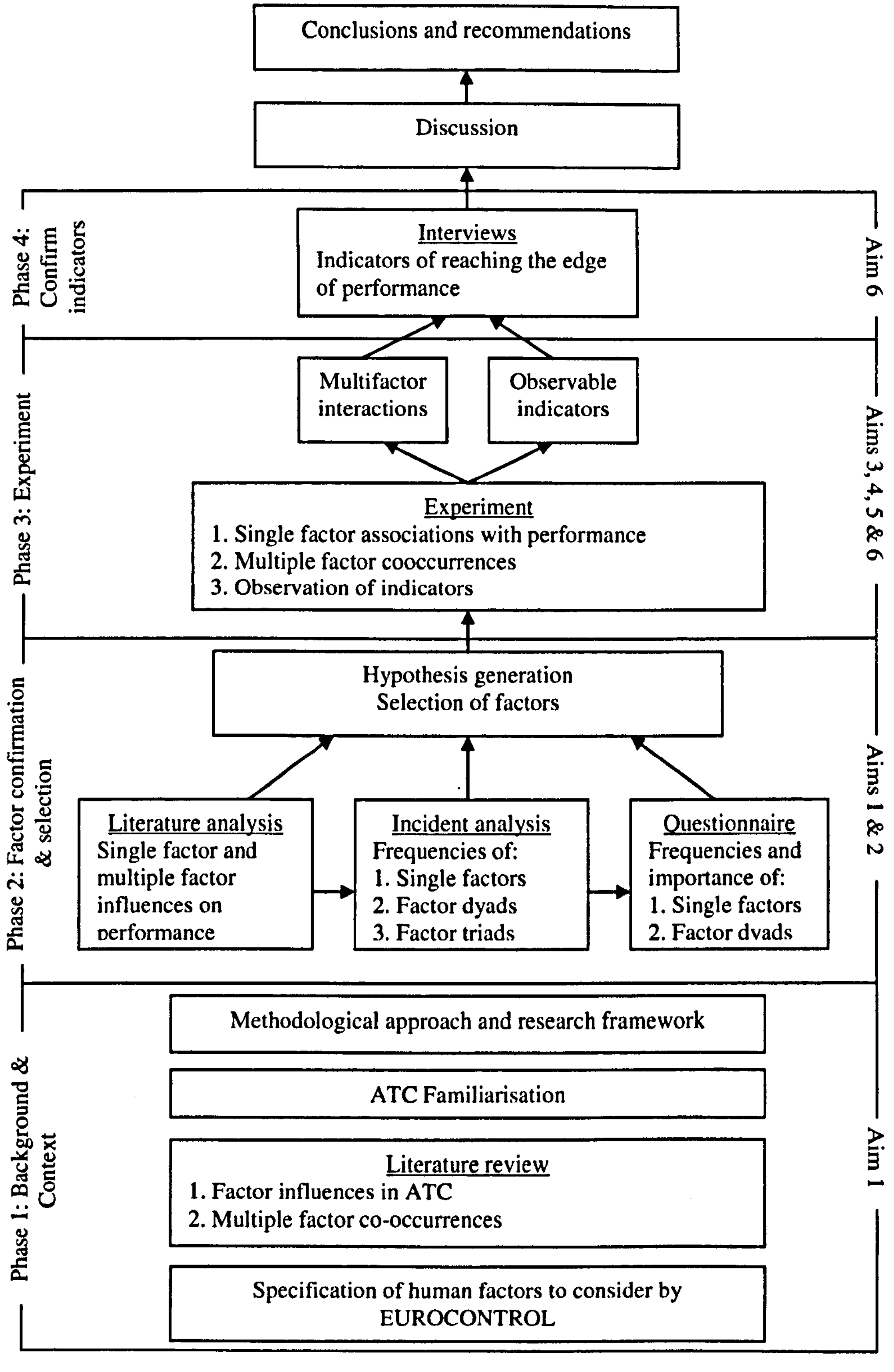
Table 4.1. Correspondence between methods and research aims

	Aim	Research methods
Aim 1	Identify a set of human factors that influence air traffic controller (ATCO) performance	• Literature analysis • Incident report analysis
Aim 2	Select a sub-group of factors that may be included in further studies pragmatics but also to see where to first focus efforts	• Controller interview: Pilot study • Questionnaire of ATC professionals
Aim 3	Investigate the relationships and potential interactions between multiple, selected human factors	• Experiment
Aim 4	Investigate the association of multiple factor relationships with human performance	• Experiment
Aim 5	Provide fundamental understanding of behaviour at the edge of performance	• Experiment
Aim 6	Identify indicators of potential performance decline	• Experiment • Interviews with ATCOs

4.3 Research framework

A research framework (Figure 4.1) provides an integrated overview of the selected methodologies. Figure 4.1 ascends vertically. Research phases are presented on the left hand side of the figure and research aims addressed by each phase are presented on the right hand side of the figure. The arrows illustrate the progression of research studies. There is no meaning to the size of boxes or length of arrows; differences are for ease of presentation.

Figure 4.1. Research framework



4.4 Overview of the methods used in this thesis

4.4.1 Research phase 1: Background and context

EUROCONTROL provided an initial set of nine factors (workload, fatigue, stress, attention, vigilance, SA, communications, teamwork, and trust) to be included in the research. The researcher was confident that the experienced professionals in EUROCONTROL understood the human factors that occur in ATC settings and affect controller performance and so the nine factors were used at the start of the research.

4.4.1.1 Literature review

A literature review was completed on previous research of human factor associations with controller performance and relationships between multiple factors (Chapter 2). The review was restricted to the nine factors provided by EUROCONTROL. The review facilitated future hypothesis generation as well as ensuring research was not unnecessarily repeated. Research gaps were identified. Few research studies considered the association of factor dyads with performance and no research studies that were reviewed investigated factor interactions in association with performance.

4.4.1.2 Familiarisation with the air traffic control domain

Visits to ATC operations rooms provided detailed information about the operators' task and working environment (Chapter 3) which was pertinent to the design of research studies. In addition, the operations room atmosphere and considered factors (such as workload, teamwork, communications) were experienced as they naturally occurred. The information facilitated the selection of methods that were appropriate to achieving the research aims within the specific domain.

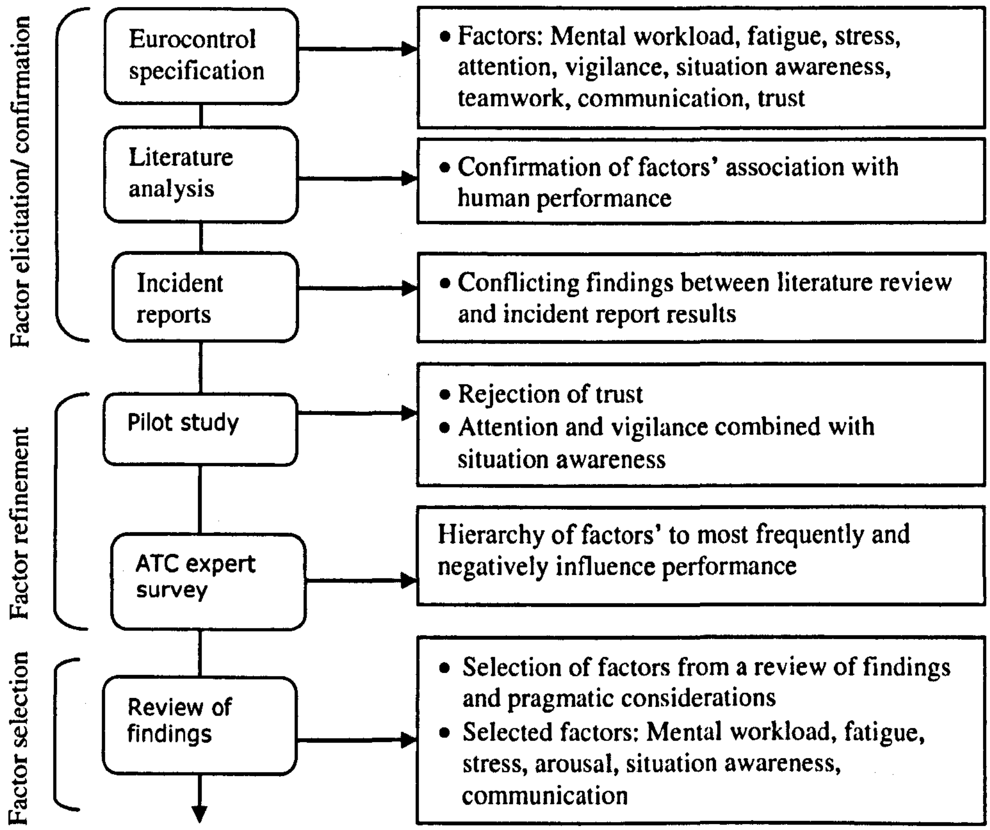
4.4.1.3 Methodological approach and research framework

The methodological approach supported the development of research studies and informed the progression of the research. For example, due to the progressive approach of the researching, findings from one study were used to contribute the aims and design of subsequent studies.

4.4.2 Research phase 2: Factor confirmation and selection

In total, three separate methodologies were applied to achieve the first research aim to identify a set of human factors that influence ATCO performance. Each method extended findings from the previous method to comprehensively address the research aim. Figure 4.2 presents a summary of the progression of methods that facilitated the elicitation and confirmation of factors that influenced ATCO performance, and the subsequent refinement and selection of a sub-set of human factors to be included in later research studies.

Figure 4.2. Methods used to elicit and confirm, refine and select factors that influence ATCO performance



4.4.2.1 Literature analysis

A literature analysis quantitatively summarised research findings through a frequency count on the reported relationships between factors. An initial confirmation of the proposed set of factors was provided from this analysis.

Limitations to the data (expanded on in Chapter 11) meant that it was necessary to confirm and extend the findings with data specific to an ATC setting to achieve the first research aim.

4.4.2.2 Incident report analysis

An analysis of European aviation incident reports was conducted to extend the findings from the literature review analysis. A quantitative frequency analysis identified single factors, factor dyads and factor triads that were most frequently recorded to contribute to ATCO performance-related incidents. Findings confirmed the factors identified in the literature analysis. However, the relative frequencies of consideration of factors differed between literature analysis and incident report analysis. Therefore, a questionnaire study was conducted to support the previous findings.

4.4.2.3 Survey-questionnaire of aviation experts

An online survey questionnaire was conducted with aviation professionals. Findings provided a hierarchy of factors and factor dyads which were considered to most frequently negatively influence controller performance.

A review of findings from the three methodologies confirmed the original factor set provided by EUROCONTROL, and a sub-set of factors which most frequently and negatively influenced performance were selected for inclusion in future studies. This addressed research aim one and two. The data generated regarding factor relationships contributed to hypothesis generation for future studies.

4.4.3 Research phase 3: Experimental investigation of factor relationships in association with performance and the edges of performance

An experiment was conducted to investigate in a controlled setting:

- The relationships between the selected subset of factors
- The association of single factors and multiple, combined factors with performance
- The edges of performance, and
- Indicators of the performance edge

Participants were 29 male students from the University of Nottingham. For pragmatic reasons, including limited resources and the political situation within EUROCONTROL, a full scale ATC simulation was not conducted. A computer-based task with en-route ATC elements was utilised. Using this form of task was the best way of ensuring the appropriate elements in the ATC task were included for investigation. This is discussed further in Chapter 8 (experimental method) and Chapter 11 (discussion). Participants received four hours training on the experiment task and were required to achieve a minimum of 18/22 on a task-related competency test.

Taskload was manipulated as the independent variable. Self-report scales were used to measure factors. Performance was the dependent variable. In addition, participants' behaviour was observed and specific behaviours recorded. The experiment study was a major part of this thesis and contributed to thesis aims 3, 4, 5, 6. The results focused on four primary areas: factor associations with performance, factor relationships in association with performance, and the nature of performance at the edge and indicators of the edge of performance.

4.4.4 Research phase 4: Investigation of indicators of potential performance decline

4.4.4.1 Experiment study findings

Participant behaviours were observed and recorded throughout the experimental trial. Findings contributed to identifying the behavioural indicators of potential performance decline.

4.4.4.2 Interview study

It was necessary to return to the field to confirm and validate the experimental study findings of the indicators of the edge of performance within an ATC setting. A total of 22 individual face-to-face interviews were conducted with active en-route controllers and supervisors and internal and external indicators of reaching the edge of performance were identified.

4.4.5 Discussion, conclusions and recommendations

The discussion chapter (Chapter 11) provides an opportunity to present results of particular interest or value that were generated throughout the course of this thesis. The contribution of the research findings to the thesis aims as well as wider research are discussed. In addition, the potential practical applications of research findings to safety critical domains are described. Findings from this research contributed to the development of a set of recommendations intended for both researchers and aviation industry experts.

4.5 Chapter summary

This chapter described the research approach used in this thesis and provided an overview of the research framework. Research studies built upon findings from previous studies. A combination of methods and data sources was applied to address specific study aims. A mix of settings, including field and laboratory settings, were also utilised as appropriate to address the research aims. The research framework provided an integrated overview of the development of the research. The chapter concluded with a summary description of each method used in the thesis, and where appropriate, a description of methods building upon previous research findings.

Chapter 5. Literature metrics and incident report analysis: Confirmation of key human factors and human factor relationships

5.1 Chapter overview

The following chapter describes two studies, a literature review analysis and an incident report analysis, which investigate the association between human factors (workload, fatigue, stress, attention, vigilance, SA, communications, teamwork, trust) in association with performance.

The chapter first describes an analysis of peer-reviewed papers that investigated the relationship between at least two of the previously identified human factors. The aims of the study are presented, followed by the method and a summary of findings. Diagrams are utilised to concisely summarise identified relationships between factors (section 5.2.4). Results identified the basis for a second study using a different data set (incident report analysis).

An incident report analysis study is described (section 5.3). The aims and research questions are outlined, followed by the methodology utilised to achieve these aims. Section 5.3.6 reviews the results of the analysis, followed by a discussion and interpretation of the results associated with both the aims of the study and the overall project aims. Finally, section 5.3.7 concludes that an additional study will consolidate, and extend the findings to date to comprehensively address the first two aims of the thesis.

5.2 Literature analysis

5.2.1 Literature analysis: Aims

The aim of the study was to investigate the frequency with which each factor was selected for inclusion in a defined literature sample of multifactor research. Findings summarise previous research trends, and provide an indication of the factors that may be considered as most important to include in multifactor research. An additional aim was to investigate the frequency and type of relationship found between factors. Findings provide a summary of research to date investigating relationships between factors, and therefore prevent unnecessary replications. Findings also provided a basis for future hypothesis generation of specific factor relationships.

5.2.2 Literature analysis: Differentiation between attention, vigilance and SA

The concepts of attention, vigilance and SA have been comprehensively reviewed in section 2.1.2. However, it is important to clarify how these interrelated constructs differentiate and why each factor has been included for consideration. Attention refers to a more general ability to attend to information in the environment (Eysenck, 2001). Vigilance is identified as a specific form of attention, and has been suggested to be synonymous with sustained attention (Aston-Jones, et al., 1994). The concept of vigilance therefore overlaps with attention but is also used to describe specific elements such as detection and response elements during a vigilance task. Vigilance is essential to the air traffic control (ATC) task as en-route controllers consistently monitor the radar to ensure the safety of aircraft.

It is worthy of note that SA also overlaps with attention and vigilance. SA encompasses the vigilance and attention constructs, but also incorporates several other elements. This concept therefore goes beyond attention and vigilance alone. All three factors were included for consideration at the start of the research to gain a comprehensive understanding of multifactor associations with each factor.

5.2.3 Literature analysis: Method

5.2.3.1 Design and procedure

The literature search was focused on papers that investigated the relationship between at least two of the following nine human factors: workload; stress; fatigue; attention; vigilance; SA; communications; teamwork and trust. These nine factors had been previously identified by subject matter experts as factors important in ATCO tasks and factors that could have a critical negative impact on ATCO performance.

Papers were selected according to the following criteria:

- All papers had been published in peer-reviewed journals or conference proceedings, or were reports from relevant organisations such as EUROCONTROL and ICAO. The quality of the studies was therefore independently evaluated by subject experts.
- Following Rasmussen and Jeppesen's (2006) methodology each article provided a definition of each included factor which was in-line with the pre-established working definitions (chapter 2). This ensured that the included studies had investigated the relationship between each factor and did not simply mention them.
- Papers were only included in the review if the relationship between at least two of the nine factors were considered.

The abstract of each paper was read prior to inclusion to ensure that the article adhered to the selection criteria and was relevant to the study. The selected papers were not restricted to a specific domain. Although papers relating to factors within the aviation domain were actively sought, papers that examined the relationship between at least two of the identified factors from any domain were included in analysis. Due to the relative lack of research investigating human factor relationships within the ATC domain, this decision was necessary in order to provide a comprehensive and informed review of research on multifactor relationships.

The papers selected for review were also not restricted by date of publication, measure or method differences. This decision was made so that a larger number of relevant papers that investigated the relationship between specific human factors could be included in the review, generating a wide review of this research area.

Papers were identified from a key-word based search of electronic databases (Ergonomics Abstracts, PsychINFO, Science Direct, Scopus and Web of Science) and a search engine (Google Scholar). The procedure followed is similar to the search procedure methods used in other literature-based analyses, such as Hetherington, Flin and Mearns (2006) and Rasmussen and Jeppesen (2006). Only papers which investigated the relationship between at least two of the identified factors were required for analysis, and so papers were searched for using combined search terms, including systematically pairing the name of two of the nine factors and the possible alternatives (e.g. concentration, distracted overlooked, phraseology, tiredness, mental fatigue, overload, underload, cognitive load, awareness, pressure, time pressure, cooperation, colleague, coordination, reliance, expectation, presume, detection, monitoring, observing).

5.2.3.2 Non-domain specific papers

A total of 25 review papers, which accounted for 30% of the 83 papers included in the review, were excluded from a domain frequency analysis as these papers had no specific domain. Instead, these papers approached factor relationships from a theoretical rather than a context specific perspective.

5.2.3.3 Domain and methodological approach of included literature

Figure 5.1 presents the domains of 58 papers (excluding 25 review papers) included in the review. University laboratory settings accounted for the largest percentage of these 58 papers (20 papers, 35%), whereas 15 papers (26%) were based in an ATC domain.

Figure 5.1. Industrial contexts of 58 papers

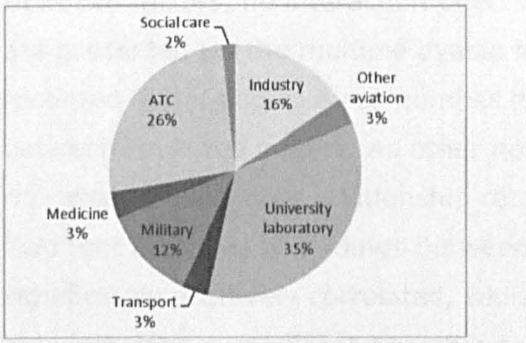
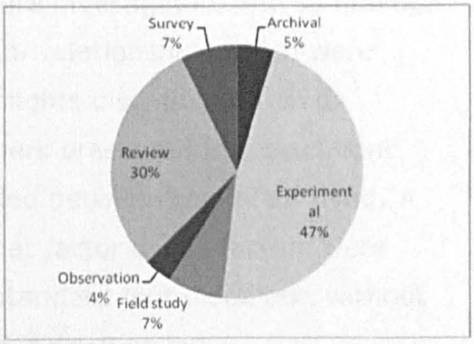


Figure 5.2. Methodological approach of 83 papers



A frequency analysis was also conducted on the methodological approach of the 83 reviewed papers (Figure 5.2). Overall, experimental approaches accounted for the largest percentage of methodological approach (39 papers, 47%). This category included both experiments within university laboratories as well as experiments within industrial laboratories. Review papers accounted for the second highest percentage (25 papers, 30%). Together, these methodological approaches accounted for 77% of all papers included in the review. This result highlights the relatively modest number of papers which used a qualitative or field-study approach.

5.2.3.4 Organisation of information pertinent to the analysis

Prior to the analysis, specific information from all 83 papers that was pertinent to the analysis (e.g. date, domain, referenced factor(s), relationships between factors, method and measures) were placed in a data sheet made specifically for the review. The categorisation of relevant data supported frequency analyses.

5.2.4 Literature analysis: Results

5.2.4.1 The frequency and direction of reported relationships between factor dyads

The frequencies of both positive and negative, significant (p<0.05) correlations between factors, reported in the literature sample, are summarised in Table 5.1. A total of 90 relationships are recorded in Table 5.1 from 83 papers (some papers in the literature sample examined more than one dyadic factor relationship, or more than two factors per relationship). For papers which presented a relationship between more than two factors, no interaction effects were investigated, and so findings are presented for the multiple dyadic factor relationships which were recorded in the paper. A red number highlights discrepant findings between reviewed papers. All other numbers presented in a black font represent a significant relationship recorded between the factor dyad. A bold font indicates all findings between that factor dyads factors were significantly positively correlated, whilst standard font black text without bold indicates a significant negative positive relationship.

Table 5.1. Frequencies of significant correlations between factors

	Fatigue	Stress	Attention	Vigilance	SA	Communications	Teamwork	Trust
Workload	4	5	5	4	4	7	2	0
Fatigue		4	1	3	1	2	0	0
Stress			9	8	0	6	2	1
Attention				3	2	1	0	0
Vigilance					3	1	1	0
SA						2	2	0
Communications							2	1
Teamwork								4

Key to table

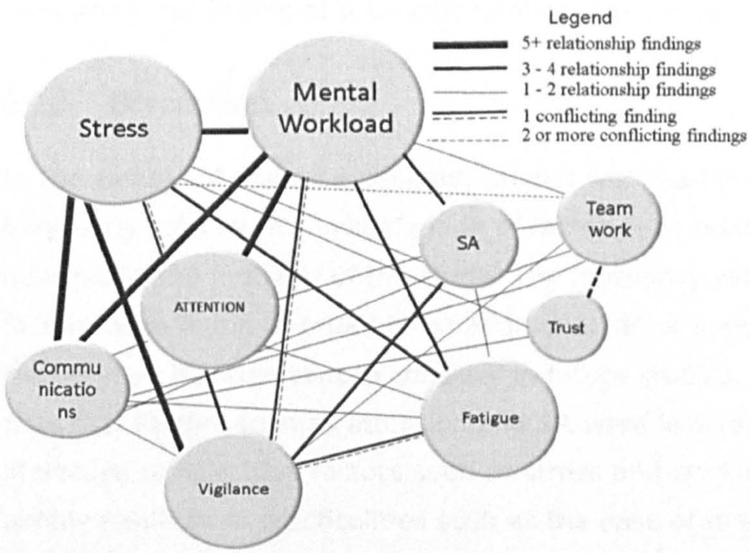
- **Bold font**: Positive relationship reported
- Standard font: Negative relationship reported
- Red font: Different findings between studies, specifically regarding whether a statistically significant relationship was reported, and/or the direction of relationship

Several factor dyads in Table 5.1 are recorded to have no relationship (0). For these factor dyads, no significant correlations were recorded in the literature sample. This result may represent where there would be no logical direct connection between the factors or where further research is needed.

Table 5.1 shows that both workload and stress were dominantly selected for investigation in the literature sample, and were recorded to both positively and negatively correlate with most other factors. Few investigations found significant relationships between trust and another factor, apart from trust and teamwork which four separate papers examined.

To further explore the potential discrepancies between dyadic factor relationship results, and for ease of representing the frequency with which each factor was included in investigations in the literature sample, Figure 5.3 presents a visual representation of the frequencies of factor relationships reported in the literature sample. The benefit of visually representing results (Figure 5.3) as well as tabling the results (Table 5.1), is that the identified relationships between factors, as well as controversies within the literature and gaps in research, are discernible.

Figure 5.3. Frequencies of research papers relating to factor interactions



Each factor is represented by a circle. The circle's size is dependent on the number of papers in the review that considered that factor; the larger the circle, the greater the number of papers which considered that factor. Most papers did not specify a causal direction of the factor dyad relationships. Therefore, the lines do not imply a direction of causal influence. Additionally, there is no meaning to the position of the circles or length of lines.

Figure 5.3 suggests that the factors of mental workload and stress and their relationships with other factors were most frequently reported. This is supported by the frequencies presented in Table 5.1. Factors of trust and teamwork were not frequently reported to have a relationship with another factor.

Correlation findings between factor dyads were mixed. Several relationships, such as the relationships between stress and vigilance, stress and communications, or workload and fatigue, were repeatedly confirmed in separate papers (Table 5.1, Figure 5.3). Several relationships were reported which had not been replicated in the literature sample, such as the relationships between communication and trust. In addition, discrepant findings regarding the relationships between stress and teamwork, and teamwork and trust, were recorded. Although papers included in the review confirmed a relationship between these factors, the reported direction of the relationship differed between papers. A minority of papers recording findings of a correlation relation between fatigue and vigilance, vigilance and workload and stress and attention, also differed in the direction of the relationship that was reported, but with most papers replicating the finding of a specific relationship direction.

5.2.5 Discussion

In the sample of papers examined, mental workload and stress were most frequently selected for investigation of factor dyad relationships, addressing the first aim of the study. The frequency with which these factors were found to relate to an additional factor suggests that these factors may be important to consider in future studies. It is interesting to note that factors such as attention and SA were less represented in the literature sample than factors such as stress and workload. This may simply result from practicalities such as the ease of measurement of each factor in a laboratory setting, or could possibly represent that the more dominantly researched factors are of a greater concern due to the effects on other factors and performance within the literature.

The frequency and type of relationships within the literature sample were also documented, addressing the second study aim. In the majority of articles, the independent variable was one of the nine factors and a second factor was measured as a dependant variable. Several factor dyad relationships were repeatedly confirmed. For example, the relationship between stress and communications was replicated in six separate investigations (e.g. Bellorini, 1996; Fernandez & Picard, 2003). Bellorini (1996) conducted an investigation in an ATC setting into the quality of communications in situations known to be stressful such as conflicting aircraft. Findings suggested that stress was associated with increased communication errors. In addition, Fernandez and Picard (2003) and Congleton et al. (1997) both reported an association between stress and speech characteristic changes, such as speed, loudness and frequency. The direction of specific speech changes in association with stress was not consistent (i.e. speech may become louder or softer in association with stress) however changes in speech were consistently reported. In addition, stress and workload were reported to be significantly, positively correlated in five studies. Findings were reported both for psychophysiological measures of stress and self-report measures. Wientjes, Gaillard and Maat (1996) reported increases in psychophysiological measures of stress (salivary cortisol, heart rate, Pco_2 indicting hyperventilation) with increases in ATC taskload, measured by number of aircraft under control, and self-reported workload (Zeier et al., 1996). In addition, Bellorini (1996) reported increases in self-report stress with increases in ATC taskload, measured by number of aircraft under control and traffic complexity. These results suggest a robust relationship between workload and stress for both psychophysiological and self-report measures. Workload and communications, stress and vigilance were also replicated in 5 or more papers, indicating particularly robust relationships between these factor pairs.

However, controversies were evident regarding the co-variation of factor relationships. A particular example is the discrepant findings of the relationship between fatigue and vigilance. Matthews (2002) investigated the effects of fatigue on vigilance-related performance in a simulated driving task. Results showed that non-fatigued participants responded to more target stimuli than fatigued participants. Matthews (2002) inferred that fatigue negatively impacted vigilance resulting in a negative relationship. However, Galinsky, Rosa, Warm and Dember (1993) researched the association between vigilance and fatigue. Participants were asked to provide subjective ratings of fatigue pre- and post- vigilance task. Fatigue ratings rose after vigilance task completion, suggesting a possible positive relationship between high vigilance and fatigue. Both papers found a relationship between fatigue and vigilance. However the direction of the relationship depended on the selected independent variable and methodological design. Therefore, discrepant results in the literature regarding the direction of factor dyad relationships may be primarily due to differences in study aims and resulting methodological design.

Every paper that was identified during the comprehensive literature search as meeting the selection criteria (83 in total) was included in this analysis. There is a relative lack of research investigating the relationships between multiple factors. Even less research in the literature sample considered the association between multifactor combinations and performance. Reasons for the lack of research may be surmised. It may reflect the preference in research to focus on exploring one factor at a time. However, an additional reason may be that it was necessary to first develop a comprehensive understanding of single factors and associations with performance, prior to extending research to multifactor relationships and associations with performance.

5.2.6 Conclusions and next steps

A general finding resulting from this study is that each of the nine factors selected have been shown to relate to other factors, providing support for further investigation of these factors. In addition, the factors of workload and stress are dominantly selected for investigation in the literature sample reviewed, suggesting that these may be of particular importance in future studies examining multifactor relationships. Factor dyads have been shown to be associated, sometimes with bi-directional relationships. The extent to which the relationship is replicated in the literature sample is dependent on the particular dyad. Further research was necessary to confirm that these factors are associated with controller performance in an ATC environment. An association between each factor and performance is suggested from the literature review (Chapter 2), although additional ATC-specific data will be relevant to extend previous findings.

Methodologies that were appropriate to investigating factor associations with performance in an ATC setting were reviewed. It was identified that an analysis of aviation incident reports, that were specific to ATCO performance-related incidents, will generate ATC-specific data and support and extend findings from the literature review. This form of retrospective study "allows for the identification of factors more likely to precipitate air traffic control errors" (Rodgers, Mogford & Strauch, 2000, p94). Implicit in this is the assumption that errors are representative of a performance decline. The analysis permits the investigation of the frequency of single factor associations with performance decline in addition to multiple co-occurring factor associations with performance decline, extending the results of the literature analysis. A comparison of results between the literature analysis and findings from an ATC environment will inform the next research steps that are required to achieve the second thesis aim of selecting a sub-set of human factors that influence controller performance. These conclusions therefore led to a study of incident reports.

5.3 Aviation incident reports analysis

5.3.1 Incident report analysis: Background

Incident and accident reports are often used as valuable sources of information. When an incident or accident occurs, a full investigation process is carried out. Retrospective analyses are applied to understand the causes and contributory factors. A report is created documenting findings. Reports are utilised to prevent similar future occurrences. Incident and accident reports also provide valuable field-specific information for contributing to related research.

Within the aviation domain, the collective term of 'safety occurrence' is used to refer to both accidents and incidents. However, each type of safety occurrence has an independent, specific meaning. Accidents refer to an event with 'physical consequences', such as an occurrence in which a person is fatally or seriously injured as a direct result of being in an aircraft, an aircraft sustains damage or structural failure, or the aircraft is missing or completely inaccessible (ICAO, Annex 13, 2001). An incident is defined as a situation in which "aircraft have violated prescribed separation minima and approached in close proximity" (Rodgers & Mogford, 2000, p77). Legal separation minima requirements exist, as specified by ICAO document 444 (2007). On the vertical dimension, aircraft must be separated by a minimum of 1000 feet at an altitude under 29000 feet, or by 2000 feet when flying at an a altitude of over 29000 feet. Horizontally, aircraft are required to be separated by a minimum of 3 or 5 nautical miles, depending on the location of the aircraft in relation to the radar antenna. If separation minima are breached, it is deemed an incident. All incidents are followed by an incident investigation and subsequently, an incident report. An incident report is therefore a product of an investigation into an aviation-related incident.

As part of the investigation, all incidents receive a severity classification. For example, the ICAO airprox classification system categorises incidents from A (risk of collision) to C (no risk of collision). EUROCONTROL have also developed a severity classification scheme resulting of a mapping of EUROCONTROL Severity Classification Scheme and ICAO AIRPROX Severity Scheme (EUROCONTROL, 2002), developed for harmonising occurrence reporting (EUROCONTROL, 2002). An incident analysis scheme is applied to assist in identifying the factors that contributed to the incident, and a full textual report, with recommendations, is completed. Therefore, a lot of detailed information can be gained regarding the incident occurrence, and the factors contributing to the incident, from an incident report.

Fortunately, accidents are rare, and as such, more can be learned from an analysis of the relatively more frequent incidents. An advantage of conducting an analysis of incident reports is that it enables a quantitative analysis of a large body of data, which may identify the factors which most frequently contribute to performance-related incidents in ATC.

5.3.2 Incident report analysis: Boundaries of focus

The incident report analysis was conducted to contribute to the first and second overall research aims. First, an assumption was made that an incident related to a decline in ATCO performance. The very occurrence of a performance-related incident suggests that safety was compromised, and therefore, performance did decline. Therefore, any factors highlighted as contributing to an incident were assumed to also viably contribute to a decline in performance.

5.3.3 Incident report analysis: Aims

The aims of the incident report analysis were three fold. One aim was to confirm if the factors identified in the literature review were present in an ATC environment. An additional aim of the study was to further previous findings by establishing the frequency with which each factor contributed to incidents. This was important in understanding which factors may negatively influence controller performance, for factor selection for use in later studies. The final aim was to determine if multifactor occurrences are reported in an ATC environment. It was necessary to determine if factors do co-occur in an ATC environment prior to any further investigation of this event.

5.3.4 Incident report analysis: Description of database and task

Incident reports were accessed from EUROCONTROL's SAFLearn database. The SAFlearn database contained a total of 420 incident reports submitted to EUROCONTROL by European air navigation service providers (ANSPs) between 2003-2005. Reports were hand-typed into the database individually. All incident reports were de-identified prior to entry into the database. HEIDI (European Incident Definition Initiative for ATM) (EUROCONTROL, 2001) factors were added to each report which served as a standardised taxonomy for identification of causal and contributory factors. A reclassification of some reports to the HEIDI taxonomy, based on the identified factors, therefore took place prior to being entered into the database. Each report contained:

1) Unique report identifier
2) Error classification
3) ICAO severity category
4) Incident overview
5) Full textual description of incident and resulting recommendations
6) Classification of factors and errors identified as part of the incident

An example of one de-identified SAFLearn report is presented in Appendix 1 and the information categories listed above (1-6) are highlighted.

5.3.5 Incident report analysis: Method

Strict inclusion criteria determined whether incident reports were included for analysis. As the aim of the study focused on the factors that influenced controller performance, only those incidents which were caused or contributed to by air traffic controllers were included. Consequently, incident reports in which the ATCO had no responsibility, control or contribution, for example pilot error, technical/maintenance error and unavoidable weather conditions, were excluded from analysis.

Incidents involving trainees were also excluded from analysis. If the supervising on the job training instructor (OJTI) had explicitly committed an error, the incident report was included for analysis based on the error of the OJTI. Incidents resulting from trainee error in which the OJTI acted appropriately were omitted from analysis. The rationale for this decision was to control for the potential confound of expert/novice differences (i.e. Malakis, Kontogiannis & Kirwan, 2010a), which may have influenced the factors documented in the incident.

Incidents occurred in a range of airspaces and a range of different flight control phases (Tower, Approach, En-route). Although this investigation is concerned primarily with en-route controllers, at this stage in the investigation it was important to gain larger amounts of data on general trends of factor associations with performance decline and error in all air traffic environments. Therefore, in order to gain a larger sample of data, all control phases were analysed.

Incidents also ranged in severity, from EUROCONTROL's severity categorisation of 'A – serious incident' to 'E- no safety effect' (respectively mapped to the ICAO categorisation of 'risk of collision' to 'no risk of collision') to generate more data.

Based on the above criteria, 272 out of a total of 420 reports incident reports were included for analysis.

5.3.5.1 Data collection

Identification of relevant incident reports began with specific word searches for incident reports within the database. This procedure allowed an efficient selection of only those incident reports that were relevant to the aims of the study. Therefore, a list of search terms was compiled for each of the nine factors previously identified as important influences on human performance (attention, communications, fatigue, mental workload, SA, stress, teamwork, trust, vigilance).

Search terms (Appendix 2) were compiled by noting separate definitions or synonyms surrounding each factor in the literature and gathering synonyms from an Oxford English Thesaurus. Search terms were also taken from HEIDI (2001) explanatory factor classification categories. Each term was typed into a text field and lists of relevant reports were generated. It was assumed that the reports which had not been returned during the search did not relate to any of the considered factors. However, consideration was given to Johnson's (2002) argument that frequent coding issues have been reported with classified incidents, namely that coding schemes may be non-standardised or dependent on contextual knowledge. Therefore, for completeness, the reports not generated from the search terms were also examined. Therefore, ultimately, all incident reports were included for review.

A total of 272 incident reports met the selection criteria, and the following information from each report was captured in a spreadsheet:

1. Report identifier
2. EUROCONTROL/ICAO Risk category
3. OJTI or standard controlling

4. Workload level (if reported)
5. Complexity level (if reported)
6. Classification of error (main cause of the incident)
7. Other notable factors (from textual incident description).

Information relating to factor contribution to the incident was also captured from each report:

1. Classification of each factor identified in the incident
2. Presence or absence of each of the previously-identified factors in each incident
3. Reported type of contribution to the incident: Within the HEIDI (2001) classification system, each factors' contribution to the incident is separated into four categories – Main cause, Causal, Contributory and Possible factor. These groupings represent the position of the classified factor, as reported by the incident investigator. In summary, the categories can be described as follows:

- *Main Cause:* An event or item that was judged to be the actual cause of the accident or incident. Without this event, it is considered that the occurrence would not have happened.
- *Causal:* An event or item that was judged to be in the causal chain of events leading to an accident or incident.
- *Contributory:* The event potentially increased the level of risk or played a role in the emergence of the occurrence.
- *Possible Factor:* An event or item that may have contributed to the causal chain or increased risk in the occurrence.

This resulted in a comprehensive data sheet which captured relevant and critical information from each incident report.

5.3.5.2 Preparation of data for analysis

Prior to analysis, the lower-level classification terms specific to HEIDI (2001) were mapped to the higher-level factor (Appendix 3). HEIDI (2001) classification taxonomy uses different levels of to characterise the incident, from high-level event types (for example, 'near collision, air-air'), to more detailed explanatory factors (for example, fatigue) and finally descriptive factors (for example, 'sleep loss'). This means that separate classifications can be categorised under one main category. For example, within the high-level descriptor of 'fatigue', sleep loss, sleep disturbance and tiredness are all HEIDI descriptors, which can be subsumed into the higher-level category. To assist in the analysis of factor contribution to incidents, it was necessary to map these lower level descriptors to the overall higher-level category factor. This factor would be then recorded to have contributed to the incident.

For consistency, it was necessary to associate the names of the HEIDI factors with similar factors which were identified from the literature review. An example of this is the HEIDI factor named 'loss of awareness' which was associated with situation awareness for the purposes of analysis. Table 5.2 documents this association. In most cases, the HEIDI factors were the same as the pre-identified factors named and defined in the literature review (Chapter 2); factors which were not included in analysis are noted in the table.

Table 5.2. The association between HEIDI explanatory factors and the existing factor set

HEIDI-defined factor	Association with previously-identified factor
Assumptions	Not included
Attention	Attention
Communications	Communications
Decision making	Not included
Fatigue	Fatigue
Forget	Not included
Judgement	Not included
Lapses	Associated with attention
Loss of awareness	Associated with situation awareness
Monitoring	Associated with vigilance
No planning	Not included
Stress	Stress
Team skills	Associated with teamwork
Trust	Trust
Workload	Workload

5.3.5.3 Incident report analysis approach

A frequency analysis was applied to the incident report data. The information gained from the frequency analyses was sufficient to address the aims of the study. The practice of only using descriptive statistics in incident report analyses is common (i.e. Beckmann, Baldwin, Hart, & Runciman, 1996; Beckmann & Gillies, 2001), potentially due to the difficulty of studying behavioural factors (Clarke, Forsyth, & Wright, 2005), and the uncertainty of producing valid and reliable results. Statistical analyses can be influenced by several uncontrolled factors in incident report studies such as recency or familiarity reporting biases. In addition, as with all incident report analyses, the bias of selection on the dependent variable means there is no comparison group from which to determine if the factors actually contributed to the incident, or were simply present at the time. This bias is known to affect the validity of statistical analyses (Winship & Mare, 1992) and so a frequency analysis sufficient.

5.3.6 Incident report analysis: Results

5.3.6.1 Overview of incident report descriptive analysis results

Descriptive analyses were conducted on the incident reports. As noted previously, incidents were of all severity classifications. A frequency analysis was conducted on the severity classification of incidents to gain an understanding of the categories which accounted for the majority of incidents. This may later influence the interpretation of factor contribution to incidents. Table 5.3 documents the frequency and percentage of incidents within each severity classification, and an ICAO (2007) definition of each classification. All category classifications have been adapted from EUROCONTROL (2002). A total of 15, or 5.51% of incidents were unclassified and are therefore not included in Table 5.3.

Table 5.3. Frequency and percentage of incidents within each severity classification

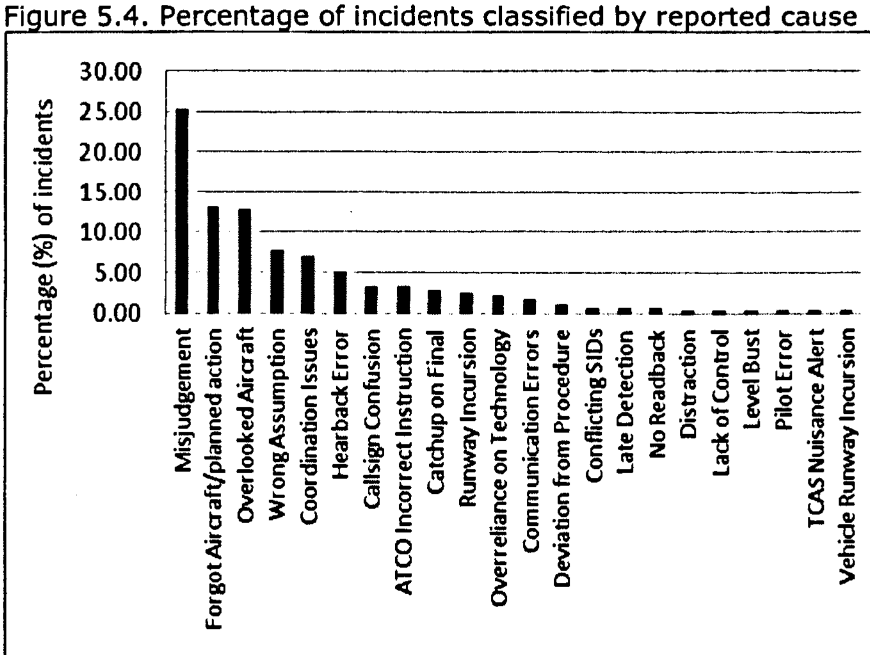
EUROCONTROL (2002) Incident severity classification	ICAO (2007) definition	Frequency	Percentage (%) of incidents
Serious Incident (A)	Risk Of Collision	30	11.03
Major Incident (B)	Safety Not Assured	116	42.65
Significant Incident (C)	No risk Of Collision	103	37.87
No safety effect (E)	Occurrences which have no safety significance. No direct mapping with ICAO	4	1.47
Not determined (D)	Risk not determined	4	1.47

As can be seen from Table 5.3 the majority of incidents (80.52%) were classified as a major or significant incident. However, as it cannot be determined whether it was the influence on performance, or simply providence which determined the categories, it is important to assess incidents in all categories.

A second frequency analysis revealed 56, or 20.59%, of incidents involved an error of an OJTI. A majority of incidents (216, 79.41%) included the contribution of an executive controller in a standard session (i.e. not training).

An additional frequency analysis was conducted on the categories specified in the reports as the cause of the incident. A total of 22 causal categories, as specified in the incident reports, accounted for 253 incidents. For 19 incident reports (6.99%), cause was not reported. Figure 5.4 displays the percentage of incidents that were accounted for by the reported causal categories. Although this provides an overview of the documented causes of ATCO-related aviation incidents, it does not reveal much about the underlying factors that influenced the cause of the incident.

Figure 5.4. Percentage of incidents classified by reported cause



5.3.6.2 Frequencies of factor contributions to incidents

To gain information regarding factor contributions to incidents, further analysis was needed. In accordance with the aims of the study, analysis was focused on the nine factors previously identified. A frequency analysis indentified the overall frequency with which each factor was reported to contribute to incidents (Table 5.4).

Table 5.4. Frequencies of factor contributions to incidents

Factor	Frequency of incidents	Percentage of incidents
Attention	119	44
Situation awareness	89	38
Communications	89	38
Teamwork	72	27
Workload	66	24
Vigilance	65	24
Trust	9	3
Fatigue	6	2
Stress	3	1

The factors represented in Table 5.4 are rank ordered according to frequency of contribution to incidents. Attention, SA, communications, teamwork were most often cited as contributing to incidents. Trust, fatigue and stress were reported least, each contributing to less than 10% of incidents. An additional frequency analysis was conducted to investigate the reported contribution of each factor (main cause, causal, contributor, possible factor) to reported incidents (Table 5.5).

Table 5.5. Factors' position of contribution to incidents

Factor	Main Cause	Causal	Contributory	Possible Factor
Attention	70	27	17	5
Situation awareness	41	26	11	11
Communications	15	21	43	10
Teamwork	15	14	33	10
Workload	0	21	27	18
Vigilance	19	33	10	3
Trust	1	1	7	0
Fatigue	0	0	4	2
Stress	2	0	1	0

5.3.6.3 Factors are reported to differentially contribute to incidents

Errors of attention and SA were primarily classified as a main cause of an incident. Conversely, the factors of communications, teamwork, workload, trust and fatigue were primarily recorded as being a contributory factor in incidents. This differential classification of the dominant position of factor contribution to incidents may suggest differences in the mechanisms by which the listed human factors are associated with, or influence, performance.

5.3.6.4 Contribution of workload to incidents

At this point, for ease of analysis, workload had been used as an overall category. To understand more about the contribution of workload to incidents, a frequency analysis was completed on the two subcategories of workload: overload and underload, and fluctuating workload. A total of 7 instances of recorded workload were not categorised. An analysis on the remaining 59 instances of reported workload revealed that overload/high complexity was reported to contribute to 37 incidents (56% of all incidents that had recorded a contribution of workload), whereas underload had contributed to 13 incidents (19.7%). Fluctuating workload was recorded as contributing to another 9 incidents (13.64%). This indicates that different extremes of workload contribute to incidents, and should be considered in future studies.

5.3.6.5 Multiple factor co-occurrences

An analysis was conducted on the frequency with which factor dyads (Table 5.6) and triads (Table 5.7) co-occurred in incident reports. For this analysis, the frequencies of attention and vigilance contributions to incidents were combined as a single factor. Although originally the factors were kept separate, vigilance was less reported than attention, and many of the co-occurrences between vigilance and another factor would have been rejected from the frequency analysis due to low frequencies. This did not make sense considering attention and vigilance co-occurred with the same factors. In addition, it could not be determined if investigators were accurately making the distinction between attention and vigilance in the reports. Therefore, by combining the two factors potentially a more comprehensive picture may have been presented.

Table 5.6 presents the frequency of co-occurring factor dyads recorded in incident reports. Factor dyads with 14 or less co-occurrences are not presented due to the large number of factor dyads with less than 14 occurrences in the incident reports. As causality relationships cannot be inferred from the reports, Table 5.6 simply displays observed common presence of factors.

The frequency of factor dyad co-occurrences in Table 5.6 ranges from 15 – 44 incident reports, out of a total of 272 reports. Attention and communications most frequently co-occurred in incident reports, with SA and attention/vigilance co-occurring with a slightly lower frequency, in 40 reports. Situation awareness and teamwork co-occurred relatively infrequently, in 15 reports.

Table 5.6. Frequencies of factor dyads in incidents

Factor dyads	Frequencies
Attention/vigilance & communications	44
Situation awareness & attention/vigilance	40
Mental workload & attention/vigilance	38
Mental workload & communications	28
Mental workload & situation awareness	22
Situation awareness & communications	22
Teamwork & communications	19
Attention/vigilance & teamwork	16
Situation awareness & teamwork	15

A frequency analysis of co-occurring factor triads recorded in incident reports was also conducted (Table 5.7). Again, Table 5.7 displays the observed common presence of factors only, as casual relationships cannot be inferred. These frequencies range from 6 – 22 out of 272 reports. Any triadic relationships that were found in less than 6 incident reports are not recorded here due to the high number of triadic relationships with occurrences in 1 – 5 reports.

Table 5.7. Frequencies of factor triads in incidents

Factor triads	Frequencies
Attention/vigilance & communications & mental workload	22
Attention/vigilance & mental workload & situation awareness	10
Attention/vigilance & mental workload & teamwork	7
Communications & mental workload & situation awareness	6
Communications & situation awareness & teamwork	6

The co-occurrence of attention/vigilance, communications and workload appeared most frequently, in total of 22 incident reports. This was more than double the occurrence of the next most frequent co-occurrence between the factors of attention/vigilance, workload and SA.

When compared with Table 5.6, it can be seen that in half the incidents in which attention and communication co-occurred, mental workload was also reported. This result, combined with the findings presented in Table 5.6 suggests workload may have a key role in this factor interaction.

Finally, it can be seen from Table 5.7 that workload is present in 4 out of 5 of the most frequent triadic factor co-occurrences, suggesting a key role of workload in incidents, but potentially only when an additional factor which also has a negative association with performance also occurs. Attention/vigilance and communications were present in 3 out of the 5 most frequently occurring factor triads, also suggesting the important effects of these factors.

5.3.7 Discussion

The distinction between performance decline and performance-related incidents is an important one in the current research. A performance decline suggests an ATCO's efficiency or safety-related performance is below what is reasonably expected. However, this may not result in an incident, as the controller may recover performance, assistance may be provided, or providence itself may result in no incident occurring. However, a performance-related incident implies that an incident has occurred due to the contribution of an actor in the system, such as an ATCO, resulting from a decline in performance. For this research which focuses on human performance and influences on human performance, both performance declines and performance-related incidents are included in the research.

The aims of the incident report analysis were three fold:

1. Confirm if factors identified in the literature review were present in an ATC environment;
2. Further previous findings by establishing the frequency with which each factor contributed to incidents;
3. Determine if multifactor occurrences are reported in an ATC environment.

The discussion is structured according to these aims. The factor set (workload, stress, fatigue, SA, attention, vigilance, communications, teamwork, trust) provides confirmation that the identified nine factors are associated with human performance within an ATC setting. The reported contribution of factors to incidents (e.g. main cause, causal, contributory) suggests that factors are differentially associated with performance (see Table 5.5). For example, SA was most frequently reported as a causal factor in incidents, supporting the suggestion from the literature that this factor may often be affected by other factors, but has a direct effect on performance. In contrast, factors such as fatigue and workload were primarily recorded as contributory factors in incidents. These factors affect other factors directly, but appear to have a more indirect effect on performance. This supports the categorisation of factors as suggested from the literature review (Chapter 2).

The frequency with which each factor contributed to incidents was reported, contributing to the second study aim. Although the factors recorded in the incident reports corresponded to factors in the literature, the relative importance of each factor differed. In the literature, workload, fatigue and stress are repeatedly noted to be associated with human performance. This is not reflected in the incident reports. Workload was only observed to contribute to 24% of incidents, whereas fatigue was recorded to contribute to 2% of incidents and stress 1% of incidents. Although the results are not directly comparable, as the literature review examined all domains as opposed to only the ATC domain, these results represent a considerable discrepancy between literature and aviation incident reports regarding the relative impact of each factor on human performance decrements, and provides mixed data to the second overall PhD aim to select a sub-set of the factors to most negatively influence performance. One explanation for this result is the findings from the literature review. As it was found that the majority (77%) of articles reviewed took either an experimental or review approach, the discrepancy between results may be partly caused by findings from experimental studies potentially not providing ecologically valid data. An additional explanation focuses on a reporting bias (Johnson, 2001). For example, Kirwan, Scaife and Kennedy (2001) found that certain factors which are seen as 'static' i.e. normally present, tend to be under-reported, since they are always there. Nevertheless, the incident report results suggest that interaction effects between factors do exist in the field, and so the third study aim is supported. This is an important finding as it suggests that anecdotal evidence of complex incidents arising from multiple factors can be supported and encourages further investigation of relationships between multiple factors, and the association of multifactor occurrences with performance. In addition, the factors found to most frequently co-occur may contribute to the overall research aim of selecting a sub-set of factors to investigate in future studies.

Causal relationships between factors cannot be inferred from this data, but it is possible to infer relationships between each of the factor dyads and triads from previous research, some of which were described in the literature review (Chapter 2), and utilise this information to provide a foundation for hypothesis generation of potential factor relationships which could be explored in future studies.

5.4 Concluding remarks

Findings from the literature analysis confirm the frequency and direction with which the identified human performance factors (attention, communications, fatigue, mental workload, situation awareness, stress, teamwork, trust, vigilance) have been found to co-vary, and provide an initial indication of the factors that may be most important to include in the next research phase. The incident report analysis confirmed that the factors are associated with performance-related incidents in an ATC setting. Multifactor co-occurrences are frequently reported and associated with performance-related incidents. Findings also suggest an initial hierarchy of the factors and factors relationships that may most negatively influence controller performance. This first thesis aim, to 'Identify a set of human factors that influence air traffic controller (ATCO) performance' is achieved by these findings. These results also provide a strong starting point in identifying the key factors that most negatively affect ATCO performance, which is the second aim of this thesis.

However, a discrepancy between the results of the literature review and the incident report analysis was found regarding the relative importance of each factor and its influence on performance. As the findings are in conflict, a selection of 3-4 factors that most negatively influence ATCO performance, which is the second aim of the project, cannot be completed with confidence. This is compounded by the potential reporting biases which are suspected to affect the reliability and validity of the findings from the incident report analysis. The selected factors will be used in the next research phases with the assumption that these factors are (negatively) associated with ATCO performance. Therefore, it is highly important that the refinement and ultimate selection of the factors is guided by consistent and reliable findings which are appropriate to the air traffic domain.

It is concluded that further research is necessary to resolve the discrepancy between findings from the literature review and incident report analysis and provide further data to inform the refinement and selection of factors that most frequently negatively influence controller performance, achieving aim two of the thesis. In addition, research is needed to identify the factor relationships that most frequently negatively influence controller performance, whilst minimising the retrospective bias inherent in incident report data. It is suggested that a questionnaire of air traffic professionals would achieve these aims. Air traffic professionals would be able provide detailed information regarding the factors and factors relationships that most negatively influence ATCO performance in current operations rooms, without a retrospective bias. These conclusions therefore led to a study of factors and factor relationships' influence on performance in current operations rooms, from the air traffic professionals' experience.

5.5 Chapter summary

This chapter presented two research studies which investigated human factor relationships and associations with performance. A quantitative frequency analysis of 83 articles, that investigated a total of 90 dyadic factor relationships, was presented. The aims of the study were to investigate the frequency with which specific factors were selected for research within a literature sample of research investigating multifactor-relationships and to investigate the frequency and direction of relationships between factors. Findings support that relationships between factors dyads are reported although discrepant results between studies exist. In addition, factors are selected for investigation with different proportions; workload and stress are most frequently selected for investigation in the reviewed literature sample. An analysis of incident reports was conducted to confirm and extend the literature analysis findings and contribute to thesis aims one and two. Results were described and interpreted in-line with the study aims. Key findings included that the set of nine factors were recorded in incident reports, supporting the association between factors and ATCO performance, and that factors were reported to co-occur in incidents. In addition, a discrepancy was identified between the two studies regarding the relative frequency of factors in association with human performance.

Chapter 6. Expert knowledge elicitation of human factors in relation to performance

6.1 Chapter overview

As concluded from the previous chapter, the data elicited from the literature review and incident report analysis differed in the degree to which factors were reported to contribute to performance decline or performance related incidents. An air traffic professional knowledge elicitation exercise was used to resolve the discrepancy between previous research findings. One advantage of capturing subject matter expert (SME) responses was that data in the research study would be informed by experts, air traffic professionals who experience and observe such influences daily. Data would provide comprehensive and up-to-date information regarding the factor influences which are associated with ATCO performance.

The chapter begins with the aims of the knowledge elicitation study. The selection process of the knowledge elicitation method and exercises is described. A pilot study of the knowledge elicitation exercise, a survey-questionnaire, using aviation professionals as participants, is presented. The pilot study aimed to gain credibility for the exercise selection and highlight modifications to meet the needs of the participant population, and the resulting modifications to the knowledge elicitation exercise are summarised. The chapter then presents the knowledge elicitation exercise in terms of method, results and discussion. The chapter concludes that the survey-questionnaire generated data which contributed to the second research aim. It is proposed that a summary and comparison of the data from the three methodologies of literature analysis, incident report analysis and knowledge elicitation exercise is required next to identify the factors that will be used in future studies, in addition to the proposal of a controlled lab-based experiment as the next research step.

6.2 Expert knowledge elicitation: Aims

The knowledge elicitation exercise had two aims. The first aim was to identify the factors that aviation professionals believed to most negatively influence controller performance. Results contributed to the later selection of factors that were most important to include in future investigations. The second aim of the study was to identify the most frequently occurring dyadic factor relationships which negatively influenced controller performance.

6.3 Selection of knowledge elicitation methodology

A review of knowledge elicitation methods was conducted. Methods were selected that had been documented in research literature to be appropriate for subjective data collection. The following options were considered: questionnaires, focus groups, interviews, influence diagram and analytical hierarchy process. The first three methods are all forms of survey method, defined as a self-report measurement administered through verbal or written techniques (Stangor, 2004). Table 6.1 presents a summary of the method options and relevant pragmatic elements. The survey questionnaire was selected as the knowledge elicitation technique. The questionnaire would be distributed on line to facilitate a large number of responses, and reduce experimenter bias. The selection was made based on the aims of the study and pragmatics for implementing the method. One of the challenges to questionnaire data suggests that experimenter effects may bias results (Bonini, 2005). However, "in comparison to interviews, questionnaires are also likely to be less influenced by the characteristics of the experimenter" (Stangor, 2004, p106). In addition, questionnaires generate more participant responses compared to the other methods, increasing the likelihood of a representative sample (Stangor, 2004). In addition, distribution is flexible and requires minimal resources.

Table 6.1. Summary of knowledge elicitation techniques and elements considered

Method	Summary	Structure	Detail of data	Number of participa nts	Exercise media	Time
Survey questionnaire	Participants respond to a set of fixed format, self-report items	Structured	Bread th of data	As many as possible	Online In person Over the phone	20-40 minut es
Focus group	Form of face-to-face interview with multiple participants	Semi-structured	Detail ed	10-20	In person	1-2 hours per group
Interview	Individual participants respond to a set of standardised questions	Semi-structured	Detail ed	10-20	In person Over the phone	1 hour per perso n
AHP	Generates a relative hierarchy of factors to most negatively influence performance using pair wise comparisons	Structured	Detail ed	20+	In person	Sever al hours per group

6.4 Selection of knowledge elicitation exercise

Two separate exercises were needed to address the two aims of the study.

6.4.1 Exercise selection for aim 1: Factors that most negatively influence controller performance

A forced ranking exercise was selected. Each item presented participants with a lead factor that was already present, and asked participants to rank three other factors that would most negatively impact performance in combination with the lead factor. The lead factor provided context for the participant by specifying pre-existing conditions, which was important to reduce participants' guessing. Instead, participants were encouraged to provide responses based on experience. In addition, contextual information facilitated similar interpretation of the question between participants. A relative hierarchy of factors that most negatively influenced performance can be generated using this method. Figure 6.1 provides as example of the exercise.

Figure 6.1. Example of forced ranking exercise question with lead factor

Which of the following performance influences would have the most negative effect on controller performance if the controller was already experiencing a *high workload*

	High workload AND Fatigue	High workload AND Inadequate communication	High workload AND Inadequate situation awareness	High workload AND Inadequate teamwork	High workload AND Stress
1 (Most impact)	○	○	○	○	○
2	○	○	○	○	○
3	○	○	○	○	○

6.4.2 Exercise selection for aim 2: Most frequent factor dyads which negatively influence controller performance

6.4.2.1 Implications grid

An Implications grid, or 'Impgrid' (Hinkle, 1965) was developed as an option to meet the study aim. An Impgrid can be defined as a modification of a traditional repertory grid method which has successfully been applied to factor dyads and triads in the ATM domain (Kirwan et al, 2001). The repertory grid method was not appropriate in this case as the factors for investigation were already known. An element is presented (i.e. a factor), and the participant is asked to identify other constructs (i.e. factors) that would be associated with the initial factor. This technique can be used to examine experts' perceived relationships between factors. A limitation of this technique was that participants would not be able to identify frequent co-occurring factor dyads in the ATC environment 'in general' due to the frequently changing environment. A scenario or vignette was used for participants' to identify the commonly occurring factor dyads in a specific context. Variations of scenarios were considered, including control event types (e.g. thunderstorm) and events identified from incident reports (e.g. call sign confusion). A limitation of scenario use is that results may only be relevant to the scenario. In addition, participants may not have experienced the scenario, possibly leading to projection of the factors expected in that situation. The exercise limitations led to the consideration of a second exercise.

6.4.2.2 Factor dyad forced-choice exercise

Participants were provided with a series of factor pairs and asked to rate the frequency of co-occurrence (very infrequently – very frequently) in an

ATC environment. The exercise therefore related to participants' experience and was not restricted to a specific event type. This exercise only permits the investigation of factor dyad frequency as the consideration of three or four factors creates an impractical number of questions for participants.

6.5 Pilot study

A pilot study that utilised aviation professionals as participants was conducted to select the most appropriate exercise. A pilot study was important so that the exercises were designed in collaboration with experts, facilitating the creation of exercises that were relevant and meaningful to the participant population. This collaboration also gained credibility that the questionnaire was relevant to this specific expert group, encouraging participation.

6.5.1 Pilot study: Methodology

6.5.1.1 Design

A sample of five ex-controllers served as expert participants to review proposed exercises for a survey questionnaire. The study used a within measures design, so each participant reviewed each exercise once. Exercises were presented on a counter-balanced basis to remove the influence of order effects on responses. The exercise presentation schedule is outlined in Table 6.2.

Table 6.2. Order of exercise presentation

	Participant 1	Participant 2	Participant 3	Participant 4	Participant 5
Day 1 Exercise	Single factor ranking	Impgrid variations and factor dyad ranking	Single factor ranking	Impgrid variations and factor dyad ranking	Single factor ranking
Day 2 Exercise	Impgrid variations and factor dyad ranking	Single factor ranking	Impgrid variations and factor dyad ranking	Single factor ranking	Impgrid variations and factor dyad ranking

A semi-structured interview technique was used for 1 hour per participant. Topic questions began with an open question to promote discussion. Participants' responses were followed with open and closed question probes. There was no fixed format for participant responses. All verbal responses were recorded via dictaphone and written notes.

6.5.1.2 Participants

Participants were five ex-controllers; four males and one female. There was no standardisation of age, years of experience, or number of years since retirement from controlling.

6.5.1.3 Pilot study Procedure

Participants were contacted prior to the study to arrange two, one hour meetings on consecutive days. In the first meeting, the participant was asked to read a study overview and instructions and asked for permission to be recorded. The stimulus material was presented and the researcher completed the interview schedule. The participant was subsequently given the opportunity to provide any other feedback they wished to discuss.

6.5.2 Pilot study: Results and discussion

6.5.2.1 Selection of exercise

In total, four of five participants preferred the dyad factor rating exercise as opposed to the Impgrid. The Impgrid was reported to be too complex and the scenarios were misleading. Participants suggested presenting a brief factor definition that was accompanied by meaningful examples with the factor dyad rating exercise.

6.5.2.2 Factor definitions and natural language

Participants reported that factor definitions needed to be modified to be meaningful and incorporate natural language that was familiar to aviation professionals.

6.5.2.3 Factors

A majority of four participants suggested modifications to the factors under investigation.

1. **Trust**: Trust was not meaningful due to the many forms and varieties in ATC. Trust in systems was perceived as binary; either the system would be fully trusted or would not be used. Therefore, three participants suggested removing the factor of 'trust'.
2. **Attention, vigilance & situation awareness**: Participants could not differentiate between these factors on a practical level, or

differentially apply each to the ATC environment. It was recommended that only one of these factors was included in the questionnaire.

3. **Mental workload**: Participants recommended dividing workload into 'high workload' and 'low workload' as both workload extremes were perceived to differentially influence performance.

6.5.3 Conclusions

Controllers approved of the single factor ranking exercise that contributed to the first study aim. Based on expert feedback, a factor ranking exercise was selected to contribute to the second aim. Factors will be refined in accordance with expert feedback and factor definitions will be created in collaboration with aviation experts.

6.5.4 Refinement of factors included for investigation based on pilot study findings

Factors were refined in line with aviation professionals' feedback from the pilot study so that all factors were meaningful. Factor refinement was also of practical benefit to reduce the number of questions in the survey questionnaire. However, it was not appropriate to base the revision of factors solely on expert feedback. In order to achieve the aims of the study it was important that the factors of interest were still included in the study, and any modifications were appropriate to the research context. Therefore, qualitative expert feedback was considered in combination with data from the previous studies of the literature analysis (section 5.2) and incident report analysis (section 5.3). Factors selected for investigation identified in the literature review sample and the incident report analysis were ranked based on the frequency of the factor's occurrence from 1-9 (1 being the most frequent). The ranks were then combined to create a single ranking for each factor based on findings from both the literature analysis and incident report analysis. Factors with the lowest rank were most frequently included in both studies (Table 6.3). Expert opinions generated from interviews were then considered.

Table 6.3. Factors ranked 1-9 (1 being the most frequent) based on frequency of occurrence in the frequency analysis and incident report analysis

Factor	Frequency of investigations in human factor/human performance literature	Frequency of contributions to incidents	Combined rank (lowest ranks indicate most frequent)
Attention	5	1	6
Communications	4	2.5	6.5
Mental workload	2	5	7
Vigilance	3	6	9
Situation awareness	7	2.5	9.5
Stress	1	9	10
Teamwork	8	4	12
Fatigue	6	8	14
Trust	9	7	16

Table 6.3 reveals the low frequency of consideration of trust in both the literature and as a contributor to incidents. The factor of trust in systems was rejected from any further analysis in line with expert recommendation. Interpersonal trust was collapsed into, and may be inferred by, teamwork. In addition attention and vigilance are similar constructs, with vigilance being defined as a specific form of attention. Both factors are also contained within level 1 situation awareness. Therefore, the questionnaire will only explicitly ask questions about the factor of situation awareness from which attention and vigilance may be inferred.

6.5.5 Summary of findings from the pilot study pertinent to the next research study

In summary, a survey questionnaire containing two exercises was selected to address two study aims. The selection was supported by aviation experts. In accordance with expert recommendations, the factor set was refined and the following factors were incorporated in the questionnaire: communications, fatigue, situation awareness, stress, high workload, low workload and teamwork. Factor definitions in the questionnaire were modified to include ATC-specific examples and were approved by aviation professionals.

6.6 Survey questionnaire: Knowledge elicitation

6.6.1 Questionnaire: Method

6.6.1.1 Design

Expert opinion of the single factors and most frequent factor dyads to most negatively influence controller performance were investigated. The study used an independent measures design with a fixed format self-report survey questionnaire that was online (Appendix 4). The online questionnaire consisted of a total of 28 items separated into two sections. Section 1 aimed to investigate the frequency of the co-occurrence of dyadic factors in performance related loss of separation incidents and controller performance decrements. Participants were required to indicate the frequency with which that factor pair influenced controller performance using a Likert scale. The scale utilised a continuum ranging from 1 (Very Rarely) to 5 (Very Often).

The second section of the questionnaire aimed to investigate the impact of each factor, when combined with another factor, on performance. Each item utilised a forced ranking response method. Participants were presented with the remaining six factors and ranked the top 3 factors (1 being most impact of the 3, 3 being the least impact). Once the questionnaire had been developed, two controllers and one incident investigator from the National Air Traffic Service (NATS), in addition to two human factors professionals, reviewed and approved the questionnaire prior to distribution.

6.6.1.1 Participants

The target population for the questionnaire was ATCOs and incident investigators. These populations were selected to capture perspectives from individual with different experiences. ATCOs are familiar with factors that influence their performance, whilst incident investigators have experience in the factors that most frequently contribute to incidents. Snowball sampling was used to generate a high number of responses. Although this form of non-probability sampling may lead to sampling bias (Stangor, 2004) a larger sample may control for this potential bias by being more representative.

6.6.1.2 Materials

A survey questionnaire was developed which used an online medium. An online platform allowed participants to access the questionnaire in their own time and easily distribute the questionnaire to eligible colleagues. At the beginning of the questionnaire, participants were presented with a 'Welcome' page which provided an overview of the study. Confidentiality and anonymity of participant responses were stated explicitly.

Exercises:

The questionnaire consisted of a total of 28 items separated into two separate sections, excluding seven optional demographic questions which were presented at the end of the questionnaire. Section 1 investigated the frequency of factor dyads in performance related loss of separation incidents and ATCO performance declines. This exercise was compulsory, and positioned first, as it was important to gather data particularly on frequencies of factor dyads associated with performance declines.

Each factor was paired with each of the 6 other factors once, (high workload, underload, stress, fatigue, inadequate situation awareness, inadequate communication and inadequate teamwork) to create 21 items. The factor pairs were counterbalanced so that each factor appeared as the first factor in three pairs and the second factor in three pairs, to reduce the potential of order effects on participant responding. In addition, the position of the items was randomised. At the start of the questionnaire, participants were asked to identify themselves as an incident investigator, a controller, or incident investigator and controller. The lead questions were slightly different for respondents who were incident investigators, and respondents who were controllers (those who self-classified as incident investigators and controllers were directed to the investigators' lead questions). Lead questions were focused on respondents' experience. This explicit reminder for participants to base responses on experience was intended to reduce projection and 'guessing' which may bias results. For incident investigators, the lead question asked: "In your experience as an incident investigator, how frequently does the following combination lead to controller-related loss of separation incidents?" However, as controllers experience few, if any, incidents throughout their career, controllers were asked: "In your experience as an air traffic controller, how frequently has the following combination negatively affected your ability to provide a safe service?" Participants were required to indicate the frequency with which that factor pair influenced controller performance using a Likert scale. The scale utilised a continuum ranging from 1 (Very Rarely) to 5 (Very Often). This was altered from the classic 'strongly disagree' to 'strongly agree' to be appropriate to the questionnaire question. In addition, these quantifiers were chosen, rather than for example 'never – always' as it was believed that these points would not be relevant to a frequently-changing environment. Figure 6.2 provides an example of a controller-related question.

Figure 6.2. A rating scale exercise for the most frequent factor dyads to negatively influence ATCO performance

In your experience as an air traffic controller, how frequently has the following combination negatively affected your ability to provide a safe service?

	Very rarely	Rarely	Sometimes	Often	Very often
Underload AND Inadequate situation awareness	○	○	○	○	○

The second section of the questionnaire aimed to investigate the impact of each factor, when combined with another factor, on performance (Figure 6.3). Some data had already been previously generated in relation to this aim and so this exercise was placed second, and in addition, was optional. Each item presented 1 of the 7 factors as a background factor, creating a total of 7 items. Again, the lead question for each item differed slightly between groups. Investigators were asked: "Which of the following performance influences would have the most negative effect on controller performance if the controller was already experiencing a (*high workload*)". Whereas controllers were asked: "Imagine you are experiencing (*high workload*). Which three of the following factors would have the most negative effect on your ability to handle the traffic?" This was again necessary due to the differing experience of each participant group. Each item utilised a forced ranking response method. Participants were presented with the remaining six factors and ranked the top 3 factors (1 being most impact of the 3, 3 being least impact).

Figure 6.3. A ranking exercise of the factors dyads that are perceived to most negatively influence controller performance.

Imagine you are experiencing *fatigue*. Which three of the following factors would have the most negative effect on your ability to handle the traffic?

	Fatigue AND Stress	Fatigue AND High workload	Fatigue AND Inadequate situation awareness	Fatigue AND Underload	Fatigue AND Inadequate teamwork	Fatigue AND Inadequate communications
1 (Most impact)	○	○	○	○	○	○
2	○	○	○	○	○	○
3	○	○	○	○	○	○

6.6.1.3 Definitions

In an attempt to reduce artificial variability in participant responding, definitions of each factor were placed at the beginning of each questionnaire page to encourage participants to read the definitions before responding. Factor definitions were created in collaboration with three ex-controllers. Definitions were developed by using traditional definitions as cited in human factors literature, and integrating natural language recommended by aviation experts. This process enabled the development of definitions which were both representative of the factor and approved by human factor experts, but were also meaningful to the participant groups. Table 6.4 displays the factor definitions utilised in the questionnaire, created from the collaborative process.

Table 6.4. Final definitions applied in questionnaire

Factor	Final definition
Fatigue	Feelings of tiredness or weariness caused by prolonged activity. E.g. Wanting to handover although it's not yet time. Making errors that don't normally happen. Missing more calls than normal. Asking for repeats
High workload	High demand (amount and complexity) imposed by ATC tasks. E.g. Insufficient process time to refine and prioritise actions. Communications moving beyond capabilities
Inadequate communications	Problems in the exchange of verbal information, including timeliness, accuracy, clarity and receptiveness. E.g. Not professional or focused language. Not in control of the communication pattern
Inadequate situation awareness	Inadequate Situation Awareness: Problems with the maintenance of a coherent mental picture for current and future controller performance. E.g. Lack of alternatives if plans change. Lack of awareness of what is coming and what is needed
Inadequate teamwork	Controllers not working together effectively. E.g. Poor sector-to-sector coordination between controllers or between tactical and planner controllers

Stress	Pressures imposed by the situation which challenge the controller's ability to cope. E.g. Extended decision making & re-planning. Perceiving traffic situations normally set up are now getting too risky. Questioning own ability to cope
Underload	Very low demand (amount and complexity) imposed by ATC tasks. E.g. Boredom due to little traffic on frequency. Becoming inattentive or distracted during very quiet periods

6.6.1.4 Factor framing

Factors were framed negatively to be consistent and comparable. Some factors already had negative connotations, such as stress or fatigue. Other factors were neutral, such as 'situation awareness'. Neutral factors were therefore negatively framed e.g. 'inadequate situation awareness'.

6.6.1.5 Questionnaire distribution procedure

The completed questionnaire was reviewed by two human factors experts, two controllers and an incident investigator prior to distribution. Distribution occurred through several channels. A series of in-person visits to European ANSPs encouraged management to distribute the questionnaire link to teams of controllers and incident investigators. In addition, an introduction and invitation email was emailed to representatives of a professional aviation groups for distribution to members. The questionnaire link was also included in a newsletter for the International Federation for Air Traffic Controllers (IFACTA). All invitations to the questionnaire encouraged respondents to forward the link to eligible colleagues. The questionnaire was closed two months after it was first accessible.

6.6.2 Results: Survey questionnaire section 1

6.6.2.1 Participant demographics

Of 65 respondents, the majority consisted of active controllers (56.9%), 20% of respondents were incident investigators, and 23.1% were both active controllers and incident investigators. The majority (76.3%) of respondents were aged between 31 - 50 years old. A large majority of respondents were male (84.5%). All participants had over 1 years' experience, with a majority of respondents (40.6%) holding between 5 and 14 years experience. A majority (40.5%) of controllers worked most frequently in the en-route sectors (48.6%). Respondents identified themselves from a total of 24 European countries: Albania, AUSTRIA, Belgium, Bulgaria, Croatia, Denmark, France, Germany, Greece, Hungary, Israel, Italy, Lithuania, Malta, Netherlands, Poland, Portugal, Slovakia, Slovenia, Spain, Switzerland, Trinidad and Tobago, Turkey and UK. The largest majority of respondents worked in Greece (13.8%), Malta (10.8%) and UK (6.2%).

6.6.2.2 Between group differences

A Mann-Whitney U test confirmed significant between group differences for 12 items ($U=254 - 383$, $p<0.05$). Therefore, the results for controller respondents and investigator respondents (including respondents who were investigators and controllers) were analysed separately.

6.6.2.3 Analysis of controllers' responses

The range of means was calculated from 1.73 (indicating a general low response to the item, suggesting the factor pair would not often contribute to incidents) to 2.59 (indicating the item may rarely - sometimes contribute to performance decline). Table 6.5 presents the means and standard deviations of the ratings of the top 10 factor pairs in rank order.

Table 6.5. Ranked means and standard deviations for each item

Item	Mean	SD
High workload & Inadequate teamwork	2.59	0.86
Inadequate SA & High workload	2.54	0.93
High workload & Stress	2.46	0.99
Inadequate communications & High workload	2.46	0.90
Fatigue & Inadequate teamwork	2.43	1.01
Inadequate SA & Inadequate communications	2.43	0.93
High workload & Underload	2.38	0.98
Stress & Inadequate SA	2.35	0.75
Fatigue & High workload	2.35	0.82
Stress & Inadequate Communications	2.35	0.82

Table 6.5 shows that the top 6 factors pairs have mean ratings between 2.43 - 2.59. High workload and inadequate teamwork received the highest mean rating ($M=2.59$, $SD=0.86$), indicating that this pair contributes to performance decrements more often than other factor pairs presented. The standard deviations are also relatively small (0.75 - 1.06), indicating concordance between respondents. A data trend can be seen in that all of the top 4 factors contain high workload. The factor pair of fatigue and high

workload was rated 9th most frequent factor pair overall, and is the only time high workload appears outside of the top five rated factor pairs. The means of the 5 factor pairs that were rated as most infrequently negatively impacting performance ranged from 1.73-1.97, with standard deviations ranging from 0.84-1.01. All factor pairs included underload.

Data were further analysed with non-parametric statistics. A Levene's test revealed the homogeneity of variance assumption was violated for 6 factor pairs ($p<0.05$), and a Kolmogorov-Smirnov analysis revealed that 18 out of 21 results did not have a normal distribution ($p<0.05$). A Friedman's ANOVA identified significant differences between item ratings ($X^2(20) = 77.2$, $p<0.0005$. Wilcoxon analyses expanded on this finding. A bonferroni correction was applied and so all effects are reported at a 0.001 level of significance. Differences most relevant to the questionnaire aims are discussed.

6.6.2.3.1 High workload vs. underload

High workload and inadequate teamwork was rated to contribute to a reduction in a safe service significantly more frequently than the four factor pairs that were rated as least frequently occurring. Interestingly, all of these factor pairs included underload: underload and fatigue ($T=30$, $z=-3.59$, $p<0.0005$), underload and inadequate situation awareness ($T=44$, $z=-3.29$, $p=0.001$), stress and underload ($T=35$, $z=-3.8$, $p<0.0005$) and inadequate teamwork and underload ($T=39$, $z=-3.56$, $p<0.0005$). In addition, inadequate situation awareness and high workload was rated significantly more frequently as contributing to a reduction in safe service than four factor pairs containing underload, including stress and underload ($T=37.5$, $z=-3.6$, $p<0.0005$)and underload and inadequate situation awareness ($T=34$, $z=-3.45$, $p=0.001$).

6.6.2.3.2 Fatigue

Ratings of factor pairs including fatigue were significantly different. Reponses to the frequency of fatigue and underload suggest that this factor pair contributes significantly less frequently to controllers' ability to provide a safe service than high workload and inadequate teamwork ($T=30$, $z=-3.59$, $p<0.0005$), inadequate situation awareness and inadequate communication ($T=27$, $z=-3.29$, $p=0.001$). However, fatigue and inadequate teamwork was rated by controllers as significantly more frequently occurring than inadequate teamwork and underload (T=63, z=-3.34, p=0.001) and stress and underload (T=48.5, z=-3.35, p=0.001).

6.6.2.4 Analysis of investigators' responses

The range of means was calculated from 2.0 (indicating the factor pair would 'rarely' contribute to incidents) to 3.25 (indicating the item may 'sometimes' contribute to losses of separation). Table 6.6 presents the means and standard deviations of the top 10 factor pairs in rank order.

Table 6.6. Ranked means and standard deviations for each item

Item	Mean	SD
Inadequate communications & HWL	3.43	0.96
HWL & Inadequate TW	3.25	0.89
Inadequate SA & HWL	3.18	0.77
HWL & Underload	2.96	1.17
HWL & Stress	2.93	0.98
Inadequate SA & Inadequate communications	2.93	0.86
Inadequate communications & Inadequate TW	2.86	1.01
Stress & Inadequate SA	2.82	1.12
Inadequate TW & Inadequate SA	2.82	0.94
Inadequate TW & Stress	2.79	0.99

Table 6.6 shows that high workload appeared in all the top 5 factor pairs rated as contributing most frequently to incidents. Inadequate communication and high workload received the highest ratings (M=3.43, SD=0.96). High workload and underload (one factor following the other) was rated as fourth most frequently contributing to incidents (M=2.96, SD=1.17), the only time underload was rated in the top 10 factors. The three factor pairs most infrequently contributing to incidents and reduction in performance all included underload, with means ranging from 2-2.29. Friedman's ANOVA suggested that participants did rate factor pairs significantly differently ($X^2(20) = 92.66$, p<0.001. Wilcoxon tests were used to follow up this finding. A bonferroni correction was applied and so all effects are reported at a 0.001 level of significance. Comparisons between 13 pairs of factors were rated significantly different at the p<0.0005 level of significance. An additional 11 pairs of factors were significant at the p=0.001 level of significance. Selected differences are discussed.

6.6.2.4.1 High workload vs. underload

Wilcoxon statistical analyses revealed each of the top rated factors containing high workload were rated as significantly more frequently contributing to incidents than those factor pairs containing underload. For example, inadequate communication and high workload was rated significantly more frequently contributing to incidents than factor pairs containing underload, including inadequate teamwork and underload ($T=21$, $z=-3.77$, $p<0.0005$) and stress and underload ($T=21$, $z=-4.11$, $p<0.0005$). In addition, high workload and inadequate teamwork was rated significantly more frequently as contributing to loss of separation incidents than underload and fatigue ($T=12$, $z=-3.55$, $p<0.0005$) and stress and underload ($T=16$, $z=-4.05$, $p<0.0005$).

6.6.2.4.2 Fatigue

Factor pairs including the factor of fatigue received a wide distribution of ratings ($M= 2.25$-2.75). Fatigue and inadequate teamwork ($T=21$, $z=-3.38$, $p=0.001$), fatigue and inadequate communications ($T=15$, $z=-3.51$, $p<0.0005$) and fatigue and stress ($T=17$, $z=-3.62$, $p<0.0005$) were all rated as significantly less frequently contributing to incidents than inadequate communications and high workload. This suggests investigators do not rate fatigue as frequently contributing to incidents.

6.6.3 Results: Survey questionnaire section 2

A Mann-Whitney U analysis revealed no significant between group differences. Therefore, results were collapsed into one data set.

6.6.3.1 Participant demographics

Of 48 respondents, the majority consisted of active controllers (58.3%), while 18.8% of respondents were incident investigators, and 22.9% were both active controllers and incident investigators. The majority of respondents (73%) were aged between 31 - 50 years old. A large majority of respondents were male (80.9%), with 41.7% holding between 10 - 19 years experience. Respondents were from a total of 21 European countries. The largest majority of respondents worked in Greece (16.7%), Malta (14.6%) and UK (6.2%). A majority of controllers worked most frequently in the en-route sectors (42.9%).

6.6.3.2 Analysis procedure

Every factor in each of the 7 questions could be rated from 1 (least impact on ability to handle traffic) to 3 (most impact on ability to handle traffic). The factors that were not ranked by participants were classed as having a rating of 0. Table 6.7 displays a summary of the factors that were overall ranked most frequently to impact performance if combined with the lead factor in the question.

Table 6.7. Factors rated to most impact performance if combined with the lead factor, as generated from overall item frequencies

Item No.	Lead factor	Most impact	2nd most impact	3rd most impact
1	Underload	Inadequate SA (Median= 2)	Inadequate teamwork (Median = 1)	Inadequate communications (Median = 1)
2	High workload	Inadequate SA (Median= 2)	Inadequate teamwork (Median = 2)	Inadequate communications (Median = 1)
3	Fatigue	Inadequate SA (Median= 2)	High workload (Median = 1)	Inadequate teamwork (Median = 0)
4	Stress	Inadequate SA (Median= 1)	High workload (Median = 2)	Fatigue (Median = 1)
5	Inadequate situation awareness	High workload (Median = 2.5)	Inadequate communications (Median = 1)	Inadequate teamwork (Median = 1)
6	Inadequate communications	Inadequate SA (Median= 2)	High workload (Median = 2)	Inadequate teamwork (Median = 1)
7	Inadequate teamwork	High workload (Median = 2)	Inadequate communications (Median = 1)	Inadequate SA (Median= 1)

In order to investigate significant differences between factor ratings, a Friedman's ANOVA was conducted on the ratings of each set of factors. For all items, Friedman's ANOVA was significant : participants did significantly differently rate the perceived impact of each factor on performance (**Item 1:** $X^2(4) = 23.66$, $p<0.0005$, **Item 2**: ($X^2(4) = 27.4$, $p<0.0005$, **Item 3:** $X^2(5) = 31.19$, $p<0.0005$, **Item 4**: $X^2(5) = 29.54$, $p<0.0005$, **Item 5**: $X^2(5) = 46.77$, $p<0.0005$, **Item 6**: $X^2(5) = 55.56$, $p<0.0005$, **Item 7**: $X^2(5) = 58.22$, $p<0.0005$). Wilcoxon tests were used to investigate these results. A bonferroni correction was applied and so all effects are reported at a 0.005 level of significance. In the first four items, inadequate SA was rated as significantly more frequently negatively impacting performance than many other factors. For example, inadequate SA was rated significantly more frequently as negatively impacting performance when combined with underload than stress ($T=88$, $z=-4.19$, $p<0.0005$). Analyses on item 2 revealed inadequate SA was again rated significantly more frequently to negatively impact performance when combined with high workload than fatigue ($T=155$, $z=-3.9$, $p<0.0005$) and stress ($T=159$, $z=-3.71$, $p<0.0005$). Inadequate SA was rated significantly more frequently to impact performance when combined with fatigue than factors including inadequate teamwork ($T=211$, $z=-3.07$, $p<0.005$) and inadequate communications ($T=136$, $z=-3.89$, $p<0.0005$). Finally, inadequate SA was found to have been rated significantly higher as having the most negative impact on performance when combined with inadequate communication when compared to fatigue ($T=135$, $z=-3.75$, $p<0.0005$), stress ($T=241.5$, $z=-3.16$, $p<0.005$) and underload ($T=29.50$, $z=-4.93$, $p<0.0005$).

High workload was also a highly rated factor. In item 4, high workload was ranked as having a negative impact on performance when combined with stress significantly more than underload ($T=13.50$, $z=-4.49$, $p<0.0005$). High workload was also rated overall as the factor that would most impact performance if combined with inadequate SA. This ranking was significantly higher than the overall ratings received for factors including underload ($T=71$, $z=-4.67$, $p<0.0005$) and stress ($T=163.5$, $z=-3.8$, $p<0.0005$). This suggests the importance of this factor in impacting the ability to handle aircraft when combined with inadequate SA. High workload was again rated significantly more frequently to impact performance when combined with inadequate communications than fatigue ($T=161$, $z=-3.4$, $p<0.005$), stress ($T=173$, $z=-3.24$, $p<0.005$), and underload ($T=66$, $z=-4.37$, $p<0.0005$). Finally, high workload was rated significantly more frequently as having a negative impact on performance when combined with inadequate teamwork than fatigue ($T=115$, $z=-4.15$, $p<0.0005$), stress ($T=135$, $z=-4.02$, $p<0.0005$) and underload ($T=22$, $z=-5.08$, $p<0.0005$). For this item, underload was also rated significantly less frequently than three other factors - inadequate communications ($T=55$, $z=-4.09$, $p<0.0005$), inadequate situation awareness ($T=64.5$, $z=-3.94$, $p<0.0005$), and stress ($T=34.5$, $z=-3.07$, $p<0.005$).

6.6.4 Questionnaire: Discussion

6.6.4.1 Survey questionnaire section 1

General, significant, data trends were found in the first questionnaire section.

6.6.4.1.1 High workload vs. underload

The top four factor pairs as rated by controllers, and the top five factor pairs as rated by investigators, all contain high workload. This may indicate that high mental workload is perceived by ATM experts to be one of the main contributors to performance decline and loss of separation incidents. Controllers, however, are highly trained to effectively manage high workload, adopting various strategies to maintain a high standard of performance (e.g. Sperandio, 1971). Therefore, the results suggest that in order for performance to be maintained under high workload, other factors within the social technical system must be operating adequately. If a component is less than adequate when a high workload is present, the risk of a performance decrement or loss of separation incident may increase.

Both controllers and investigators rated factor pairs containing underload as very infrequently influence performance. The factors paired with underload were the same factors that appeared in the top four factor pairs with high workload, suggesting the level of workload is the determiner of the impact of a factor pairs on performance. For example, under a high workload, inadequate teamwork could enhance the complexity and risk of a situation. However, with few aircraft on frequency, a controller may have the spare capacity to support the deficit arising from inadequate teamwork.

6.6.4.1.2 High workload and underload

Both controllers and investigators highlighted the transition between workload extremes as frequently contributing to loss of separation incidents and performance decrements. These workload transition effects are well-known colloquially (e.g. Cox-Fuenzalida, 2007; Kirwan, 2011). However, very little research has investigated this effect. Future research should investigate the relationship between workload extremes, and the impact of the transition effects on performance. The only time underload was ranked highly in the questionnaire was when it was combined with high workload (one would follow the other). This relationship may suggest that the so called gear shift, or workload transition, effect impacts performance negatively (Cox-Fuenzalida, 2007). Further research should consider this relationship in more experimental settings to further understand the interactions between these factors and the impact on performance.

6.6.4.1.3 Fatigue

Factor pairs containing fatigue received a wide dispersion of overall ratings. Only fatigue and inadequate teamwork was rated by controllers as 5^{th} most frequent to impact performance. Investigators rated all factor pairs containing fatigue infrequently occurring. The results suggest fatigue may be dependent on the associated factor to determine its impact on performance. This is an interesting result as fatigue has been widely reported in literature to be a primary cause of human error and resulting performance decrements and incidents (e.g. Dorrian, Roach, Fletcher, & Dawson, 2007). These results suggest that this view may not be reflected in the wider ATM professional population.

6.6.4.2 Survey questionnaire section 2

The results of section 2 of the questionnaire support findings from section 1. Table 6.7 suggests that inadequate SA was rated as the factor that would have the most impact on performance, followed by high workload, then inadequate teamwork, and finally inadequate communications. These factors have been reported by aviation experts to associate negatively with performance and may be considered for inclusion in future research. The factors that were considered to have the most negative influence on performance were inadequate SA and high workload. These findings may therefore be particularly important for inclusion in future research.

Interestingly, fatigue, stress and underload were not perceived to most negatively influence performance. This finding reflects the incident report findings.

6.7 Chapter summary

A knowledge elicitation study was required to resolve the discrepancy in results from the literature analysis and incident report analysis. The knowledge elicitation study aimed to identify the single factors that aviation professionals believed to most negatively influence controller performance and identify the most frequently occurring factor dyads that negatively influenced controller performance. Results contributed to the second overall research aim. An online survey questionnaire was selected as the knowledge elicitation method. The questionnaire incorporated two exercises. A pilot study with five ex-controllers as participants was conducted and the questionnaire was modified in accordance with expert recommendations. The questionnaire was distributed through European ANSPs and professional aviation societies. Results suggest that the factor combination of a high workload with factors such as inadequate teamwork and inadequate SA most frequently negatively influence controller performance. Controllers are trained to maintain a high performance with a high workload. Therefore, the combination of a high workload with an additional factor may influence performance decline. In addition, inadequate SA was reported to most negatively influence performance, followed by high workload, inadequate teamwork, and inadequate communications. These results will be considered in combination with previous data to select the factors for inclusion in future investigations.

Chapter 7. Selection of experimental factors

7.1 Chapter overview

Chapters 5 and 6 have described a literature analysis, incident report analysis and knowledge elicitation study that generated data towards two overall research aims: identification of a set of human factors that influence ATCO performance, and the selection of sub-group of factors for inclusion in the next research phase. At this stage, a comparison of research findings from the three methods is needed to inform the selection of a sub-group of factors. The selection will be based on the single factors that most negatively influence controller performance, and the factors that most frequently co-occur in an ATC domain.

The chapter begins with a summary of the three studies and a comparison of the single factors and factor dyads that were most frequently recorded to negatively influence controller performance. The results of this comparison are combined with pragmatic considerations. Six factors are selected for inclusion in future studies.

7.2 Summary of previous studies and associated findings

A literature analysis, incident report analysis and survey questionnaire investigated the frequency of factors and factors relationships that were associated with controller performance. Each study built on the previous method to provide confirmation of, and extend, research findings. The literature review provided confirmation of an initial factor set of nine factors (workload, stress, fatigue, SA, attention, vigilance, communications, teamwork, trust) that were provided by EUROCONTROL, and identified previous research that indicated factors did co-vary. It was important to investigate factor co-occurrence, and association with performance, within the ATC domain. An incident report analysis confirmed that the factors identified in the literature were associated with ATCO performance-related incidents, and provided an initial hierarchy of the most frequent factors, and co-occurring factor dyads and triads, reported to contribute to ATCO-performance related incidents.

A discrepancy was identified between the results of the literature analysis and incident report analysis regarding the frequency that factors were selected for investigation in the sample of peer-reviewed literature, and the factors that were reported to contribute to performance-related incidents. It was therefore necessary to resolve the discrepancy. An aviation-expert knowledge elicitation method was selected to generate current data that was specific to the ATC domain. A survey-questionnaire investigated human factors in relation to performance. Results confirmed that the factor set was perceived by experts to negatively influence controller performance. In addition, results indicated a hierarchical ranking of the factors that most negatively influenced performance, and the factor dyads that were perceived to most frequently co-occur to negatively influence controller performance. The data generated from these three consecutive studies were compared.

7.3 Comparison of results from a literature analysis, incident report analysis and survey-questionnaire

A set of nine factors (workload, fatigue, stress, attention, vigilance, SA, communications, teamwork and trust) were included in the literature analysis and incident report analysis. However, the factors were refined prior to the knowledge elicitation study; the factor set now consisted of workload, fatigue, stress, SA, communications and teamwork. Two comparisons are presented. Section 7.3.1 compares findings relating to the single factors that most frequently, negatively influence ATCO performance. Section 7.3.2 presents a comparison of findings relating to the factor dyads that most frequently co-occurred in association with ATCO performance.

7.3.1 Comparison of results: Single factors most frequently reported, and most frequently reported to have a negative association with performance

Table 7.1 presents a hierarchy of the single factors that were recorded to influence performance, from most frequent to least frequent, reported for three methodologies. Factors which are common between methodologies are presented in bold. Factors which are not included in the questionnaire have been presented in red. In all methodologies, the factors of workload, communication, teamwork and SA are reported to influence controller performance. Stress and fatigue are documented to influence controller performance in the literature analysis and incident report analysis. The frequencies of the reported results differ, potentially due to the different focuses of the methodologies. The hierarchy of factors reported in the incident report analysis and questionnaire, similar in focus and specific to the ATC domain, are similar. Excluding the factors that were not included in the questionnaire, SA, workload teamwork and communication appear in the top four positions for both methodologies. Interestingly, fatigue and stress were not rated in the top factors. The concordance between results from three separate methodologies suggests that the original nine factors considered did negatively influence controller performance. The comparison of results also highlights the factors that may most frequently negatively influence performance and may be considered for inclusion in future investigations. The selection of factors was further informed with a comparison of the most frequent factor dyads to negatively influence controller performance, as reported from three methods.

Table 7.1. Comparison of findings: Single factors' influence on performance

Factor position (Most – least frequent)	Literature	Incident Analysis	Survey questionnaire – controllers & investigators
1	Stress	Attention	**SA**
2	**Workload**	**SA**	**High workload**
3	Vigilance	**Communication**	**Inadequate teamwork**
4	**Communications**	**Teamwork**	**Inadequate communications**
5	Attention	**Workload**	
6	Fatigue	Vigilance	
7	**SA**	Trust	
8	**Teamwork**	Fatigue	
9	Trust	Stress	

7.3.2 Comparison of results: Frequency of factor dyads identified to co-occur, and the association with performance

Table 7.2 presents a comparison of the factor dyads which were most frequently reported. For brevity, a maximum of ten most frequently recorded dyads are presented. A key to the table is presented under the table itself. The same four factors highlighted in the single factor hierarchy (Table 7.1) specifically workload, SA, communications and teamwork, are also reported as co-occurring most frequently to negatively influence controller performance. In addition, stress and fatigue are also within the top five factor dyads reported by the literature analysis and questionnaires to also co-occur with other factors to negatively influence controller performance. Table 7.3 presents a summary of the factor dyads recorded in all methodologies and two of the three methodologies. All factors apart from stress were also included in the single factors to most negatively influence performance. It can therefore be stated with confidence that these factors, recorded by three separate methodologies, should be considered for inclusion in future research as the factors that are most negative and frequently influence performance. The most frequent factor dyads to negatively influence performance were considered for hypothesis generation for the next research phase.

Table 7.2. Comparison of findings of the most frequent co-occurring factor dyads

Factor position	Literature	Incident Analysis	Questionnaire–controllers	Questionnaire – incident investigators
1 (most frequent)	Stress and attention	Vigilance & communications	High workload and teamwork	**High workload and communications**
2	Stress and vigilance	Situation awareness & attention/vigilance	**High workload and situation awareness**	High workload and teamwork
3	**Workload and communications**	Workload & attention/vigilance	High workload and Stress	**High workload and situation awareness**
4	Stress and communications	**Workload & communications**	**High workload and communications**	High workload and underload following each other
5	Workload and stress	**Workload & situation awareness**	Fatigue and teamwork	High workload and Stress
6	Workload and attention	Situation awareness & communications	Situation awareness and communications	Situation awareness and communications
7	Workload and fatigue	Communications and teamwork	High workload and underload following each other	Communications and teamwork
8	**Workload and situation awareness**	Vigilance & teamwork		
9	Workload and vigilance	Situation awareness & teamwork		
10	Fatigue and stress			

Key
Factors in **BOLD** = recorded in all three methodologies
Factors in GREEN = recorded in two methodologies

Table 7.3. Factor dyads that have been identified by at least two of the three methods

Factor dyads recorded by three methods	Factor dyads recorded by two methods
Workload & communications	Situation awareness & communications
Workload and SA	Workload and stress
	Teamwork & communications

7.4 Selection of subgroup of factors for inclusion in the next research phase

Selection of a subgroup of factors to be included in future research was based on findings from the three previous studies documented above, as well as pragmatics for implementing measurements in planned future experimental research. In line with previous findings, the factors selected are:

1. Workload
2. SA
3. Stress
4. Fatigue
5. Communications (with reservations)

Teamwork is the notable exclusion from this factor set. This factor was recorded repeatedly in previous findings (Table 7.1, Table 7.2). However, it was not possible in an experimental task to replicate the teamwork between adjacent controllers and executive and coordinating controllers due to restrictions on resources and equipment. Communication was selected as a factor that may be included in the next research study. Communications were reported to influence controller performance. However, the next research task will use naive participants (i.e. participants who were not trained as controllers) with elements of an ATC task. It may not be feasible to train naive participants to communicate using aviation phraseology in a short time. It was decided that communication would be remain in the selected factor set, and the practicalities of inclusion would be examined in future studies.

Fatigue was included in the selected factors. Fatigue was not reported frequently in incident reports or the questionnaire, however there is cause to suggest that these findings may not be a true reflection of the occurrence of fatigue, and association with controller performance, in ATC.

As outlined in Chapter 2, section 2.2.1.2, the relationship between fatigue and performance is complex, and problematic to reliably document (Wickens et al., 2004; Matthews et al., 2000). The indirect relationship of fatigue and performance means that fatigue may manifest differently depending on the context; for example fatigue may contribute to a controller overlooking an aircraft. Although fatigue may be an underlying, or at least contributory, influence, the factor reported to contribute to an incident may be associated with 'vigilance'. In addition, as discussed in Chapter 5, section 5.3.7, reporting biases may have influenced the presence of fatigue in incident reports. Johnson (2001) and Kirwan, Scaife and Kennedy (2001) both report the occurrence of biases in incident reporting, including a retrospective bias in which specific factors such as fatigue are problematic to identify retrospectively, and under-reporting of factors that are normally present.

Recent developments in the aviation domain confirm the significance of fatigue within ATC. Currently, there is significant focus within the aviation domain on fatigue and the association with performance, both within the Federal Aviation Authority and Europe, with the European Aviation Safety Agency deciding to make fatigue risk management systems (defined as "a data-driven means of continuously monitoring and managing fatigue-related safety risks" ICAO, 2012, p1-1) mandatory in the near future. Therefore, in addition to the recognition that fatigue may be underreported within the aviation domain, there is an industrial recognition of the importance of fatigue in association with human performance. For these reasons, it was decided that fatigue will be included in the sub-set of factors.

A decision was made to include the measurement of arousal within the next research stage. Cox and Mackay (1985) suggest that whilst stress is related to subjective experiences of unpleasantness/pleasantness, arousal is related to wakefulness/drowsiness, which the measurement of stress alone may not capture effectively. Stress and arousal are closely related concepts (Mackay et al., 1978) which are reported to covary (Cox & Mackay (1985). Cox and Mackay (1985) argue that "it has now become obvious that feelings of unpleasantness/pleasantness (stress) may partly reflect how appropriate the level of arousal is for a given situation" (p183). As with stress, the relationship between arousal and performance is curvilinear and so 'inappropriate' levels of sustained arousal level may influence the experience of stress, whilst 'appropriate' levels of arousal are generally reported to be beneficial to task performance (e.g. Matthews & Davies, 2001). Stress and arousal were therefore both selected for measurement in the next research stage to generate a more comprehensive understanding of participants' response to the task (in terms of arousal and stress) and the associated relationship with performance.

7.5 Next research phase: Experimental study

The first two research aims have been addressed. The next research phase will contribute to the third, fourth, fifth and sixth research aims. The most appropriate methodology to generate data to contribute to these aims and investigate the selected factors is an experimental method. A controlled, laboratory environment is required for investigation of factor relationships and the association between factors and performance and performance decline, in order to maintain control over the environment/variables. The subset of factors selected in section 7.4 will be included in analysis. An experimental task that replicates a number of ATC elements will be utilised with naive participants. A high fidelity ATC simulation was not feasible due to resource restrictions.

7.6 Chapter summary

This chapter compared findings from three separate methodologies regarding the single factors and factor dyads that most frequently negatively influenced ATCO performance. The comparisons facilitated the identification of the factors and factor dyads that most frequently, negatively influenced ATCO performance and were prioritised for inclusion an investigation in future studies. Factors were selected based on the findings from the previous studies and the pragmatic considerations of implementing measurements of these factors in an experimental context. A subset of six factors was selected: workload, fatigue, arousal, stress, SA, communications. The chapter continued to review the overall research aims. An experiment method was selected as the next research phase that would achieve the remaining third, fourth and fifth research aims.

Chapter 8. Experiment method

8.1 Chapter overview

This chapter describes the methodological development and design of the off-line experimental study using students as participants. The chapter opens with the aims of the experimental study and continues to describe pre-study considerations. A pilot study is then described, and further changes to the design are documented. The chapter provides a summary of the participant training process and selection to take part in the experiment. Experimental hypotheses are subsequently listed. The chapter finishes on a summary of analysis considerations.

8.2 Experiment: Aim and experimental questions

The aims of the experiment were to explore the relationships between identified factors and the association with performance, and investigate performance at the edge of performance. Research questions were developed to address this aim:

1. Does a relationship exist between factor dyads?
2. Do interactions between multiple factors occur?
3. What is the association between factor interactions and performance?
4. How does performance change at the edge of performance?
5. Are observable participant behaviours indicators of potential performance decline?

The experiment utilised a cognitive task with ATC elements. Due to resource and political pressures, a full scale simulation with qualified ATCOs was not feasible. Male students from the University of Nottingham served as participants. The use of a student sample was a pragmatic option that permitted an experimental study, which was essential in order to measure in a controlled environment the relationship between multiple factors and associations with performance. In addition, a student sample of participants allowed for a more homogenous group, which may reduce variability and confounding factors introduced into the experiment, therefore potentially positively influencing the reliability of results.

8.3 Pre-experimental considerations

8.3.1 Experiment task design considerations

8.3.1.1 Design

The study used taskload variation as the only independent variable and had one condition. Taskload was varied to create a total of five separate taskload periods, separated into three low taskload periods, two high taskload periods, and four taskload transition periods (two low-high taskload transitions and two high-low taskload transitions). The length of each taskload period was 20 minutes. This period of time was informed by previous research, and took into consideration that the taskload period needed to be long enough to permit the collection of several measures per factor, but not so long as to create participant boredom. The transition between taskload periods was four minutes long. Participants received a 20 minute break after 60 minutes on task. The length of break reflected the period of time that ATCOs are permitted between sessions.

8.3.1.2 Manipulation of taskload

Taskload was manipulated through the frequency of aircraft under control (Tenney & Spector, 2001) and complexity of traffic demands, created by the number of aircraft requiring vertical movements and the number of aircraft on conflicting paths (Brookings, Wilson, & Swain, 1996). This design improved on the methods of both Tenney and Spector (2001) and Brookings et al. (1996) who had utilised only one of the two taskload drivers to manipulate taskload, potentially creating greater variability in taskload. Tenney and Spector (2001) presented 20 aircraft per 10 minutes in the low taskload condition and 40 aircraft per 10 minutes in the high taskload condition. Taskload conditions were associated with self-reported workload. Findings were used to inform the design of taskload in the current study.

In the current experimental design, an average of 30 aircraft per 10 minutes was presented in low taskload periods and an average of 103 aircraft per 10 minutes was presented in high taskload periods. High taskload periods also contained higher frequencies of aircraft requiring vertical movements and aircraft on conflicting paths compared to low taskload periods. Each similar taskload phase (i.e. low taskload periods 1, 2, and 3 and high taskload periods 1, 2) was created to generate similar levels of taskload, however, the phases did not use the same pattern of traffic in order to control for practice effects.

8.3.2 Experiment: Measures

8.3.2.1 Measurement of factors

Measurement options were reviewed for each factor included in the experiment (workload, fatigue, stress/arousal, SA, communications). Measures were assessed on pragmatic considerations, including the level of intrusiveness and distraction of the participant, time for administration, as well as available resources, ease of application and analysis time.

The instantaneous self-assessment (ISA) scale (Appendix 5) was selected to measure workload. The measure was brief and less intrusive than other measures and could be applied without stopping the experiment. In addition, the psychophysiological measure of heart rate (HR) was used to support self-reported workload. The Karolinska sleepiness scale (Appendix 6) measured participant sleepiness at the beginning of the experiment. Several scales of self-reported fatigue were reviewed (Appendix 7) but a fatigue measure was not identified with consistently documented reliability and validity. A fatigue visual analogue scale (VAS) (Appendix 8) was selected to measure fatigue throughout the experiment. A fatigue VAS measure is quick, non-intrusive, and has been reported to have "good validity [and] excellent reliability" (De Boer, Lanschot, Stalmeier, Van Sandick, Hilscher, De Haes, Sprangers, 2004, p311). The stress-arousal check list (SACL) (Appendix 9) was selected to measure stress and arousal. The measure can be applied during short breaks in the experiment. The situation present assessment method (SPAM) (Durso et al., 1995) was selected to measure situation awareness (SA). The measure could be used without stopping the experiment. In addition, SPAM is reported not to be confounded by a reliance on memory for which other measures have been criticised (e.g. situation awareness and global assessment technique, SAGAT) (Durso et al., 1995). To minimise distraction, only non-directive SA questions were utilised (Appendix 10). Posture and HR were recorded continuously using a monitor for psychophysiological data. Participants' overt behaviours were observed and recorded throughout the study task by the researcher. Frequencies of observed behaviour for each participant were calculated.

8.3.2.2 Measures of performance

A literature review was conducted to identify peer-reviewed experimental designs and previous performance measures utilised in ATC-related studies. An initial list of performance measures were generated from the review (Table 8.1). Multiple aspects of performance will be measured independently (Buckley, 1976; Griffin, Neal & Neale, 2000) rather than creating a general cumulative performance score (e.g. Yeo & Neal, 2008). A combined score will prevent investigation of factors in association with different aspects of performance. Frequency of short term conflict alerts was included to provide an indication of safety-related performance. Short term conflict alerts (STCAs) indicate that aircraft will lose separation if action is not taken. More frequent STCAs therefore indicate that participants' are not identifying or resolving conflicts in time, considered to be a poorer performance. Time to respond to offered aircraft was included as an efficiency-related measure of performance. Participants were instructed to respond to aircraft as soon as they identified the offer. Slower reaction times may indicate slower detection times of the offered aircraft, or reduced priority on this task element. Time to assume aircraft was also included as an efficiency-related measure. However, as in actual control tasks, assuming aircraft was treated as an essential task that should be performed quickly. Participants were instructed to assume aircraft as quickly as possible. Finally, frequency of route directs was also used as a measure of efficiency-related performance. Routing an aircraft direct refers to the instruction to an aircraft to change the route to a more direct path. Participants were told that this action should be completed when they felt they had they time to do so, but without putting safety at risk. Higher route direct frequencies may therefore indicate that participants felt comfortable with the taskload, whereas low frequencies of route directs may indicate that a participant felt that task demand required prioritisation of tasks.

Table 8.1. Initial performance measures generated from literature review

Measure	Implementation	Justification
Frequency of short term conflict alerts	Exercise input log	Safety related measure of performance. STCA suggests the participant overlooked aircraft or conflicts. More sensitive than the more infrequent loss of separation.
Time to respond to offered aircraft	Exercise input log	Efficiency-related measure. May indicate when efficiency is declining. Required but may not be a priority.
Time assumed aircraft	Exercise input log	Efficiency-related measure. May indicate when efficiency is declining. May be more sensitive than time to respond to offered aircraft as this measure is an immediate priority.
Frequency of route directs	Exercise input log	Efficiency-related measure. Increases the efficiency of aircraft. May reflect more efficient performance
Behavioural indicators	Observation	Observable behavioural indicators e.g. sighing, noises expressing panic conveying negative emotion were observed by researcher

8.3.3 Experiment: Application of measures

8.3.3.1 Measurement periodicity

Measure periodicity decisions were important to record granularity of factor changes whilst minimising interruptions to the experiment. Psychophysiological measures and behavioural observations were non-intrusive and so were recorded throughout the simulation. Workload and SPAM measures were applied at four minute intervals and so measures were collected five times per 20 minute taskload period. Increasing the number of measures would provide more granularity, but would also result in increased distraction to the participant. Measures of fatigue and stress/arousal were administered twice every 20 minutes. The stress/arousal measure required participants to pause the simulation to respond to complete a measurement scale. Performance measures were recorded continuously.

8.3.3.2 Order of presentation of measures

Participants verbally responded to ISA (on a scale of 1-5) prior to an SA-related question being asked. ISA was brief and unlikely to influence SA answers. In comparison, administering an SA question first may result in an increase in experienced workload. During pauses in the simulation exercise, the fatigue VAS scale was completed prior to the SACL, again due to the brevity of the fatigue measure being less likely to influence stress/arousal responses.

8.3.4 Experiment task

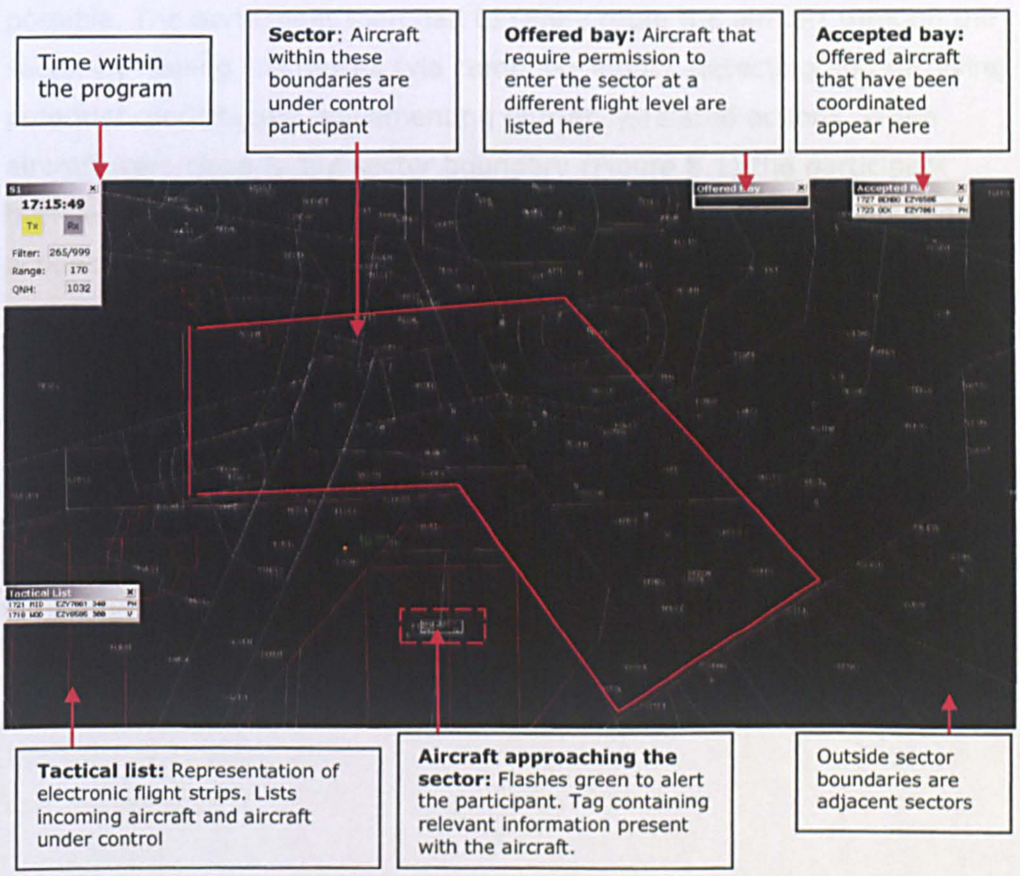
8.3.4.1 Exercise task

The experiment task used elements of an en-route ATC task. The task was computer-based and required participants to manage aircraft safely and efficiently through a sector of airspace. The task was custom-built by the software owners, DM Aviation, modified from an ATC simulation program 'London control, Version 1.42'. A bespoke design allowed the control of taskload phases, and ensured that the task was repeatable between participants.

8.3.4.2 Selection of an airspace sector for the experiment task

An authentic en-route sector was selected which handled high level traffic to the south-west of London (Figure 8.1). The sector was selected due to sector characteristics which allowed the design of taskload changes. The sector was relatively small, which increased complexity during high traffic density. There were several points of conflicting route paths.

Figure 8.1. Airspace sector used in the study task



8.3.4.3 Requirements of the exercise task

Figure 8.1Figure 8.1 presents a screen shot of the sector that participants were responsible for in the task. The sector boundaries are highlighted in red. Within these lines, participants had control of aircraft; outside of these lines were adjacent sectors. An offered bay listed aircraft that requested to enter the sector at a specific flight level. The participant decided to accept or revise the entry level, at which point the aircraft would move to the 'accepted bay'. The tactical list represented electronic flight strips which provided relevant information about aircraft about to enter the sector and aircraft under control. Aircraft were represented with a square and had an associated tag that contained relevant information such as call-sign, current flight level, required flight level.

Participants were instructed to complete specific actions for each aircraft based on the en-route ATC task (Figure 8.2, Figure 8.3). When aircraft appeared in the offered bay, participants would decide to accept or revise the requested flight level to enter the sector. When an aircraft approached the sector the participant assumed the aircraft as quickly as possible. The participant then had to safely route the aircraft through the sector by issuing clearances (via computer input), detecting and resolving potential conflicts and implementing efficiency-related actions. When aircraft were close to the sector boundary (Figure 8.1) the participant transferred the aircraft to the adjacent sector. Figure 8.2 presents these actions as a process for each aircraft, including optional tasks such as routing an aircraft direct. This can be compared to Figure 8.3, which summarise essential actions in the control task. The experiment task requirements are similar to the en-route control task requirements.

Figure 8.2. Correct process in the simulation and possibilities for error occurrences

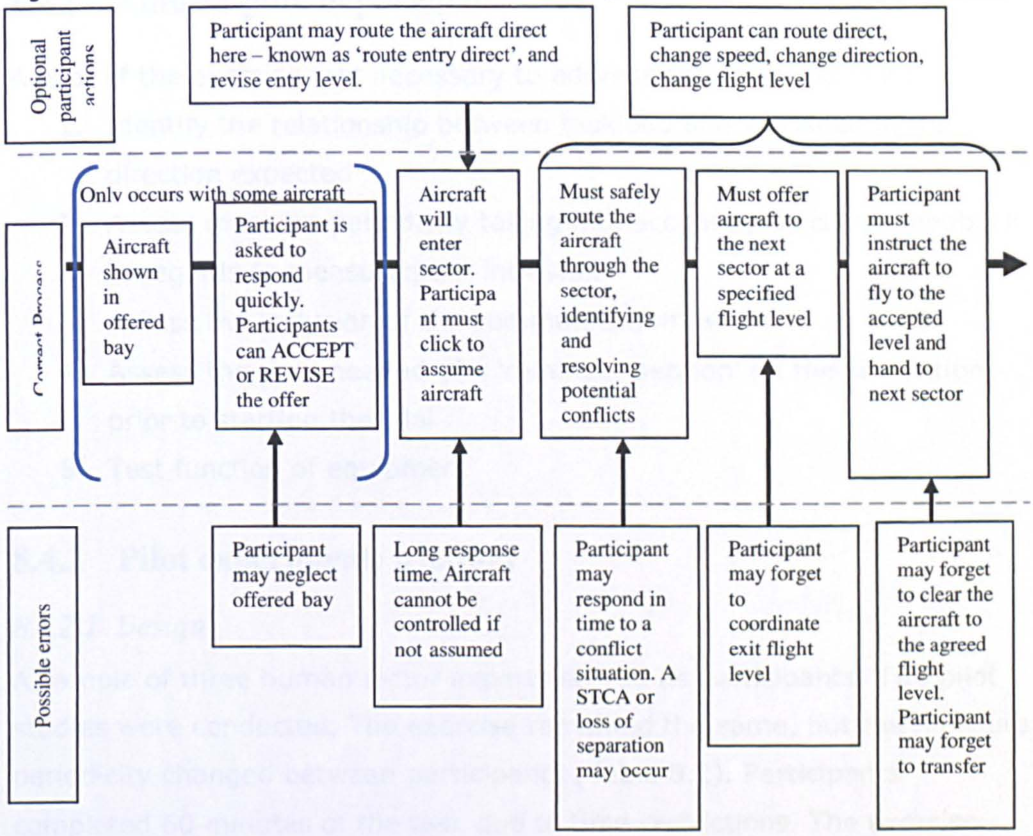
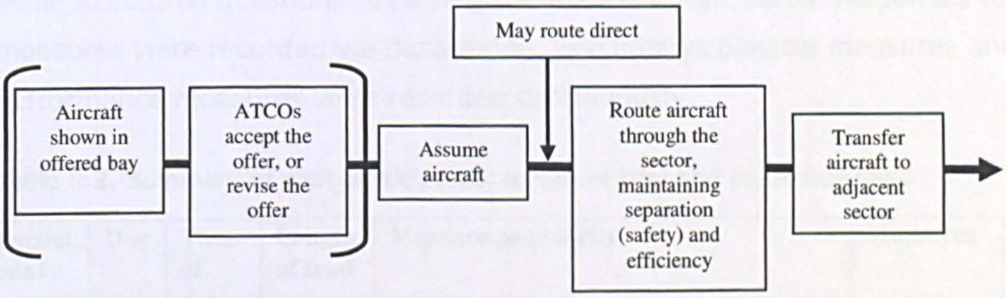


Figure 8.3. High level en-route ATC tasks for each aircraft



8.3.4.4 Experiment task: computer program functionality

Aircraft were controlled via keyboard and mouse presses. The software generated a pilot's voice and so each aircraft communicated with the participant in the same way as a pilot communicates with an ATCO. The software automatically recorded all input by participants via keyboard and mouse presses.

8.4 Pilot experiment

8.4.1 Aims of pilot experiment

A pilot of the exercise was necessary to address the following aims

1. Identify the relationship between taskload and workload in the direction expected
2. Assess measure periodicity taking into account participant feedback in regards to measurement intrusion
3. Assess the inclusion of the communication factor
4. Assess the time needed of a 'reminder session' on the simulation prior to starting the trial
5. Test function of equipment

8.4.2 Pilot experiment: Method

8.4.2.1 Design

A sample of three human factor experts served as participants. Two pilot studies were conducted. The exercise remained the same, but the measure periodicity changed between participants (Table 8.2). Participants completed 60 minutes of the task due to time restrictions. The exercise was refined in line with participant feedback, and the third participant then completed the full exercise. After the trial, participants were asked a set of semi-structured questions regarding the exercise trial. Verbal responses to measures were recorded via dictaphone. Psychophysiological measures and performance measures were recorded continuously.

Table 8.2. Summary of pilot participants, length of trial and measures used

Participant	Day	Time of day	Length of trial	Measure periodicity	Measures
1	Day 1	Morning	60 minutes	• ISA, SPAM: Every 3 minutes • Fatigue, SACL: every 11 and 13 minutes alternately (at the start of the fifth minute from the beginning of a taskload period and the fifth minute from the end of a taskload period) • Psychophysiological measures: continuous	Karolinska sleepiness scale, ISA, SPAM, Fatigue VAS, Stress-arousal checklist, , Behavioural observation
2	Day 1	Afternoon	60 minutes	• ISA, SPAM: Every 4 minutes • Fatigue, SACL: every 20 minutes • Psychophysiological measures: continuous	
3	Day	After	116	Selected the best options from previous	

	8	noon	minutes	trials: •ISA, SPAM: Every 4 minutes •Fatigue, SACL: every 11 and 13 minutes alternately (at the start of the fifth minute from the beginning of a taskload period and the fifth minute from the end of a taskload period) Psychophysiological measures: continuous	Heart rate, Posture

8.4.2.2 Participants

A total of three participants took part in the pilot exercise. Participants were three human factor experts (two males and one female), aged 27-39.

8.4.2.3 Materials and equipment

As described in section 8.3.2.

8.4.2.4 Pilot experiment procedure

Participants received a booklet 24 hours prior to the simulation pilot that contained basic information on ATC. On the trial day participants received a two hour training session on the program followed by a 30 minute break. Participants received a 10 minute practice session prior to the start of the trial. Measures were implemented at different periodicities (Table 8.2). After the trial was complete, participants were asked for feedback. Audio and written responses were collated and a summary of participants' suggestions participants was produced.

8.4.3 Pilot experiment: Results and discussion

8.4.3.1 Pilot experiment results: The association between taskload and workload

All participants reported workload levels which varied as expected with taskload phase. In addition, participants did not feel that the high taskload periods provided too many aircraft to manage. The taskload variations were therefore used in the full exercise.

8.4.3.2 Pilot experiment results: Experiment measures

Participants reported that the equipment measuring heart rate and posture was comfortable, and that the self-report measures were easy to understand. Performance measures were recorded continuously without any issues.

8.4.3.3 Pilot experiment results: Measurement periodicity

The first participant felt that asking for ISA and SPAM measures every 3 minutes disrupted concentration, and reported that it was difficult to re-engage with the exercise due to an expectation of the next question. The participant felt that the periodicity of fatigue and SACL was appropriate. The second participant reported that the ISA and SPAM measures every 4 minutes were acceptable. The participant stated that although it was a slight distraction, the period between the questions provided time to reengage with the exercise. Regarding the frequency of fatigue and SACL measures, the participant reported that it would be feasible to increase the periodicity without creating a distraction. Based on this feedback, the third participant was issued with the ISA and SPAM measures every 4 minutes and the fatigue and SACL measures every 11 and 13 minutes alternately. The participant reported that they did not feel distracted by the measures and recommended that the periodicity be applied in future trials.

8.4.3.4 Pilot experiment results: Verbal communications

All participants reported that when using verbal communications with 'pilots' as well as inputting instructions via computer, they found themselves focusing on the verbal instructions and phraseology rather the actual task. One participant stated that s/he felt that performance was suffering because s/he had to concentrate on remembering the correct phraseology. It was a concern that the added demand of communication would reduce performance measures. Relationships between performance and associated factors could not then be determined. Therefore, verbal communications were not considered in the full experimental trial and were not measured.

8.4.4 Conclusions

The pilot trials indicated that manipulated taskload was associated with self-reported workload in the expected direction. High taskload periods, although demanding, were manageable. Self-report measures were acceptable to participants and easy to use. However, feedback also influenced exercise design changes. The measure periodicity was selected to be every 4 minutes for ISA and SPAM and the 5th minute into the taskload period and 5 minutes before the end of the taskload period for fatigue and SACL. Communication was not included in future studies in order to reduce the possibility of artificial performance declines. A brief semi-structured interview regarding participants' perception of the task and performance after the trial will also be included in future studies.

8.5 Training for participants on the experimental task computer program

Participants received training on the exercise program. This was an improvement on several ATC-related studies which used non-expert participants without training (e.g. Neal & Kwantes, 2009) and was recommended by several research studies (Yeo & Neal, 2008; Brookings et al., 1996). A sample of male students from the University of Nottingham served as participants. Training sessions were four hours long, including three breaks totalling 30 minutes and a 25 minute competency test. Participants received payment for their training time at a rate of £10 per hour. Participants were taught in a lecture style on ATC background, use of the program, controlling strategies, conflict prevention and resolution and efficiency considerations (e.g. 'route direct') for a maximum of 90 minutes. The next 90 minutes was dedicated to practice on the program. The experimenter was available for questions. Once the practice was completed, participants received a short break and subsequently completed the competency test. The competency test was utilised to select the participants who were most competent on the exercise program. Areas of knowledge tested are listed in Appendix 11. The test had a total of 22 questions, based on a total of 12 competencies. Participants were required to gain 18/22 (81%) or over on the competency test to be selected for future trials. Summary results are presented in Table 8.3. Based on the competency results, 30 participants were invited to participate in the experiment study.

Table 8.3. Summary of competency test results

Competency test score (/22)	Number of participants
17	34
18	30
19	24
20+	13

8.6 Experiment method

8.6.1 Design

The association between single factors and performance, and the relationship between co-occurring factors and the subsequent association with performance, was investigated. A sample of 29 students from the University of Nottingham served as paid participants (Nunes & Kramer, 2009). All participants received four hours of training on the simulation program, and were selected based on achieving 81% or higher in a purpose-designed competency test. The study used a within measures design, with one condition, so all participants performed the same task. Taskload was the only independent variable that was manipulated. Taskload varied between low and high, with a short transition phase between each variation. Taskload was not guaranteed to influence participants' subjective experience, and so the measured factors were considered to be covariates. Performance was the dependent variable (Figure 8.4).

Figure 8.4. Diagram presenting design of study, in terms of IVs, DVs and covariates

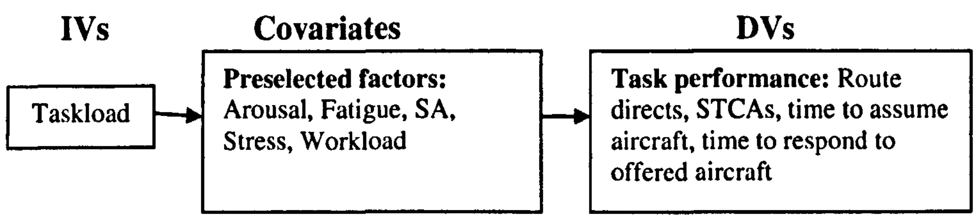
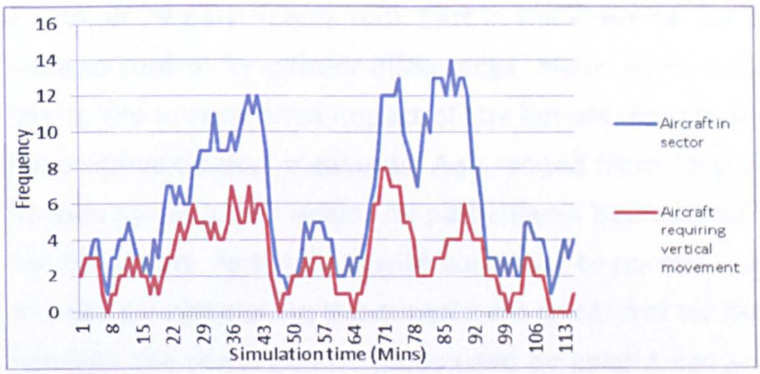


Figure 8.5 presents frequency of aircraft in the sector and frequency of aircraft requiring vertical movements across task time. It was not feasible to create a graph of the potential conflicts as participants could choose how to control aircraft and create new conflicts.

Figure 8.5. Number of aircraft in sector and number of aircraft in sector requiring vertical movement by minute



Participants had a 10 minute practice prior to starting the exercise which was excluded from analysis (Yeo & Neal, 2008). The exercise lasted for a total of 116 minutes (e.g. Yeo & Neal, 2008), and consisted of 5 periods of alternating taskload, beginning with a low taskload. Each taskload period was 20 minutes long (Galster et al, 2001; Gronlund et al, 1998) interspersed with a 4 minute taskload transition period. Participants received a 20 minute break period after 60 minutes on task. Participants were required to complete all control actions, including assuming aircraft, coordinating aircraft, instructing aircraft and transferring aircraft. A total of 29 participants took part in the trial. Trials were conducted over a period of one month and up to two trials a day were conducted.

Both discrete and continuous measures were applied. Performance measurements and psychophysiological measures (heart rate, posture, e.g. Vogt, Hagemann, & Kastner, 2006) were recorded continuously. Psychophysiological recordings were started 10 minutes prior to the experimental trial so that participants' could relax and measures stabilise. Every 4 minutes, participants were asked to verbally rate their workload from 1-5 (Tattersall & Foord, 1996) and were asked to respond to a SA-related question, as per the SPAM technique (Durso et al., 1995). Every 5 minutes in to a taskload period, and 5 minutes before the end of each taskload period participants were asked to pause the simulation and complete a fatigue (VAS) and stress (SACL) measure. To ensure participants were motivated to perform to the best of their ability, all participants were instructed to try to be as safe and efficient as possible and a cash voucher prize was made available to the top 3 performing participants.

8.6.2 Participant details

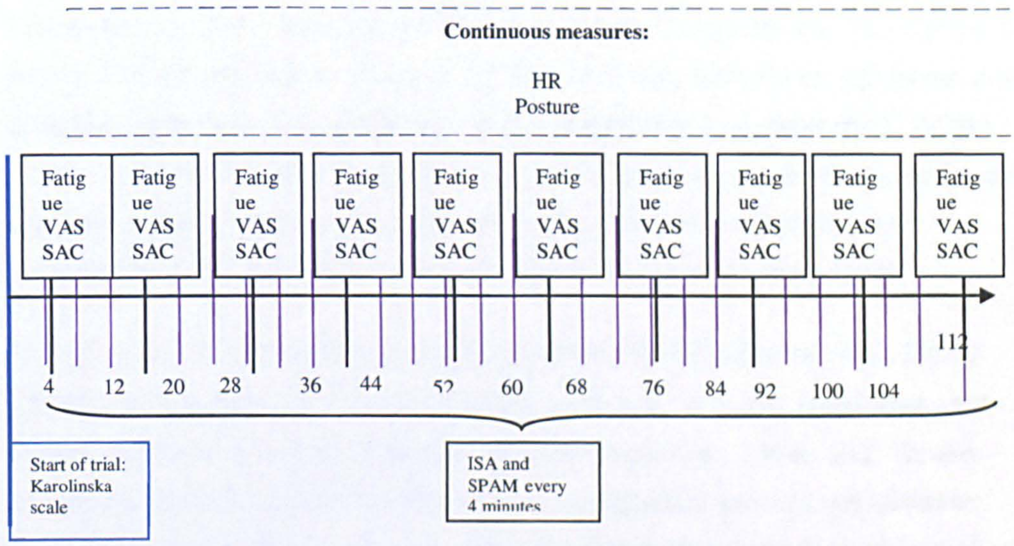
A total of 29 participants took part in the exercise. All participants were male to control for gender differences. Males were selected over females due to the uncontrolled impact of the female menstrual cycle on the psychophysiological measures. Age ranged from 18 years - 27 years with an average of 20.83 years. All participants had normal or corrected to normal vision. Participants with corrected to normal vision were asked only to wear glasses during the experiment to control for potential discrepancies between the correction methods used by eyeglasses and contact lenses. All participants used English as a native language. Participants were required to have the ability to use, and familiarity with, a computer a mouse, and did not have any known colour-blindness, hearing impairments, or uncontrolled heart or respiratory condition. All participants were educated to at least an A-level standard. All participants were paid in high street vouchers for their time to attend the training session at a rate of £10 per hour. Participants ranged in videogame playing experience from 0 - 21+ hours per week. All participants were free to withdraw at any time.

8.6.3 Measures and materials

8.6.3.1 Experiment study: Measurement periodicity

Figure 8.6 summarises periodicity of measures collected across the study session. Workload and SA were measured on a different time scale (every 4 minutes) to the factors of fatigue, stress and arousal (5 minutes in to a taskload period, and 5 minutes before the end of each taskload period). Psychophysiological and performance measures were recorded continuously.

Figure 8.6. Measure periodicity per 4 minute interval



8.6.4 Experiment study: Measures

8.6.4.1 Instantaneous self assessment (ISA) of workload

The instantaneous self assessment (ISA) of workload is a quick and efficient measure, initially developed for use in an ATC context (Eurocontrol, 2002). The participant is required to provide a verbal rating of perceived workload from 1 (very low) to 5 (very high). To increase the sensitivity of the measure, participants were permitted to respond in increments of 0.5. Each whole number was anchored with a description: 1. Under-utilised, 2. Relaxed, 3. Comfortable, 4. High, 5. Excessive.

8.6.4.2 Karolinska sleepiness scale

The Karolinska sleepiness scale consists of a 7 point scale, with descriptive anchors at associated with alternate numbers, from 'extremely alert' to 'extremely sleepy'. The scale assessed self-reported sleepiness prior to beginning the exercise.

8.6.4.3 Fatigue visual analogue scale

The measure used a 100mm horizontal line (Lee, Hicks, Nino-Murcia 1990) with one anchor at each end, from 'not at all fatigued' to 'extremely fatigued'.

8.6.4.4 Stress Arousal Checklist (Mackay et al., 1978).

The stress-arousal checklist (SACL) consists of 30 adjectives, 18 relating to stress and 12 relating to arousal. Of the 18 stress adjectives, 10 items are phrased positively (i.e. bothered) and 8 negatively (i.e. peaceful). Of the 12 arousal-related adjectives, 7 are phrased positively (i.e. alert) and 5 are phrased negatively (i.e. idle). All negatively phrased adjectives are reversed-scored. Participants respond on a four-point Likert scale.

8.6.4.5 Situation present assessment method (SPAM) (Durso et al., 1995)

SPAM is a non-intrusive measure of SA, which is "a query technique that [does] not have a memory component" (Durso et al., 1998, p1). Seven questions relevant to the exercise were constructed around the present and future of the traffic situation. The questions were not randomly picked, but instead pre-selected to be relevant to specific points in the exercise. The traditional workload measure included within SPAM (by asking participants to say when they are ready for the question) was not used, as ISA was used to gain granularity of measurement. All participants had a time limit of 20 seconds to answer the question, after which a non-response was recorded.

8.6.4.6 Performance measures

Performance measures of STCA frequency, route direct frequency, time to respond to offered aircraft and time to assume aircraft were calculated from an automatically generated program log.

8.6.5 Materials

A standardized brief, screening questionnaire, consent form and demographic questionnaire were used prior to the start of the experimental trial. At the end of the trial, participants received a debrief which contained the researchers' contact information in case of any further questions. An observation checklist recorded frequencies of participants' observable behaviour. Participants were not aware of the checklist.

8.6.6 Equipment

The following equipment was used in the experiment trial:
A London Control simulation program and bespoke exercise program both by DM Aviation (2008).
A 'Stone' desktop computer and monitor running the exercise program. Inputs and outputs were a keyboard, mouse and Logitech wired speakers.
A second 'Stone' desktop monitor, connected with the participants' screen, for the researcher to monitor participants' actions on the simulation program.
Three Sony Handy Cams to record participants' performance and behaviours from different angles
A Logitech webcam to record participants' facial expressions
A Sony Viao laptop with Microsoft Excel 2007 program which recorded participants' verbal responses to measures
A Samsung laptop used to record wireless physiological data
A BIOPAC Bio Harness™ Physiology Monitoring System (Bio systems), including a bio harness chest strap (part number RXCHESTSTRAP) wireless transmitter and AcqKnowledge for Bio Harness (Application Software) version 3.9
A stopwatch for accurate timing of measure administration

Figure 8.7 and Figure 8.8 present the experimental set-up and position of equipment, from the researcher's view (Figure 8.7) and the participants' view (Figure 8.8).

Figure 8.7. Pictures of experimental set up: Researcher's view

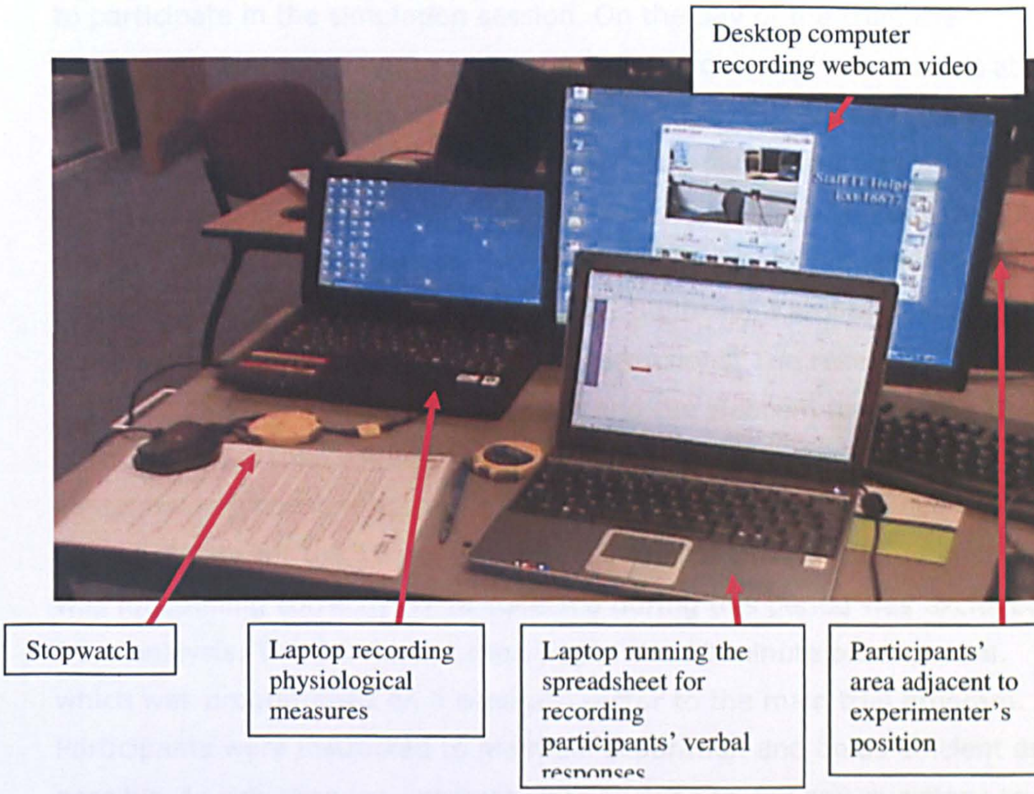
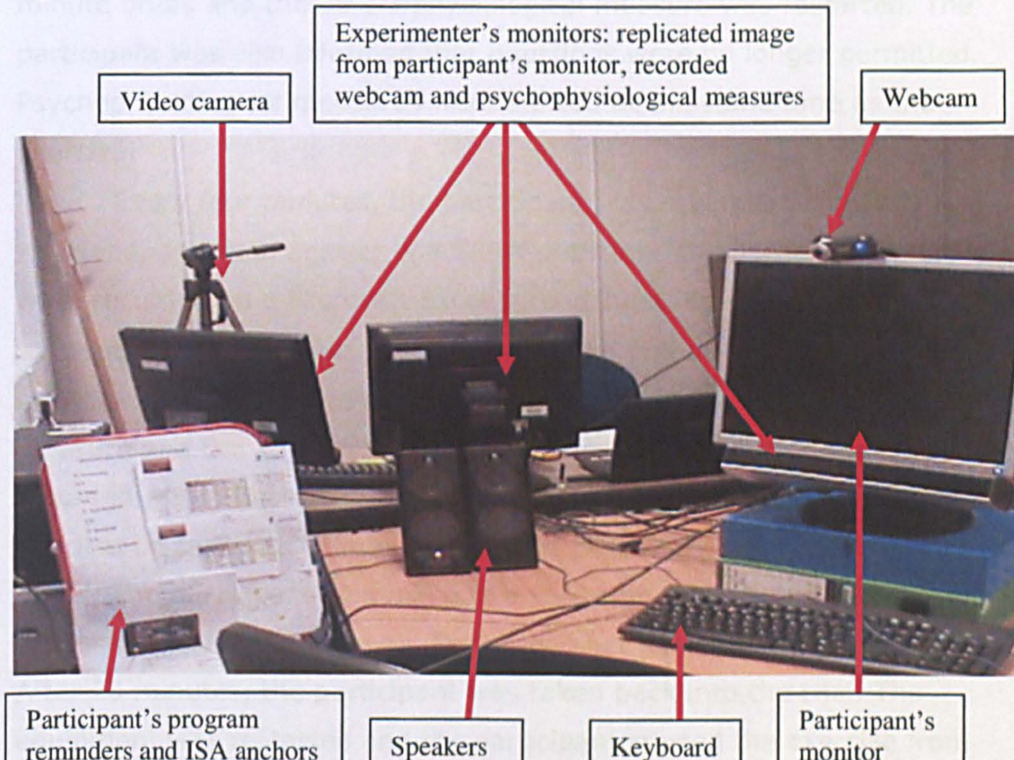


Figure 8.8. Pictures of experimental set up: Participant's view



8.6.7 Procedure

Participants with a competency score of at least 18/22 (81%) were invited to participate in the simulation session. On the day of the trial, the participant was welcomed into the experiment room and asked to sit at the study desk. The study brief, selection criteria and medical screening questionnaire were presented on the desk. The participant was asked to read the brief, and check they met the selection criteria. The participant signed an informed consent form if they were happy to proceed. The participant completed a demographic questionnaire, Karolinska sleepiness scale, and then read the standardised instructions. The researcher used this time to set all three video cameras and the webcam to 'record'. The participant was then asked permission for the heart rate monitor, contained in a chest strap, to be placed on their torso. The device was set to record data for the 10 minutes prior to the start of the trial to ensure it was functioning correctly. Data collected during this period was excluded from analysis. The participant then began the 10 minute practice trial, which was programmed on a separate sector to the main trial program. Participants were instructed to maintain separation and be as efficient as possible. In this time, participants were allowed to ask any questions to the researcher. After 10 minutes, the participant was provided with a 5 minute break and the psychophysiological measure was restarted. The participant was also informed that questions were no longer permitted. Psychophysiological measures were started at the same time as the exercise.

Every four minutes, the participant was asked to verbally rate workload, and then answer one SPAM question. The participant's responses were recorded on a Microsoft Excel spreadsheet. Every five minutes into a taskload period, and five minutes before the end of a taskload period, the exercise was paused and the participant completed the fatigue VAS measure and the stress-arousal checklist (SACL). The exercise was resumed when the participant had completed the measures. After 60 minutes on task (excluding pauses), the participant received a 20 minute break. The participant was taken to a rest area and offered a cold drink (water or sugar-free squash). The researcher remained with the participant. After 20 minutes, the participant was taken back into the trial. The equipment was restarted and the participant started the exercise from where it had been paused. At the end of the task participants were asked to share comments and feedback about the task. The participant then received payment, thanked for their time and shown out of the study room.

8.6.8 Experimental hypotheses

The following experimental hypotheses were developed, aligned with the study research questions (section 8.2):

1. Factors will correlate with at least one other factor
2. Factor dyads and triads will interact
3. Factor dyads and triads will explain a larger range of performance variance
4. At least one of three hypothesised shapes of performance decline will be observed
5. Observed participant behaviours will be associated with measures of workload, fatigue, stress, arousal, SA and measures of performance

Following from hypothesis 4, detailed hypotheses specifying the shape of performance decline in association with multifactor influences was developed. It was hypothesised that 1 of 3 possible shapes or data trends of performance decline may occur, which may reflect the edge of performance (Figure 8.9, Figure 8.10, Figure 8.11). Performance may decline in a linear fashion (Figure 8.9). This shape is hypothesised to occur infrequently, as participants can employ strategies that may mitigate the influence of multifactor combinations on performance. An alternative hypothesised shape of decline is that performance will be maintained when associated with a majority of multifactor combinations, but may decline steeply and suddenly when associated with a specific multifactor combination; this may reflect participants reaching the 'edge of performance' at this time (Figure 8.10). A final hypothesis is that performance may have periods of maintenance interspersed with periods of gradual performance decline, prior to a steep decline when associated with a specific multifactor combination (Figure 8.11). Again, a steep performance decline may represent the 'edge' of performance.

Figure 8.9. Hypothesised performance shape using hypothetical data – gradual performance decline

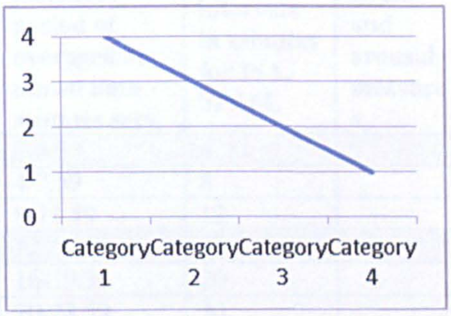


Figure 8.10. Hypothesised performance shape using hypothetical data – maintained performance followed by a sudden decline

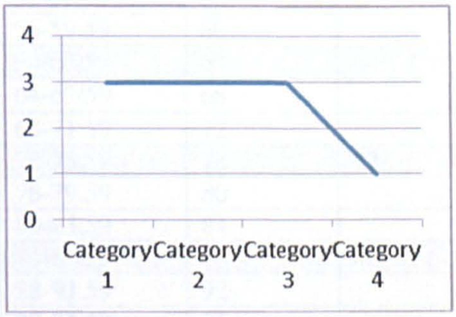
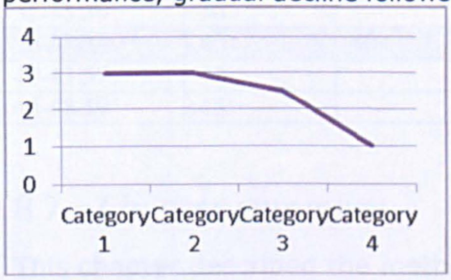


Figure 8.11. Hypothesised performance shape using hypothetical data – maintained performance, gradual decline followed by a steep decline



8.6.9 Experiment study: measurement periodicity and implications for analysis

Workload and SA were measured every four minutes. Performance was recorded continuously, but was summed (for frequency of STCAs and frequency of route directs) or averaged (for time to assume aircraft and time to respond to aircraft) across the four minute period prior to the workload and SA measure (Table 8.4). Summing or averaging performance data over 4 minute periods was expected to be more meaningful and provide more granular data than averaging data across larger intervals, for example, to associate with fatigue and stress measures. Measures that were closest in time to each other were used in analysis, highlighted by coloured cells in Table 8.4.

Table 8.4. The measures used for factors and performance, shown by minutes into the simulation

Performance measure: period of averaged/summed data - minutes.secs	**Time intervals in minutes for ISA, SPAM,**	**Fatigue, stress and arousal measures**
0-3.59	4	5
4-7.59	8	
8-11.59	12	
12-15.59	16	16
16-19.59	20	
20-23.59	24	
24-27.59	28	29
28-31.59	32	
32-35.59	36	
36-39.59	40	40
40-43.59	44	
44-48.59	48	
49-51.59	52	53
52-55.59	56	
56-59.59	60	
60-63.59	64	64
64-67/59	68	
68-71.59	72	
72-75.59	76	77
76-79.59	80	
80-83.59	84	
84-87.59	88	88
88-91.59	92	
92-95.59	96	
96-99.59	100	101
100-103.59	104	
104-107.59	108	
108-111.59	112	112
112-116	116	

8.7 Chapter summary

This chapter described the methodological development and application of an experimental study. Taskload was manipulated as the independent variable, which was intended to create variability in the covariate factors included in the study (workload, fatigue, stress, arousal, SA). Self-report measures were selected for measurement of factors. Task performance was the dependent variable. A total of 29 male students served as participants. The experimental hypotheses are listed. The chapter ends with a summary of the association of data from separate measures in preparation for analysis.

Chapter 9. Experiment results: Multiple factor relationships and associations with performance

9.1 Chapter overview

Results from the experiment study are presented in the order of the research questions (section 8.2) and associated hypotheses (section 8.6.8). Figures are used throughout the chapter to provide a visual representation of results. A discussion of findings is presented at the end of each results section to facilitate the reader in the interpretation of the results in relation to the research questions.

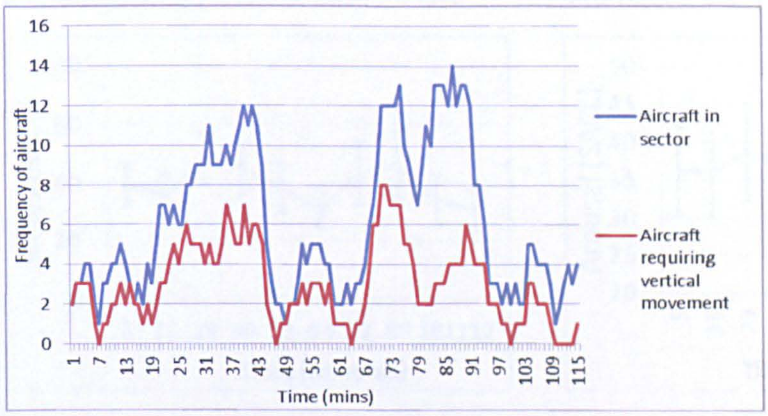
Section 9.2.1 presents descriptive data for taskload variance across the task. The association between each factor (workload, fatigue, stress, arousal, SA) and performance is then reported followed by findings of the relationship between factor dyads. A median split analysis is used to investigate factor interactions and the association with performance.

9.2 Overview of experimental results

9.2.1 Taskload variation and manipulation check

A review of the descriptive statistics suggests that taskload did vary in the direction expected (Figure 9.1) and appeared to be similar between equivalent sections. The number of aircraft in the controlled sector was similar between low taskload periods one (M=3.1, SD=1), two (M=3.2, SD=1.3), and three (M=3.1, SD=1.9) and between high taskload periods one (M=9.3, SD=1.75) and two (M=11.4, SD=1.9). The number of aircraft requiring vertical movements (creating complexity) was similar between low taskload sections one (M=1.9, SD=0.9), two (M=1.8, SD=0.9) and three (M=1.2, SD=1), and between high taskload sections one (M=5.2, SD=0.9) and two (M=4.5, SD=1).

Figure 9.1. Taskload across the study task by minute, represented by number of aircraft in sector and number of aircraft in sector requiring vertical movement



9.2.2 Single factor variations with taskload

Figure 9.2- Figure 9.8 present taskload variation with measures. Self-reported workload, fatigue, stress and arousal and heart rate were expected to positive relate with taskload, for example, increasing as taskload increases. SA was expected to negatively relate to taskload. Participant's posture was expected to positively relate with taskload, moving forward with high taskload and moving back with low taskload. Table 9.1 supports Figure 9.2- Figure 9.8 by presenting the means and standard deviations for each measured factor averaged across each 20 minute taskload period.

Figure 9.2. Self reported workload throughout simulation every four minutes

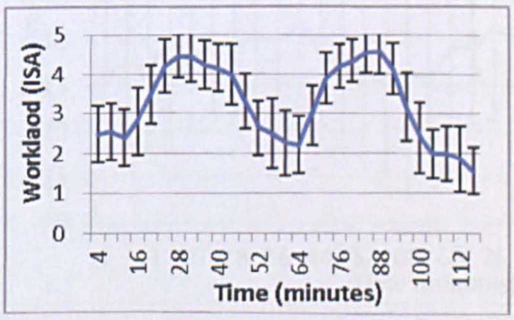


Figure 9.3. Self reported fatigue throughout experiment measured alternately every 11th or 13th minute

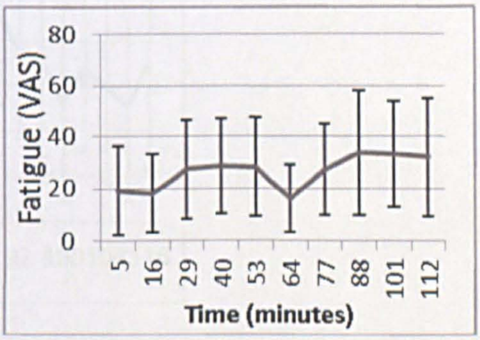


Figure 9.4. Self reported stress throughout experiment measured alternately every 11th or 12th minute

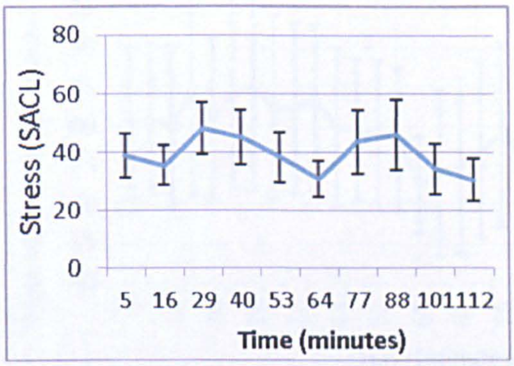


Figure 9.5. Self reported arousal throughout experiment measured alternately every 11th or 12th minute

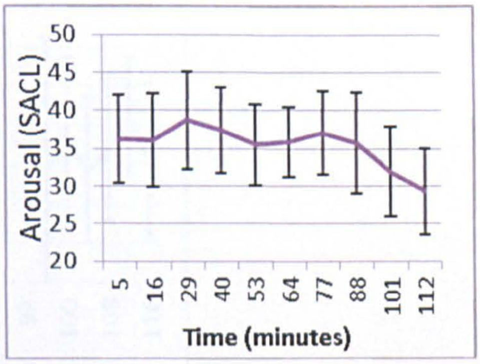


Figure 9.6. SA: Time in seconds to respond accurately to SPAM questions averaged over 4 minute periods

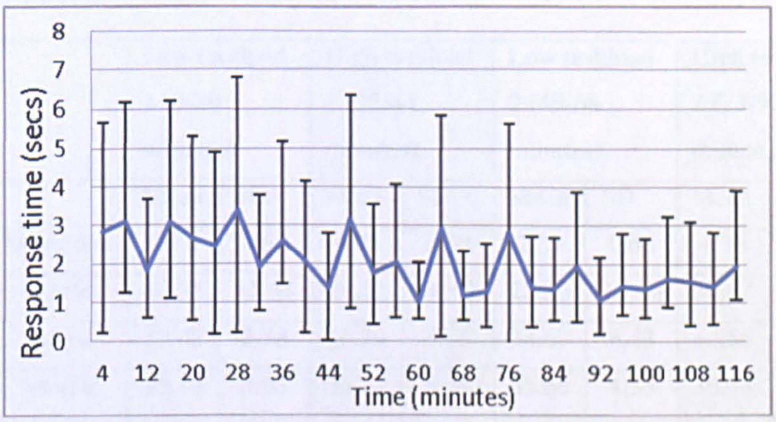


Figure 9.7. Posture averaged over 4 minute periods

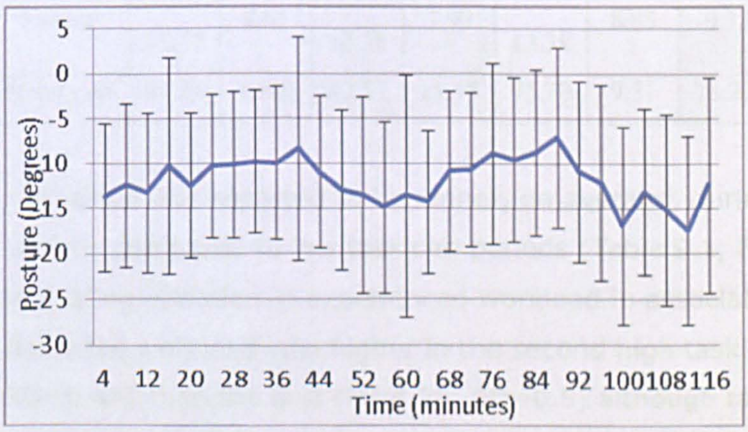


Figure 9.8. Heart rate averaged overall 4 minute periods

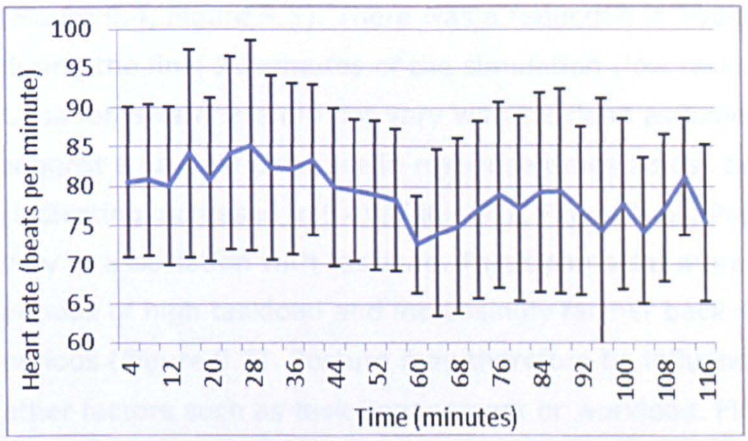


Table 9.1. Means and standard deviations for measured factors averaged across taskload sections

	Low taskload 1 (0-20 minutes)		High taskload 1 (25-44 minutes)		Low taskload 2 (49-68 minutes)		High taskload 2 (73-92 minutes)		Low taskload 3 (97-116 minutes)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Workload	2.74	0.62	4.26	0.50	2.53	0.66	4.36	0.46	1.96	0.58
Fatigue	18.95	15.43	28.12	18.07	22.36	13.90	30.67	19.86	32.69	20.99
Stress	37.02	6.38	46.79	8.68	34.67	6.43	44.86	10.66	32.55	7.33
Arousal	35.86	5.93	38.12	5.76	35.69	4.35	36.38	5.57	30.66	5.31
SA	2.71	1.05	2.16	1.00	1.74	0.90	1.59	0.79	1.53	0.62
Posture	-12.72	8.61	-10.28	7.99	-13.38	8.85	-9.73	9.37	-14.71	10.33
Heart rate	81.27	10.60	82.57	11.15	75.70	9.31	78.29	12.02	77.16	9.41

Workload was reported to be higher, on average, during high taskload periods compared to low taskload periods (Table 9.1, Figure 9.2), indicating variation in experienced workload in association with taskload. Reported workload was higher in the second high taskload period (M=4.36, SD=0.46) than the first (M=4.26, SD=0.5) although taskload drivers were similar. Figure 9.2 shows that experienced workload increased quickly in high taskload periods, although unexpectedly remained high at the start of low taskload periods. Fatigue was recorded to increase across equivalent taskload sections and was highest in the final low taskload section (Table 9.1, Figure 9.3) possibly indicating a cumulative increase in fatigue throughout the exercise. Participants reported an increase in both stress and arousal during high taskload periods compared to low taskload periods (Figure 9.4, Figure 9.5). There was a reduction in average reported arousal during the final 20 minutes of the simulation (low taskload period 3). Situation awareness did not vary with taskload as expected; findings suggest a gradual decrease in response times across taskload periods (indicating increased in SA) (Table 9.1, Figure 9.6). Posture appeared to vary in association with taskload. Participants sat more forward during periods of high taskload and increasingly farther back during low taskload periods (Figure 9.7). Posture may therefore be influenced by, or reflect, other factors such as task engagement or workload. Finally, average heart rate did vary as expected, but only marginally. Most factor measures (excluding SA) appear to vary with the taskload manipulation as expected. This suggests that the taskload manipulation created variability in the data in the intended direction.

9.2.2.1 Individual differences

A review of Figure 9.2 - Figure 9.8 and means and standard deviations for measured factors per taskload phase (Table 9.1) suggests that individual participants reported differential scores for each factor. All participants reported similar levels of workload throughout the simulation (SD range=0.49-0.89) suggesting the average results are representative of the sample. Larger individual differences were present for the factors of fatigue (SD range=13.04-23.97), stress (SD range=6.32-12.05), arousal (SD range=4.6-6.68). SA results were relatively representative of all participants (SD range=0.44-3.19). Posture had a larger range (SD range=7.93-13.36) as did heart rate (SD range=9.31-10.60). The larger standard deviations suggest that the average measures may not be representative for all individuals on each measure. Individual differences in factor measures are of note. Individual scores are considered through a series of figures (Appendix 12). The aim of this investigation and results section is to examine the relationship between multiple factors, and the association with of factor covariance in performance. Therefore, the occurrence of individual differences in the measured single factors will not be considered further.

9.2.3 Discussion of taskload manipulation and measured factor variations across the study task

Findings show that taskload was manipulated as intended, with more aircraft and higher complexity (more aircraft requiring vertical movements) in the high taskload periods as compared to low taskload. Findings also indicate that the self-reported factors of workload, fatigue, stress and arousal also varied with taskload in the direction expected, suggesting that the taskload manipulation did create variability in the data, and in the intended direction. Posture and heart rate (HR) also varied with taskload in the direction expected. Findings for the SA measure were unexpected; response times to SA questions (indicating increased SA) decreased over the study task. One interpretation of this finding is that SA may increase with time on task. Alternatively, practice effects may have artificially affected the measure. HR did not differ between taskload phases as much as expected. Heart rate variability may have provided a more accurate reflection of the data although this detailed analysis technique was outside the scope of this study. Heart rate will be discounted from further analyses due to the limited variation in the data.

Reported workload rapidly increased between the first low taskload and first high taskload periods (Figure 9.2). However, workload remained relatively high even when taskload began to decline between minutes 28-32. Workload after-effects generated from the high taskload period may influence experienced workload even when taskload begins to decrease.

9.2.4 Performance across the study task

Figure 9.9 - Figure 9.12 present measures of performance averaged over 4 minutes across the period of the cognitive task. Short term conflict alerts (STCAs), were expected to increase during the high taskload periods. Conversely, route directs were expected to increase during periods of low taskload when participants may not be preoccupied with safety concerns, and decline in high taskload. Time to assume aircraft and time to respond to offered aircraft were both expected to increase during periods of high taskload due to the increase number of aircraft to control during these periods.

Figure 9.9. Frequency of STCAs averaged over 4 minute periods

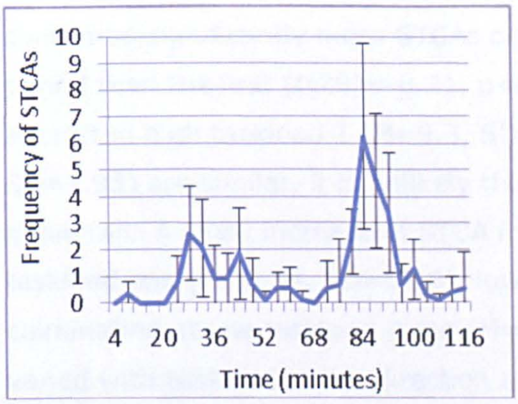


Figure 9.10. Frequency of route directs averaged over 4 minute periods

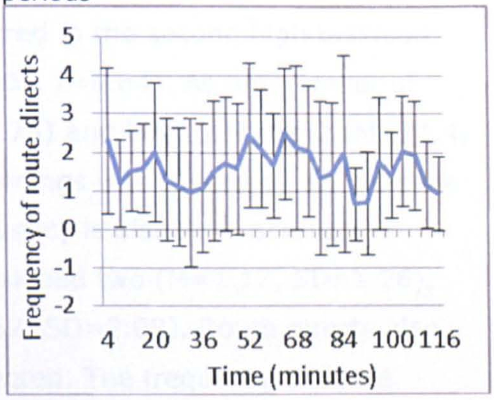


Figure 9.11. Time to assume aircraft in seconds, averaged over 4 minute periods

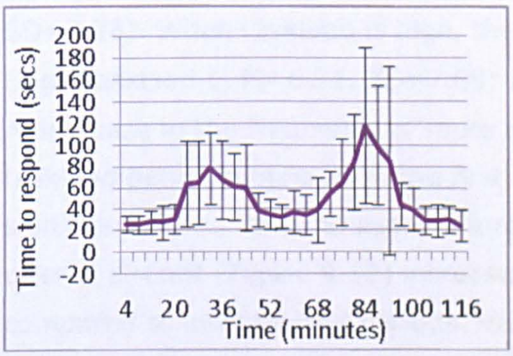


Figure 9.12. Response time to offered aircraft in seconds, averaged over 4 minute periods

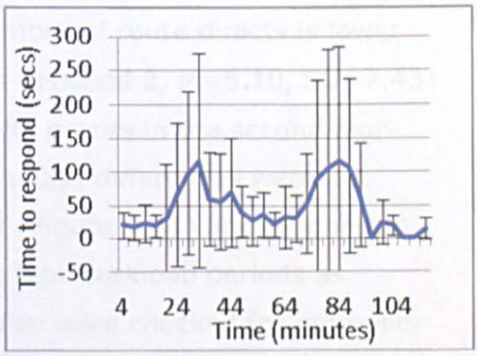
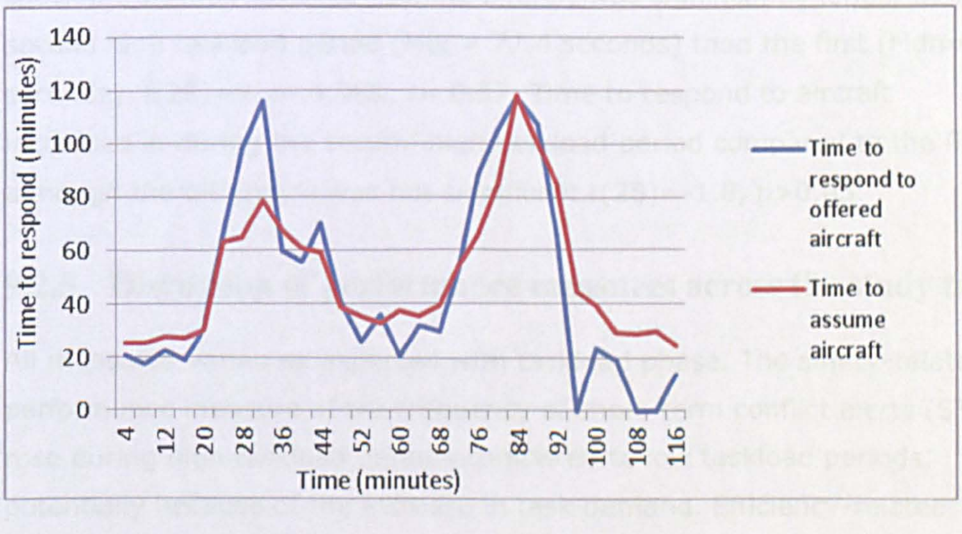


Figure 9.13. Time to assume aircraft and respond to offered aircraft



The average frequency of short term conflict alerts (STCAs) rose in the second high taskload period (M=17.24, SD=5.26) compared to the first high taskload period (M=8.34 SD=3.46). Variables were checked for normality and all were found to be within acceptable limits of skew (+/-2) and kurtosis (+/-5) (Kendall & Stuart, 1958). A paired-sample t-test confirmed significantly more STCAs occurred in the second high taskload period than the first ($t(28)=-8.21$, $p<0.001$, $r=0.84$). As the number of aircraft in high taskload 1 (M=9.3, SD=1.75) and high taskload 2 (M=11.4, SD=1.93) are similar, it is unlikely this findings was caused by an increase in aircraft. A small increase in STCA frequency is also seen across low taskload one (M=0.34, SD=0.48), low taskload two (M=1.17, SD=1.26), culminating at low taskload three (M=2.52, SD=2.08). Route directs also varied with taskload in the direction expected. The frequency of route directs is inverse to the taskload phases (Figure 9.10); when taskload is low, the number of route directs is higher (low taskload 1, M=8.62, SD=5.82; low taskload 2, M=10.86, SD=6.09; low taskload 3, M=7.48, SD=3.26). When taskload is high, the number of route directs is lower (high taskload 1, M=6.34, SD=7.09; high taskload 2, M=6.10, SD=7.43). A decrease in the frequency of route directs occurs in the second high taskload period compared to the first, although differences were not significant. Time taken to assume aircraft (Figure 9.11) and respond to offered aircraft (Figure 9.12) increased in high taskload periods as compared to low taskload periods. Variables were checked for normality and all were found to be outside acceptable limits of skew (+/-2) and kurtosis (+/-5) (Kendall & Stuart, 1958). A Wilcoxon signed ranks test showed that time taken to assume aircraft was significantly longer in the second high taskload period (Mdn= 77.4 seconds) than the first (Mdn=58 seconds), $t(28)=8$, $p<0.001$, $r= 0.57$. Time to respond to aircraft increased in during the second high taskload period compared to the first although the difference was not significant $t(28)=-1.8$, $p>0.05$.

9.2.5 Discussion of performance measures across the study task

All measures varied as expected with taskload phase. The safety-related performance measure of the frequency of short-term conflict alerts (STCA) rose during high taskload periods compared to low taskload periods, potentially because of the increase in task demand. Efficiency-related performance measures (frequency of route directs, time to assume aircraft, time to respond to offered aircraft) all decreased during high taskload periods. An interpretation of this finding is that in periods of high taskload, participants prioritised actions so that efficiency-related tasks may have been prioritised lower than safety-related tasks. Figure 9.13 indicates that participants prioritised time to assume aircraft over time to respond to offered aircraft, at least in the first high taskload period. This may be explained by the experimental design as participants were instructed to assume aircraft as quickly as possible.

STCA frequency and time to assume aircraft significantly increased (indicating decreased performance) in the second high taskload compared to the first. Moderating factors such as fatigue may have influenced the results. Time on task effects may also have influenced participant performance. STCA frequency consistently increased across low taskload periods, potentially explained by time on task effects.

9.3 Single factor associations with performance

9.3.1 Presentation of results

The relationships between single factors (workload, fatigue, stress, arousal and SA) and performance measures (STCA frequency, route direct frequency, time to assume aircraft and time to respond to offered aircraft) were investigated. Data violated the parametric assumption of independence and so Spearman's correlation coefficient was selected to investigate factor relationships. Scatterplots were utilised to support interpretation.

9.3.2 The relationship between workload and performance measures

For clarification, workload refers to the experienced, self-reported workload as opposed to objective taskload used in previous analyses. It is expected that frequency of STCAs, time to assume aircraft and time to respond to offered aircraft will positively relate with workload and increase with experienced workload. Frequency of route directs are expected to be negatively associated with workload.

Figure 9.14. Scatterplot of STCA frequency against workload

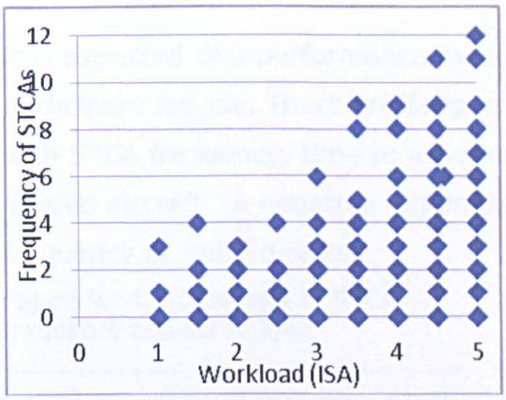


Figure 9.15. Scatterplot of route direct frequency against workload

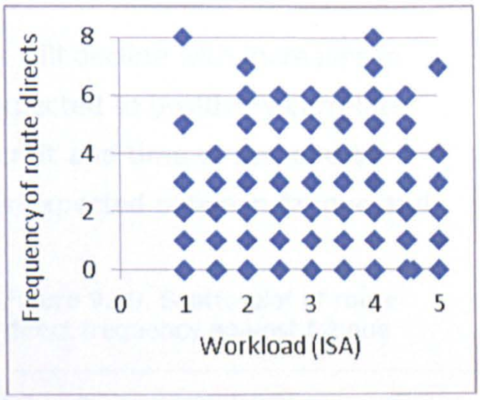


Figure 9.16. Scatterplot of time to assume aircraft against workload

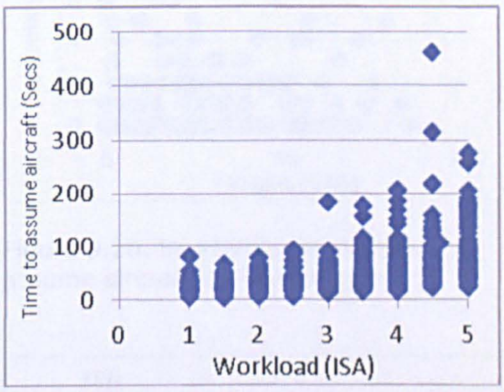


Figure 9.17. Scatterplot of time to respond to offered aircraft against workload

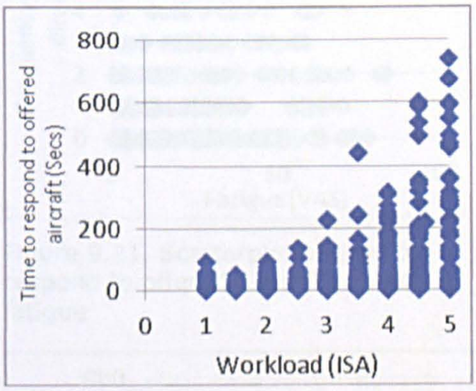


Figure 9.14 indicates a potential positive relationship between workload and STCA frequency. Spearman's correlation coefficient confirmed a significant, positive relationship between workload and the frequency of STCAs, r_s=0.5, p<0.001. A relationship between workload and route direct frequency was not observable in Figure 9.15 although a Spearman's correlation confirmed a significant negative relationship between workload and frequency of route directs, r_s=-0.25, p<0.001. The correlation coefficient is low which may be used to infer a weak relationship. The relationship between workload and time to assume aircraft (Figure 9.16) was significant and positive, r_s=0.59, p<0.001. Figure 9.17 indicates a positive relationship between workload and time to respond to offered aircraft. The spread of data points at workload rating 5 suggests a large variation in participants' time to respond, potentially representing individual strategies or priorities. Workload and time to respond to offered aircraft were significantly positively related, r_s=0.44, p<0.001.

9.3.3 The relationship between fatigue and performance measures

It is expected that performance measures will decline with increases in participant fatigue. Therefore fatigue is expected to positively correlate with STCA frequency, time to assume aircraft and time to respond to offered aircraft. A negative relationship is expected between fatigue and frequency of route directs.

Figure 9.18. Scatterplot of STCA frequency against fatigue

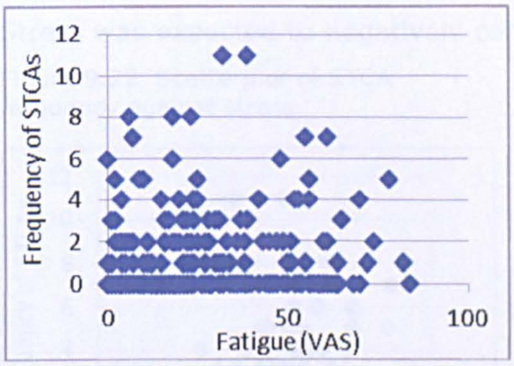


Figure 9.19. Scatterplot of route direct frequency against fatigue

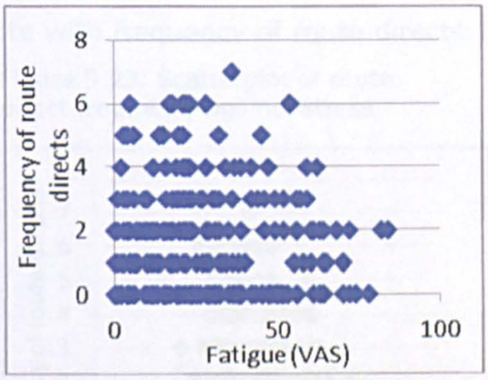


Figure 9.20. Scatterplot of time to assume aircraft against fatigue

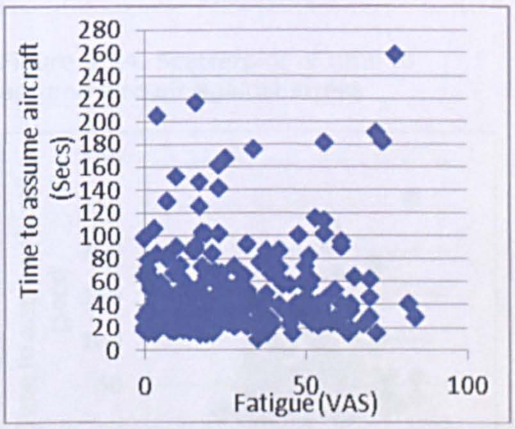
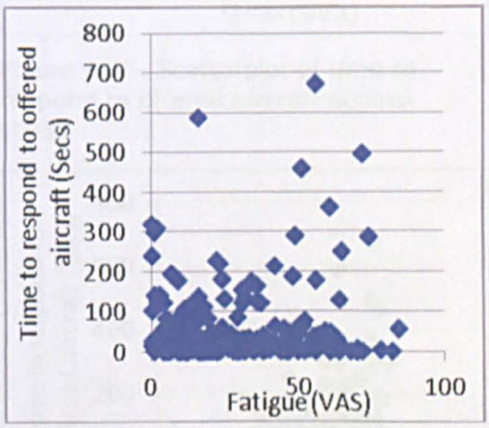


Figure 9.21. Scatterplot of time to respond to offered aircraft against fatigue



The relationship between fatigue and STCA appears to be relatively weak although a positive relationship trend can be seen in the clustered data (Figure 9.18). A Spearman's correlation coefficient confirmed higher fatigue ratings were significantly positively associated with STCAs (r_s=0.12, p<0.05), although the small coefficient and significance level suggests a weak relationship. A negative trend between fatigue and route direct frequency is observed in Figure 9.19 although the relationship was not significant (r_s=-0.39, p>0.05, NS). In addition, the relationship between fatigue and time to assume aircraft (Figure 9.20) was not significant, r_s=0.11, p>0.05, NS. The relationship between fatigue and time to respond to offered aircraft (Figure 9.21) was also not significant, r_s=-0.06, p>0.05, NS.

9.3.4 The relationship between stress and performance measures

Stress was expected to positively correlate with STCA frequency, in addition to time to assume aircraft and time to respond to offered aircraft. Stress was expected to negatively correlate with frequency of route directs.

Figure 9.22. Scatterplot of STCA frequency against stress

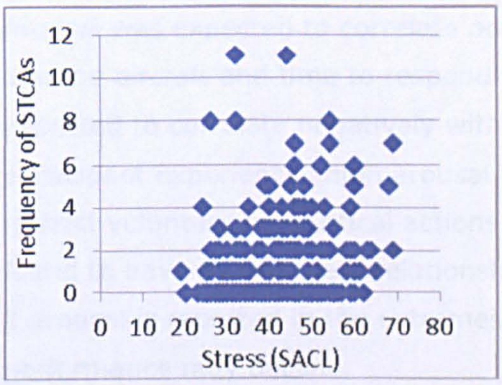


Figure 9.23. Scatterplot of route direct frequency against stress

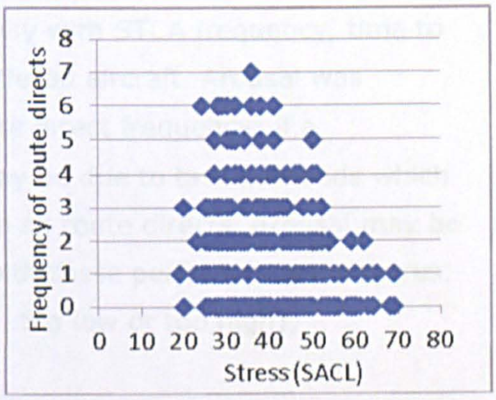


Figure 9.24. Scatterplot of time to assume aircraft against stress

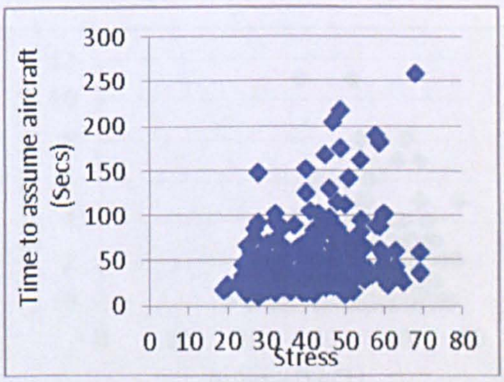
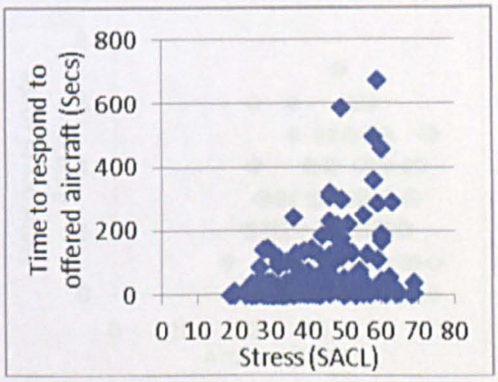


Figure 9.25. Scatterplot of time to respond to offered aircraft against stress



A general positive data trend between stress and STCA frequency is observed in Figure 9.22. Spearman's correlation coefficient analysis confirmed the relationship was significant and positive, r_s=0.31, p<0.001. The relationship between stress and route direct frequency may be curvilinear (Figure 9.23). The highest frequency of route directs occur when stress is reported at the middle of the scale (40/72). This may suggest that there may be an optimal level of experienced stress to elect to use route directs. Spearman's correlation coefficient confirmed a significant negative relationship between stress and route direct frequency, r_s=-0.24, p<0.001; as reported stress rose route direct frequency declined. A positive relationship was observed between stress and time to assume aircraft (Figure 9.24). Stress and time to assume aircraft significantly correlated, r_s=0.41, p<0.001, as did stress and time to respond to offered aircraft (Figure 9.25) r_s=0.39, p<0.001.

9.3.5 The relationship between arousal and performance measures

Arousal was expected to correlate positively with STCA frequency, time to assume aircraft and time to respond to offered aircraft. Arousal was expected to correlate negatively with route direct frequency; if a participant experiences high arousal it may be due to task demands which restrict voluntary non-critical actions such as route directs. Arousal may be found to have a curvilinear relationship with these performance measures; if arousal is reported in the extremes (i.e. too low or too high), performance may decline.

Figure 9.26. Scatterplot of STCA frequency against arousal

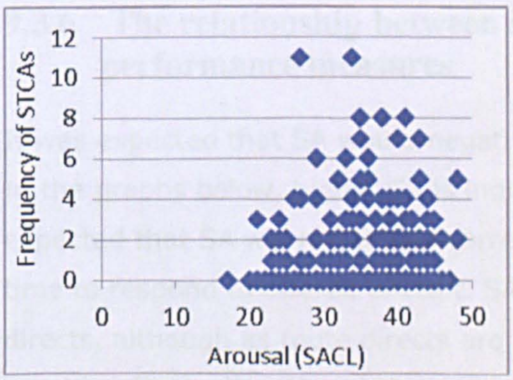


Figure 9.27. Scatterplot of route direct frequency against arousal

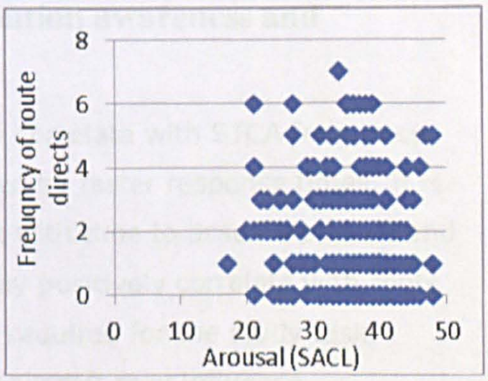


Figure 9.28. Scatterplot of time to assume aircraft against arousal

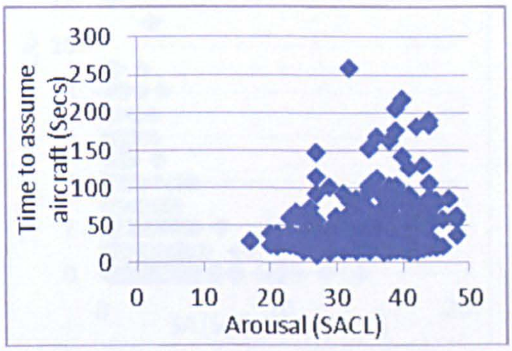
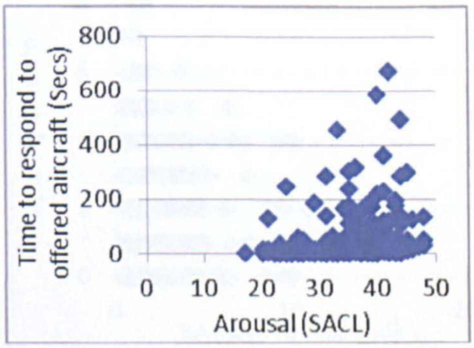


Figure 9.29. Scatterplot of time to respond to offered aircraft against arousal



STCAs appear to increase with higher reported arousal (Figure 9.26). Several data points indicate that 3 and above STCAs occur when reported arousal is below the scale mid-point (20 out of a possible 48). Arousal and frequency of STCAs were not significantly related, $r_s=0.11$, $p>0.05$. Figure 9.27 indicates a possible curvilinear relationship between arousal and route direct frequency. Route directs are most frequent around the mid-point of the arousal scale (35 out of a possible 48). Arousal and route direct frequency correlated significantly and negatively, $r_s=-0.17$, $p<0.005$. Time to assume aircraft significantly and positively correlated with arousal (Figure 9.28), $r_s=0.19$, $p<0.005$, as did arousal time to respond to offered aircraft (Figure 9.29), $r_s=0.38$, $p<0.001$.

9.3.6 The relationship between situation awareness and performance measures

It was expected that SA would negatively correlate with STCA frequency. In the graphs below, higher SA is indicated by faster response times. It is expected that SA will negatively correlate with time to assume aircraft and time to respond to offered aircraft. SA may positively correlate with route directs, although as route directs are not required for the study task, considerations other than being aware of aircraft may influence participants' decision to route aircraft direct.

Figure 9.30. Scatterplot of STCA frequency against SA

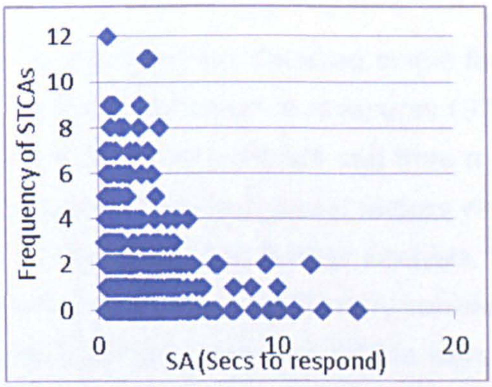


Figure 9.31. Scatterplot of route direct frequency against SA

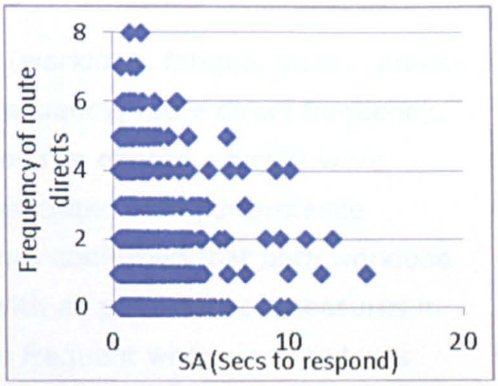


Figure 9.32. Scatterplot of time to assume aircraft against SA

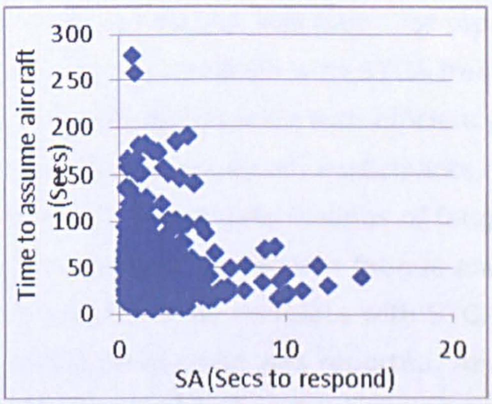
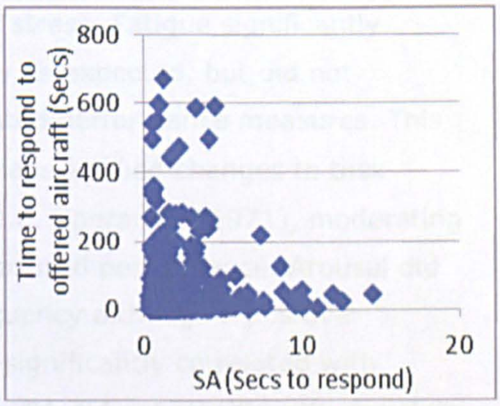


Figure 9.33. Scatterplot of time to respond to offered aircraft against SA



A positive relationship trend is observed between SA and STCAs so that fast responses to SA questions, indicating good SA, appear to be associated with more STCAs (Figure 9.30). This finding was unexpected. The relationship between SA and STCA frequency was not significant, r_s=-0.76, p>0.05, NS. A positive relationship trend between SA (indicated by faster response times to SA-related questions) and route direct frequency is observed in Figure 9.31. The relationship was not significant, r_s=-0.2, p>0.05, NS. Higher SA was observed to be associated with longer times to assume aircraft (Figure 9.32) although the relationship was not significant, r_s=-0.06, p>0.05, NS. In addition, higher SA appeared to associated with longer response times to offered aircraft (Figure 9.33) although the relationship was not significant, r_s=0.04, p>0.05, NS. Findings were contrary to expectations.

9.3.7 Discussion of the relationship between single factors and performance measures

The relationships between single factors (workload, fatigue, stress, arousal, SA) and performance measures (STCA frequency, route direct frequency, time to assume aircraft and time to respond to offered aircraft) were analysed to investigate if factors were associated with performance measures prior to further analysis. Findings confirmed that both workload and stress were significantly correlated with all performance measures in the direction expected. STCAs were more frequent when workload was high, and route directs were less frequent. Time to assume and respond to offered aircraft were also longer with higher reported workload. The same pattern of results was found for reported stress. Fatigue significantly positively correlated with STCA frequency as expected, but did not correlate significantly with efficiency-related performance measures. This finding is unexpected. Participants may have applied changes to task strategy to mitigate feelings of fatigue (e.g. Sperandio, 1971), moderating the relationship between fatigue and measured performance. Arousal did not significantly correlate with STCA frequency although a positive relationship trend was reported. Arousal significantly correlated with efficiency-related performance measures. SA did not significantly correlate with performance measures. The positive relationship trends between faster response times to SA questions (indicating higher SA) and STCA frequency and longer times to respond to aircraft are not in the direction expected. A potential interpretation is that during times of higher task demand (which may result in more STCAs and response times to aircraft) participants may have responded to SA questions quickly in order to minimise disturbance on the task.

A curvilinear relationship may be present between some factors and performance measures. A potential curvilinear relationship was identified between arousal and route direct frequency, with route direct frequency increasing at the mid-point of the arousal scale (40/72). In addition, the relationship between stress and route direct frequency may also be curvilinear. The highest frequency of route directs occur when stress is reported at the middle of the scale (40/72). Statistical results should be interpreted with caution due to the possibility of a curvilinear relationship which will not be accounted for by a Spearman's correlation analysis.

9.4 Does covariance between factors exist?

9.4.1 Presentation of results

Associations between the five measured factors (workload, fatigue, stress, arousal, SA) produced 10 factor dyad relationship correlations. For brevity, only the results that were significant are presented. Spearman's correlation coefficient analysis was used to explore statistical significance (Table 9.2).

Table 9.2. Spearman's correlation coefficient results for all factor dyads

Factor 1	Factor 2	Correlation coefficient and significance value
Workload	Fatigue	0.16, p=0.007
	Stress	0.6, p=0.0005
	Arousal	0.37, p=0.0005
	Response times to SA questions	-0.003, p=0.93 NS
Fatigue	Stress	0.31, p=0.0005
	Arousal	-0.4, p=0.0005
	Response times to SA questions	-0.25, p=0.0005
Stress	Arousal	0.25, p=0.0005
	Response times to SA questions	0.09, p=0.16 NS
Arousal	Response times to SA questions	0.22, p=0.001

9.4.2 The relationship between workload and other factors (fatigue, stress, arousal, SA

Workload was expected to significantly positively correlate with fatigue, stress and arousal. Workload is expected to negatively correlate with SA; the higher the experienced workload, SA is expected to decline (i.e. longer response times to SA questions).

Figure 9.34. Scatterplot of fatigue against workload

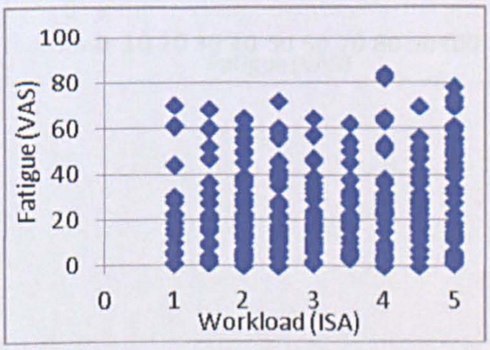


Figure 9.35. Scatter plot of stress against workload

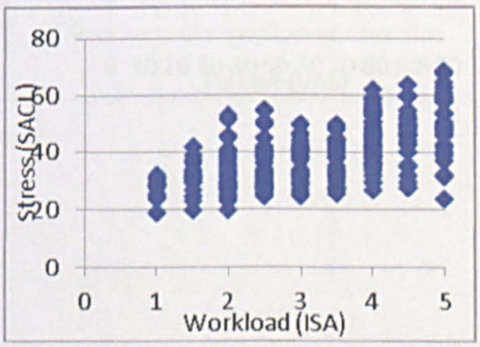
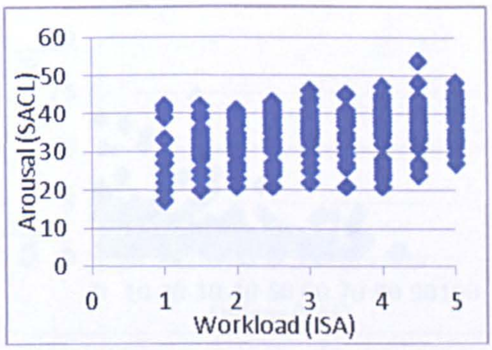


Figure 9.36. Scatterplot of arousal against workload



A significant positive correlation was found between workload and fatigue (Figure 9.34) (r_s=0.16, p<0.01). A possible curvilinear relationship is observed in Figure 9.34; fatigue ratings are slightly lower around the midpoint of the workload scale (3-3.5). Significant positive correlations also occurred between workload and stress (r_s=0.6, p<0.001) (Figure 9.35) and workload and arousal (r_s=0.37, p<0.001) (Figure 9.36).

9.4.3 The relationship between fatigue and other factors (stress, arousal, SA)

It was expected that fatigue would significantly positively correlate with stress and arousal. Fatigue is expected to significantly negatively correlate with SA.

Figure 9.37. Scatterplot of stress against fatigue

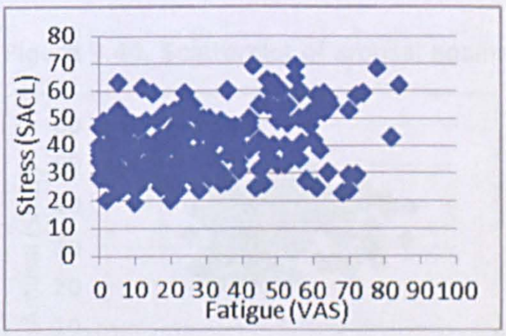


Figure 9.38.Scatterplot of arousal against fatigue

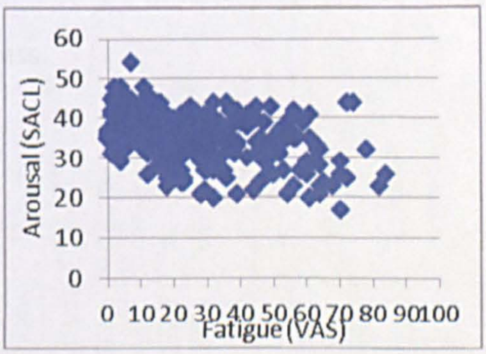
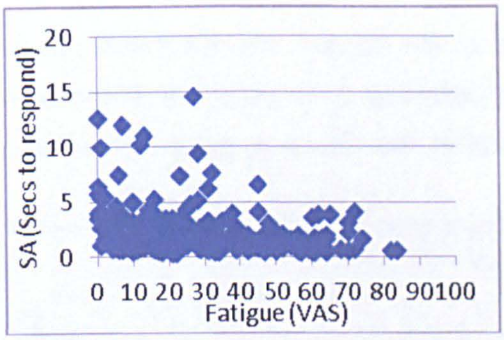


Figure 9.39. Scatterplot of SA against fatigue

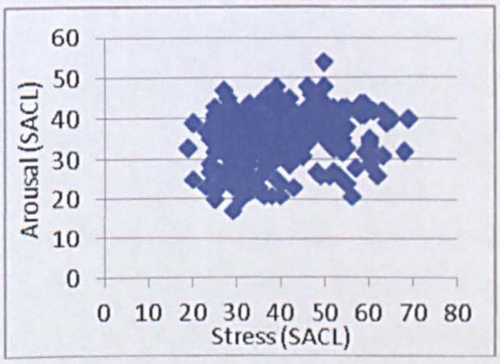


Fatigue and stress appeared to be positively associated (Figure 9.37) although participants' reported fatigue appears more variable with higher stress. Spearman's correlation analysis confirmed a significant, positive relationship between fatigue and stress (r_s=0.31, p<0.001).Fatigue and arousal were significantly negatively correlated (Figure 9.38)(r_s=-0.4, p<0.001). Data points were tightly clustered suggesting low individual variability when fatigue was rated below the scale midpoint (50 out of 100). A significant relationship between fatigue and SA (Figure 9.39) was reported r_s=-0.25, p<0.001. However the direction of the relationship was not expected; as fatigue increased, time to respond to SA questions reduced, indicating higher SA.

9.4.4 The relationship between stress and arousal

It was expected that stress and arousal would significantly positively correlate.

Figure 9.40. Scatterplot of arousal against stress

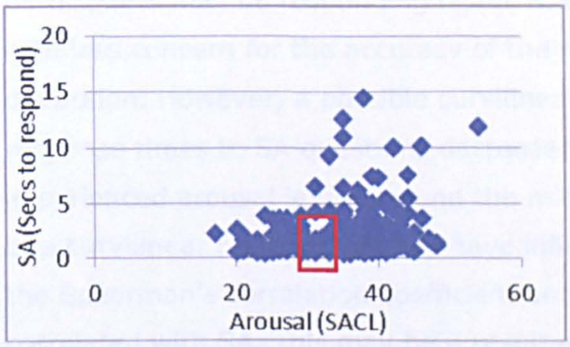


Stress and arousal appear to correlate positively. As reported stress rose, reported arousal rose (Figure 9.40). The relationship was significant, r_s=0.25, p<0.001.

9.4.5 The relationship between arousal and SA

It was expected that arousal would significantly positively correlate with SA; as arousal increases SA is expected to increase. However, based on previous findings, a curvilinear relationship may be reported.

Figure 9.41. Scatterplot of SA against arousal



A significant relationship between arousal and SA (Figure 9.41) was reported (r_s=0.22, p<0.005), as arousal rose, response times to SA questions also rose, indicating poorer SA. This result not in the direction expected. However, as highlighted in Figure 9.41, the relationship may be slightly curvilinear. The red square highlights clustered data where response times to SA questions (indicating higher SA) dropped around the mid-point of the arousal scale (30 out of 48).

9.4.6 Discussion of the relationship between factor dyads

Findings indicate that many factor dyads do co-vary. Significant relationships were identified between the majority (8/10) of factor dyads. Workload significantly correlated with fatigue, stress and arousal in the direction expected. An unexpected finding was that workload did not correlate significantly with SA. A data trend suggested that as workload increased, response times to SA questions reduced, indicating higher SA, which is contrary to the expected direction of relationship. It is possible that this result may have been influenced by participants responding quickly without a motivation for accuracy, in order to focus on the task during high workload periods. Fatigue was found to significantly positively correlate with stress and arousal as expected. Higher reported fatigue is related to higher stress and higher arousal. Fatigue also significantly correlated with SA, although not in the direction expected. Higher reported fatigue was associated with shorter response times to SA questions indicating higher SA. Again, this result may be due to the SPAM measure; participants may respond quickly but with less motivation to respond accurately due to general lethargy.

Similarly, arousal and SA were reported to significantly correlate but not in the direction expected. Higher reported arousal was associated with longer response times to SA questions, indicating poorer SA. Again, participants may be responding faster when experiencing high arousal but with less concern for the accuracy of the response, to minimise task disruption. However, a possible curvilinear data trend was identified; response times to SA questions decreased when participants reported experienced arousal levels around the mid-point of the scale. The presence of a curvilinear relationship may have influenced the statistical results from the Spearman's correlation coefficient analysis. Stress was not significantly correlated with SA. This may be a result of the use of the measurement of SPAM.

9.5 The relationship between multiple factors and performance

The relationships between multiple factors (factor dyads and triads) and the subsequent association with performance was investigated to address the third aim of the thesis. Correlation analyses were not appropriate because of the restriction to analysing the relationship between only two variables. It was therefore necessary to identify an appropriate statistical approach that was capable of investigating the relationship between 2 or more variables in association with dependent variables (performance measures).

9.5.1 Review of potentially relevant statistical approaches

9.5.1.1 Review of a regression model approach

A multiple regression model using continuous predictor variables was considered as an appropriate statistical technique to analyse multifactor relationships and the association with performance measures. A simple multiple regression method was not appropriate. A multiple regression would assess the variance of performance measures accounted for by single factors as opposed to investigating any interactive factor effects. The statistical approach also needed to account for curvilinear relationships;

the possibility of curvilinear relationships between single factors and performance measures, as well as factor dyads, was previously reported (sections 9.3, 9.4). Therefore, a non-linear, multiple regression, with mediator and moderator variables would be the appropriate statistical analysis approach. A power analysis suggested that for a simple regression, with a significance level of 0.05, assuming a medium effect size and a power of 0.8, 76 participants would be needed. Many more would be needed for the appropriate regression. The study generated data from 29 participants and so statistically significant results were considered to be extremely unlikely if this analysis was applied. In addition there may not have been enough control in the exercise for regression findings to allow an inference of strength. Participants were permitted to use their own control strategies. A regression model approach was therefore concluded not to be appropriate to analyse multiple factor relationships and associations with performance.

9.5.1.2 Review of median split analysis approach

The measures of each factor and performance measures generated continuous data, which restricted statistical approaches to the analysis of relationships between variables. Miles and Shevlin (2001) recommend that "one of the simplest ways [to explore continuous data for interactions] is to create a dichotomous variable from the continuous predictor variables (categorising high or low around the mean or median)" (p180). In accordance with Miles and Shevlin's (2001) recommendation, a median split analysis method was selected to investigate potential interactions between multiple factors and the association with performance measures.

The median split analysis method requires a transformation to covariate factors through the median split method by splitting continuous data into two groups around the median. The data is transformed from continuous data into categorical data. The factors are now treated effectively as independent variables with two levels - high and low. Tests of difference can be used to analyse the transformed variables.

The method of applying median splits to continuous variables to allow tests of difference has been widely applied in previous research (e.g. Denollet et al., 1996). However, the method has been criticised on the basis that splitting the data around the median and subsequently grouping the data into 'high' and 'low' categories, results in a loss of information and variance in the data, therefore reducing the power of applied statistical tests (Maccallum, Zhang, Preacher & Rucker, 2002). A risk of type II error is therefore increased. However, the median splits approach was the most practical method of analysing multiple factor relationships, including multifactor interactions, and the association of multifactor relationships with performance measures, which were necessary to achieve the third and fourth thesis aims.

9.5.2 Procedure of applying median splits

Median splits were applied to the results generated from the measured factors (workload, fatigue, stress, arousal, SA). There was a potential for a large number of results. To make the analysis manageable, the median split method was only applied to data collected during the two high taskload periods. Data collected during high taskload periods were selected for analysis because the high task demands create the potential for participants to reach the edge of performance, which was one of the aims for investigation. In addition, high workloads may create more variability in performance measures, reducing the likelihood of ceiling effects (perfect performance) which may inhibit the investigation of the association of factors with performance.

The median split approach was applied to the data. First, means were calculated of each participant's score for each factor, per 20 minute high taskload period. Means for each factor were rank ordered. The factor was then split into two groups (high and low) based on the median number of participants in each group. Participants rating a factor above the median were placed in the 'high' factor grouping, and participants with ratings below the median were categorised into the 'low' factor group. A step-by-step summary of the procedure of applying the median split approach to the data is documented in Appendix 13.

Table 9.3 presents the median of each factor at which the measure was split, and the number of participants in each group.

Table 9.3. Splits of each factor and the number of participants in each factor groups

	High taskload 1		High taskload 2	
Factor	Median split	Number of participants	Median split	Number of participants
Mental workload	≤4.2 Low workload	13	≤4.4 Low workload	15
	≥4.3 High workload	16	≥4.5 High workload	14
Fatigue	≤24 Low fatigue	15	≤24.5 Low fatigue	15
	≥25.5 High fatigue	14	≥33 High fatigue	14
Stress	≤46.5 Low stress	15	≤44.5 low stress	15
	≥48 High stress	14	≥45 High stress	14
Arousal	≤39 Low arousal	15	≤36.5 Low arousal	15
	≥39.5 High arousal	14	≥37 High arousal	14
SA	≤1.94 Fast response	15	≤1.36 Fast response	15
	≥1.96 Slow response	14	≥1.47 Slow response	14

9.5.3 Presentation of results

Statistical analyses were conducted on all possible factor and performance combinations (Appendix 14). However, because of the vast amounts of data it is not practical to present all results. Therefore, only significant and relevant data trends identified from the statistical analysis (Appendix 14) will be presented. The author is therefore approaching the discussion as an intelligent observer.

Scatterplots are used to visually represent associations between factor dyads and performance. Bar charts are utilised to visually represent associations between factor dyads or factor triads and performance. Differences between performance measures associated with different multifactor groups were analysed. Factor measures that satisfied parametric assumptions (Table 9.4, Table 9.5) were analysed using an analysis of variance (ANOVA). A majority of measures did not meet the parametric assumptions of homogeneity of variance and normal distribution and were analysed using Mann-Whitney U tests with a bonferroni correction.

Table 9.4. Factors associated with specific performance measures which satisfied parametric assumptions for high taskload period 1

Factor	Performance measure
Fatigue	STCA

Table 9.5. Factors associated with specific performance measures which satisfied parametric assumptions for high taskload period 2

Factor	Performance measure
Fatigue	STCA
Stress	STCA
Arousal	STCA
SA	STCA

9.5.4 Multifactor associations with performance – a cumulative effect?

The association between multifactor combinations and measures of performance was investigated. Several findings of interest are reviewed. For clarity, the construction and interpretation of the figures associated with the first finding that is presented are explained in detail. This level of explanation is presented for the first finding only to familiarise the reader with the meaning of the figures; subsequent figures are interpreted in the same way.

The factor combination of workload and SA was investigated in association with STCA frequency. Figure 9.42 presents a scatter graph of the association between workload and response time to SA related questions (SA) for each participant. In addition, each data point is colour coded to represent the frequency of STCAs the participant created in the four minute period after the workload and SA measure was collected. The key to the side of each figure presents the meaning of the colour codes. For example, if one participant reported a workload of 3 at minute 28 in the task, and responded to an SA question in 2 seconds at minute 28, a data point is placed on the graph to represent these data. That data point is then colour coded to represent the number of STCAs the same participant created between minute 28 and minute 31.59 of the task. Therefore, Figure 9.42 represents three variables: two covariate factors and one performance measure.

The data medians are presented on the graph to visually represent where the data are split. The splits around the median result in four quadrants:

- Quadrant 1: Participants with good SA (fast response times) and experienced low workload
- Quadrant 2: Participants with good SA and experienced high workload
- Quadrant 3: Participants with poor SA (slower response times) and experienced low workload
- Quadrant 4: Participants with poor SA and experienced high workload.

For clarity, the quadrants are demarcated in Figure 9.42 by small boxes containing the quadrant number (i.e. '1' on the graph relates to 'Quadrant 1', defined above).

Figure 9.42. Scatterplot of SA against workload and the association with frequency of STCAs, per participant across high taskload 1

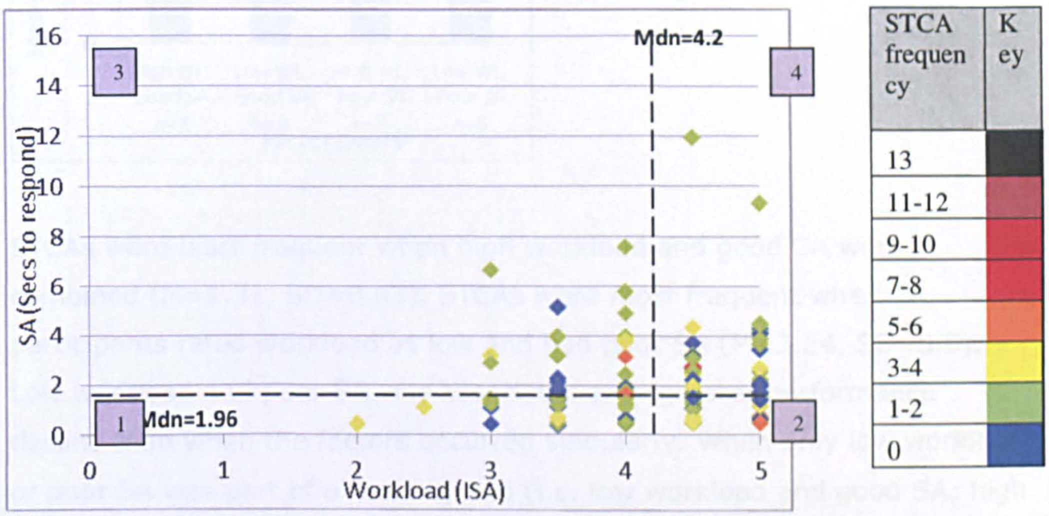
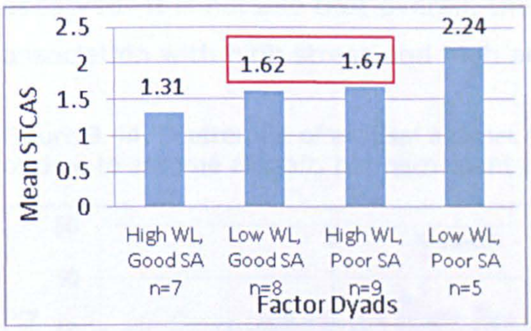


Figure 9.42 indicate that participants with poorer SA (longer response times) and low workload (quadrant 3) experienced between 0-6 STCAs. The green data points (1-2 STCAs) and yellow data points (3-4 STCAs) are dominant, indicating that participants within this grouping frequently experienced STCAs. Participants who reported high workload appear to have fewer STCAs overall, indicated by the frequency of blue (no STCAs) and green (1-2 STCAs) data points especially if SA was also good (shorter response times) (quadrant 2).

A median split was applied to the data. Figure 9.43 presents the means for each data quadrant associated with mean STCA frequency. The use of the bar chart supports Figure 9.42 by presenting summaries of data for each quadrant.

Figure 9.43. Median split application to scatterplot data: bar chart showing the average performance (frequency of STCAs) under different levels of workload and SA in high taskload 1



STCAs were least frequent when high workload and good SA were combined (M=1.31, SD=0.63). STCAs were most frequent when participants rated workload as low and had poor SA (M=2.24, SD=0.8). Low workload and poor SA was associated with greater performance decline than when the factors occurred singularly. When only low workload *or* poor SA was part of a factor group (i.e. low workload and good SA; high workload and poor SA) mean STCAs were not as frequent (range 1.62-1.67). When low workload and poor SA co-occurred, significantly more STCAs were reported compared to participants who reported a high workload and good SA (W=33, p<0.05, r=-0.38.). The combination of low workload and poor SA may have interacted to be associated with a cumulative influence on performance.

A trend of note is that performance appears to remain stable in association with different multifactor combinations. The co-occurrence of one factor from the group associated with least STCAs and one factor from the group associated with most STCAs (i.e. low workload, good SA; high workload, poor SA) were associated with moderate STCA frequencies. STCA frequency was not was not significantly different when associated with the different factor combinations of low workload and good SA and high workload and poor SA, W=69, p>0.05.

The association of specific combined factors with greater performance decline, compared to the single occurrence of these factors, was also observed with efficiency related measures (Figure 9.44, Figure 9.45). The combination of stress and arousal was investigated in relation to time to assume aircraft. Figure 9.45 indicates that time to assume aircraft was fastest with low stress, represented by more data points which are coded blue to indicate a response time of between 1-24 seconds. When low stress is combined with high arousal, some longer response times are observed. It is notable that overall, the longest response times occur in association with high stress and high arousal.

Figure 9.44. Scatterplot of arousal against stress and the associated performance of time to assume aircraft, per participant across the full simulation

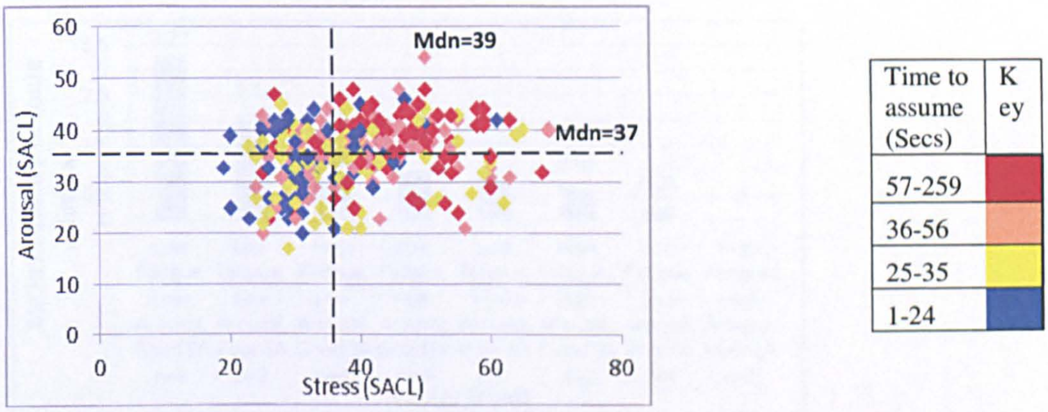
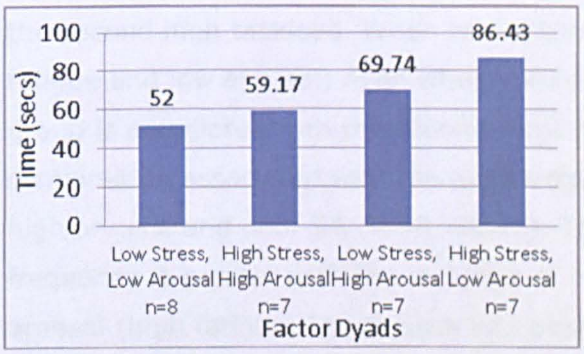


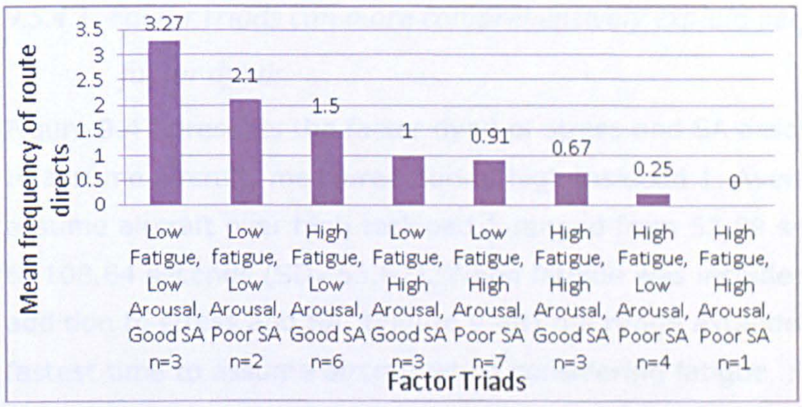
Figure 9.45. Median split application to scatterplot data: bar chart showing the average performance (time taken to assume aircraft) under different levels of stress and arousal in high taskload 1



A median split analysis was applied (Figure 9.45). Time to assume aircraft was fastest when participants reported lower stress and lower arousal (M=52, SD=9.45). Time to assume aircraft was significantly slower when high stress and low arousal (M=86.43, SD=49.51) were combined (W=46.5, $p<0.05$, r=-0.38). However, the large standard deviation suggests that the spread of scores around the mean is large and may not be fully representative of the results for individual participants.

The association of a triad of co-occurring factors (fatigue, arousal and SA) and frequency of route directs in the second high taskload period was investigated. Frequency of route directs is an efficiency-related performance measure; more route directs indicates participants routed aircraft more efficiently. It was not possible to use a scatterplot to present the data for four variables (three factor measures and one performance measures) and so bar charts are utilised to provide a visual representation of data (Figure 9.46).

Figure 9.46. Bar chart showing average performance (frequency of route directs) under different levels of fatigue, arousal and SA in high taskload 2



The combination of low fatigue, low arousal and good SA is associated with most mean route directs (M=3.27, SD=1.22) for the 20 minute period of the second high taskload. When two of these factors are present (low fatigue and low arousal) even when combined with poorer SA, the factor group is associated with the second most route directs. The factor combination associated with the least frequent route directs is high fatigue, high arousal and poor SA (M=0, SD=0). The decline in route direct frequency is greater with the inclusion of high arousal compared to low arousal (high fatigue, *low arousal* and poor SA, M=0.25, SD=0.38). In addition, combined high fatigue and poor SA are associated with the least frequent route directs. When either high fatigue *or* poor SA are combined with other factor combinations (i.e. *high fatigue*, low arousal and good SA), the co-occurring factors are associated with a more moderate decline in mean route direct frequency (Figure 9.46).

The difference between the most mean route directs (associated with low fatigue, low arousal and good SA) and least mean route directs (associated with high fatigue, high arousal, poor SA) approached significance (W=1, p<0.1, r=-0.67). The significance level may have been influenced by small numbers of participants in each group. The difference between the most mean route directs (associated with low fatigue, low arousal and good SA) and second least mean route directs (associated with high fatigue, low arousal, poor SA) was significant (W=10, p<0.05, r=-0.8). In addition, the difference between the most mean route directs (associated with low fatigue, low arousal and good SA) and mean route directs associated with high fatigue, high arousal, good SA) was significant (W=6, p<0.05, r=-0.8).

9.5.4.1 Factor triads can more comprehensively explain performance than factor dyads

Figure 9.47 presents the factor dyad of stress and SA associated with time to assume aircraft, measured during high taskload 1. Average time to assume aircraft over high taskload 1 ranged from 52.89 seconds (SD=8.44) to 108.64 seconds (SD=53.67). When fatigue was included in analysis in addition to stress and SA, (Figure 9.48) the range extended. The average fastest time to assume aircraft when considering fatigue, stress and SA was of 47.8 seconds (SD=9.09), 5.09 seconds shorter as compared to the average fastest time associated with two factors (M=52.89, SD=8.44). The average slowest time to assume aircraft when associated with three factors was 139.47 seconds (SD=42.67), 30.83 seconds longer compared to the average slowest time to assume aircraft when associated with two factors (M=108.64, SD=53.67). Findings indicate that including multiple factors for analysis in association with performance explains more performance variance than single factors.

Figure 9.47. Bar chart showing the average performance (time to assume aircraft) under different levels of stress and SA, high taskload 1

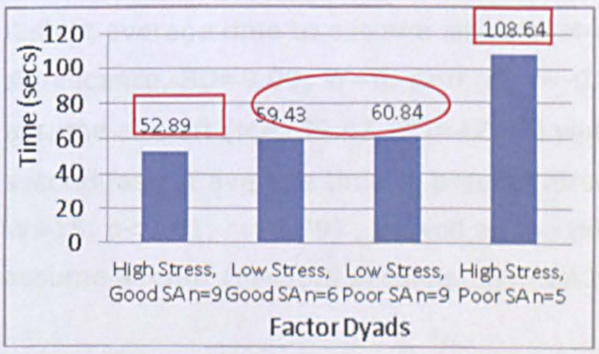
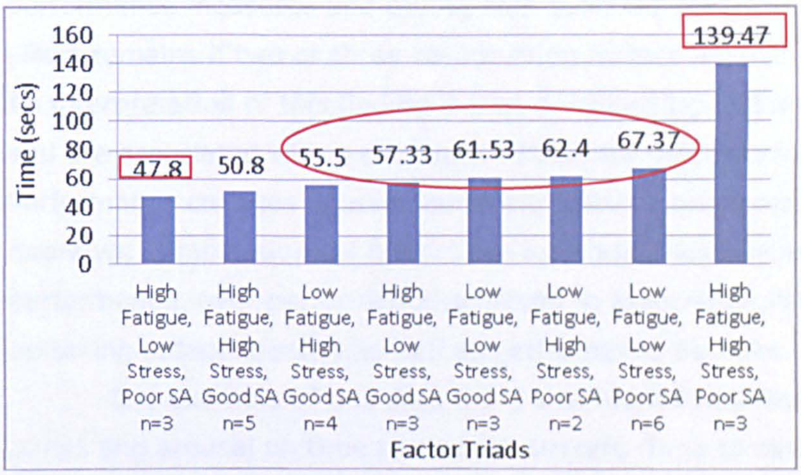


Figure 9.48. Bar chart showing the average performance (time to assume aircraft) under different levels of fatigue, stress and SA on reaction time to assume aircraft, high taskload 1



A median split approach was applied to the data. Mann-Whitney U tests were used to analyse differences between performance associated with two co-occurring factors. One significant difference was found between the average fastest time to assume aircraft (52.89, SD=8.44) when associated with high stress and good SA, and the average slowest time to assume aircraft (108.64, SD=53.67) when associated with high stress and poor SA ($W=52.5$, $p<0.05$, $r= -0.53$). The association between time to assume aircraft and three co-occurring factors (fatigue, stress, SA) was investigated. A Bonferroni correction was applied (0.05/3) and so all effects are reported at a $p=0.01$ level of significance. Three significant differences between performance measures were found. The slowest average time to assume aircraft (M=139.47, SD=42.67) compared to the fastest average time to assume aircraft (M=47.8 seconds) neared significance, SD=9.09; $W=6$, $p=0.05$, $r=-0.8$. The slowest average time to assume aircraft (M=139.47, SD=42.67) was significantly slower than the second fastest average time to assume aircraft (M=50.8 seconds, SD=8.78; $W=15$, $p<0.01$, $r=-0.79$) , as well as the third fastest average time to assume aircraft (M=55.5 seconds, SD=8.42; $W=10$, $p<0.01$, $r=-0.8$).

9.5.5 Discussion of the association between multiple factors and performance

A robust data trend was identified that specific factor combinations were associated with greater performance changes than when the factors occurred independently in other factor groups. This result was reported repeatedly, and is observed for both safety and efficiency related performance measures and during high taskload periods 1 and 2. The effect remains if two or three co-occurring factors are included in analysis. An interpretation of this finding is that co-occurring factors may interact and are associated with a cumulative influence on performance. Performance changes in association with factor groups may be positive or negative; combinations of factors are associated with increased performance, over performance achieved in association with the factors occurring independently, as well as performance declines.

One example of this data trend was identified in the association of stress and arousal on time to assume aircraft. Time to assume aircraft was slower when high stress and low arousal were combined than when these factors independently occurred with other factors, indicating a potential interactive effect and an association with a cumulative influence on performance. Numerous possible explanations exist for the association of high stress and low arousal with the slowest time to assume aircraft out of the four factor dyad groupings. It may be that experienced high stress led to the prioritisation of other, safety critical actions. Combined with lower reported arousal which may indicate that participants were lower in energy, response times to assume aircraft increased. It is also important to interpret the factor dyads in context; as data were collected in the first high taskload period, scores of arousal in the 'low' group are relative to the spread of scores for arousal under demanding task conditions. Arousal scores in the 'low arousal' group may not indicate absolute low arousal, but that arousal is lower than other participants reported during this time. A lower arousal score during the high taskload period may indicate coping with a high task demands. Interpreted in this way, participants experiencing high stress, but lower arousal, may again have decided to prioritise the most safety, or time-critical actions over assuming aircraft quickly.

Overall, the data trend that specific factor combinations are associated with greater performance changes than when the factors occurred independently in other factor groups was robust, and indicates a possible interaction effect between co-occurring factors, and an associated cumulative influence on performance.

An additional data trend of note is that average performance measures can remain stable when associated with different co-occurring factors. An example of this data trend was identified in the analysis of workload and SA in association with average STCA frequency. High workload and good SA were associated with average least STCAs out of the four factors grouping. This may be expected, as a high workload may elicit a higher level of alertness in participants (Repetti, 1989; Rose, Jenkins, & Hurst, 1978) and a good SA would allow detection and prevention of potential conflicts prior to a STCA. When these factors independently occur with other factors (e.g. high workload and poor SA; low workload and good SA) performance was similar. One interpretation of this finding is that when factors are combined, a factor associated with increased performance may moderate a factor that is associated with performance declines.

Findings also suggest that more performance variance may be explained with the inclusion of multiple, co-occurring factors. This is supported by statistical findings as more significant differences between average performance measures were identified when associated with triadic factor combinations as opposed to dyadic factor combinations (Table 9.6). Table 9.6 summarises the percentage of significant differences found between performance measures when associated with single factors, co-occurring factor dyads and co-occurring factor triads.

Table 9.6. Percentage of significant differences between performance measures when associated with single factors, factor dyads and factor triads

	High taskload 1	High taskload 2
Single factors	3 significant/25 analyses = 12%	1/25 = 4%
Factor dyads	24/95 = 25%	18/81 = 22%
Factor triads	77/209 = 37%	50/151 = 33%

Table 9.6 confirms that as more factors are analysed in combination with associated performance markers, more variance in performance is explained, leading to more significant differences between levels of performance. Findings therefore support the analysis of multiple factors to gain a more comprehensive and potentially realistic view of human performance in association with human factor influences.

9.6 The shape of the edge of performance associated with multifactor co-occurrences

9.6.1 Presentation of results

The shape of performance decline was investigated using data generated from the median split analysis. Performance averages were associated with factor dyads and factor triads. Performance averages were ranked and presented in line graphs, from highest average performance to lowest average performance. The figures provide a visual representation of the pattern of performance decline in association with multifactor combinations. Figure 9.49, Figure 9.50, Figure 9.51 are intended to remind the reader of the hypothesised performance shapes. Findings are considered in order of presentation of the hypothesised performance shapes.

Figure 9.49. Hypothesised performance shape using hypothetical data - gradual performance decline

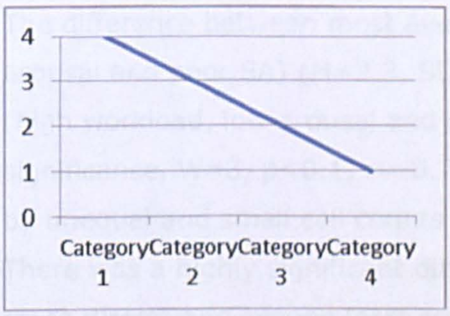


Figure 9.50. Hypothesised performance shape using hypothetical data - maintained performance followed by a sudden decline

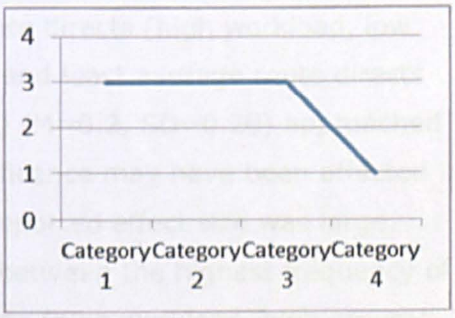
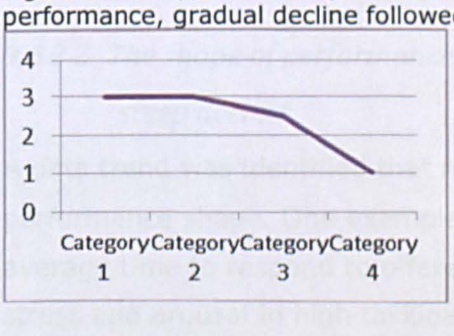


Figure 9.51. Hypothesised performance shape using hypothetical data - maintained performance, gradual decline followed by a steep decline

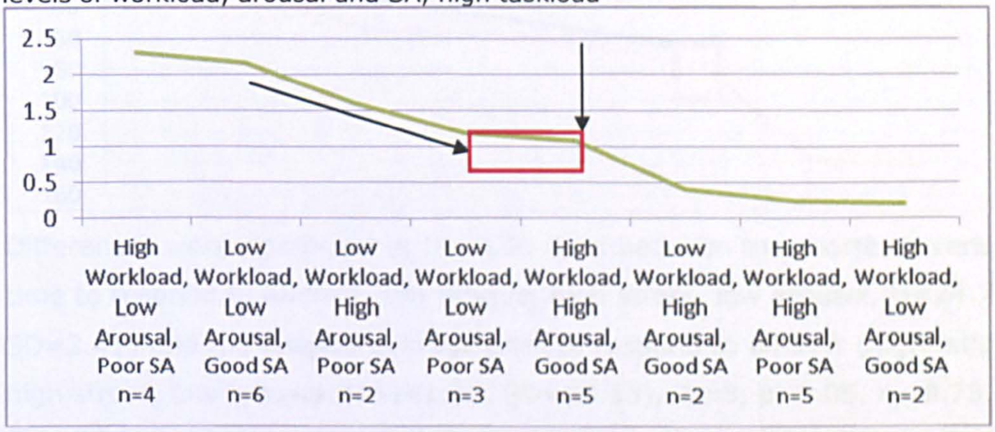


9.6.2 The shape of performance and the performance edge

9.6.2.1 The shape of performance: Constant performance decline

A linear performance decline was not identified in the data as hypothesised in Figure 9.49. However, a gradual performance decline interspersed with periods of performance maintenance was identified in average route direct frequencies associated with workload, arousal and SA (Figure 9.52). Four Mann-Whitney tests investigated statistical differences between average route directs associated with different factor groupings. A Bonferroni correction was applied (0.05/3) and so all effects are reported at a p=0.01 level of significance.

Figure 9.52. Average performance (frequency of route directs) under different levels of workload, arousal and SA, high taskload

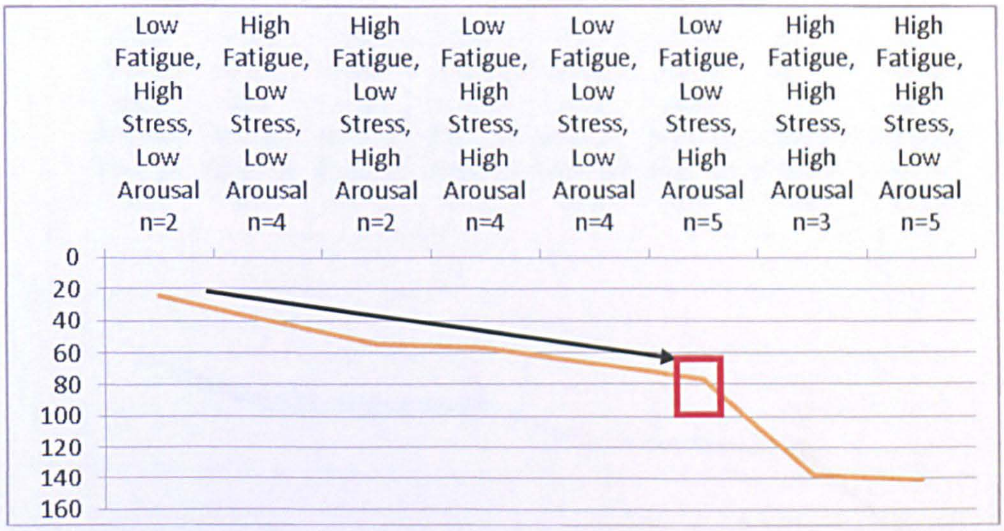


The difference between most average route directs (high workload, low arousal and poor SA) (M=2.3, SD=1.23) and least average route directs (high workload, low arousal and good SA) (M=0.2, SD=0.28) approached significance, W=3, p<0.1, *r*=-0.76. Significance may have been affected by unequal and small cell counts as the reported effect size was large. There was a highly significant difference between the highest frequency of route directs and second least route directs (high workload, high arousal, poor SA, M=0.24, SD=0.26) W=15, p<0.01, *r*=-0.82.

9.6.2.2 The shape of performance: Maintained performance, followed by a steep decline

A data trend was identified that resembled the second hypothesised performance shape. One example of this data trend was found in the average time to respond to offered aircraft in association with fatigue, stress and arousal in high taskload 1 (Figure 9.53). A gradual performance decline is observed prior to a steep decline, highlighted by a red square. This performance 'break', where a steep performance decline follows stable or gradual declining performance, may represent a performance 'edge'.

Figure 9.53. Average performance (time to respond to offered aircraft) under different levels of fatigue, stress and arousal in high taskload 1

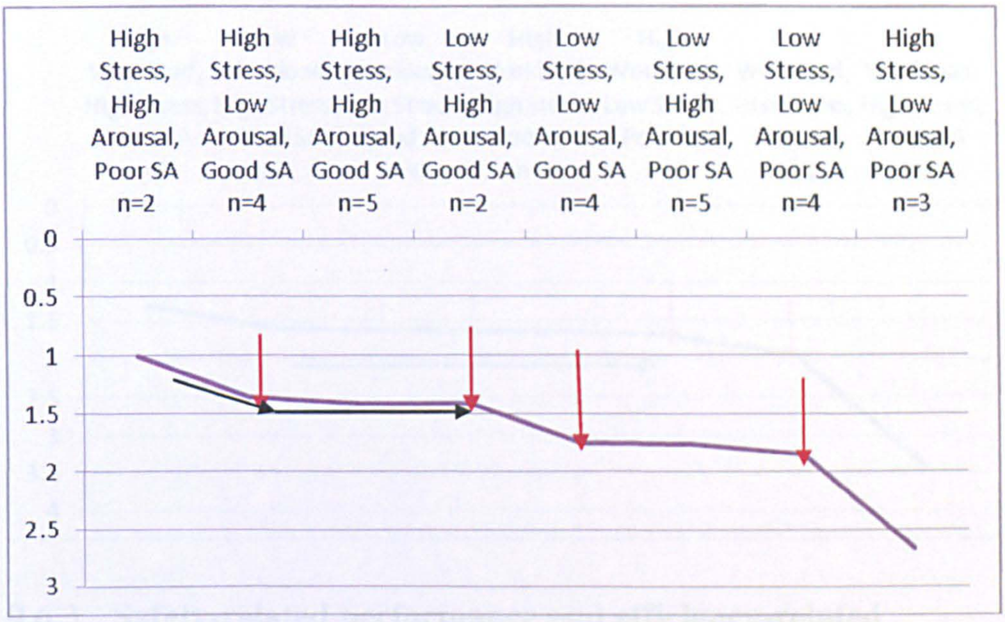


Differences were significant at the 0.05 level between the shortest average time to respond to aircraft (low fatigue, high stress, low arousal, M=24.76, SD=3.41) and the longest average time to respond to aircraft (high fatigue, high stress, low arousal, M=141.32, SD=86.13), W=3, $p<0.05$, *r*=-0.73. The difference between second fastest time to respond (high fatigue, low stress, low arousal, M=39.86, SD=22.64) and slowest time to respond (high fatigue, high stress, low arousal, M=141.32, SD=86.13) was also significant (W=12, $p<0.05$, *r*=-0.65).

9.6.2.3 Performance shape 3: Gradually declining performance interspersed with periods of maintenance

The most frequently observed data trend was a series of performance declines interspersed with periods of performance maintenance similar to the third hypothesised performance shape. One example of this data trend was observed in the average frequency of STCAs associated with stress, arousal and SA during the first high taskload period (Figure 9.54). After an initial small increase in average STCAs, performance remains similar when associated with 3 separate factor groupings, high stress, low arousal, good SA (M=1.35, SD=0.57), high stress, high arousal, good SA (M=1.4, SD=0.75) and low stress, high arousal, good SA (M=1.4, SD=0.85). An additional decline in performance then occurs (Figure 9.54) (low stress, low arousal, good SA, M=1.75, SD=0.53) followed by another period of stable performance.

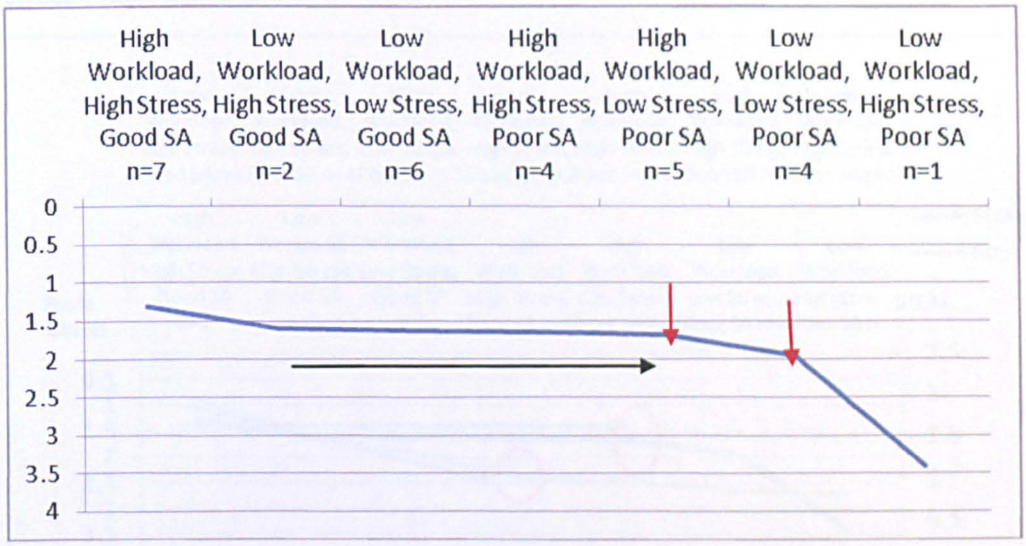
Figure 9.54. Average performance (frequency of STCAs) under different levels of stress, arousal and SA in high taskload 1



The performance difference between the least STCAs (high stress, high arousal and poor SA, M=1, SD=0) and most STCAs (high stress, low arousal, poor SA, M=2.67, SD=0.64) approached significance, W=3, p=0.08, *r*= -0.8, and was significantly different to the second most STCAs (associated with low stress, low arousal and poor SA, M=1.85, SD=0.5), W= 3, p<0.05, *r*= -0.82. There were also significantly more STCAs (high stress, low arousal, poor SA, M=2.67, SD=0.64) than the second least STCAs (high stress, low arousal, good SA, M=1.35, SD=0.57) W= 10.5, p<0.05, *r*= -0.75. The results suggest that gradual performance declines occur prior to a steep performance decline.

The frequency of gradual performances declines and periods of stability can differ between performance measures. Figure 9.55 presents STCA frequency associated with workload, stress and SA during high taskload 1. Average STCA frequency was similar across several difference association factor groups. Low workload, high stress and poor SA (M=3.4, SD=0) was the only factor combination associated with a steep performance decline, potentially representing the 'edge' of performance. The number of factor combinations associated with declines in performance therefore appears to be dependent on the performance measure and associated co-occurring factors.

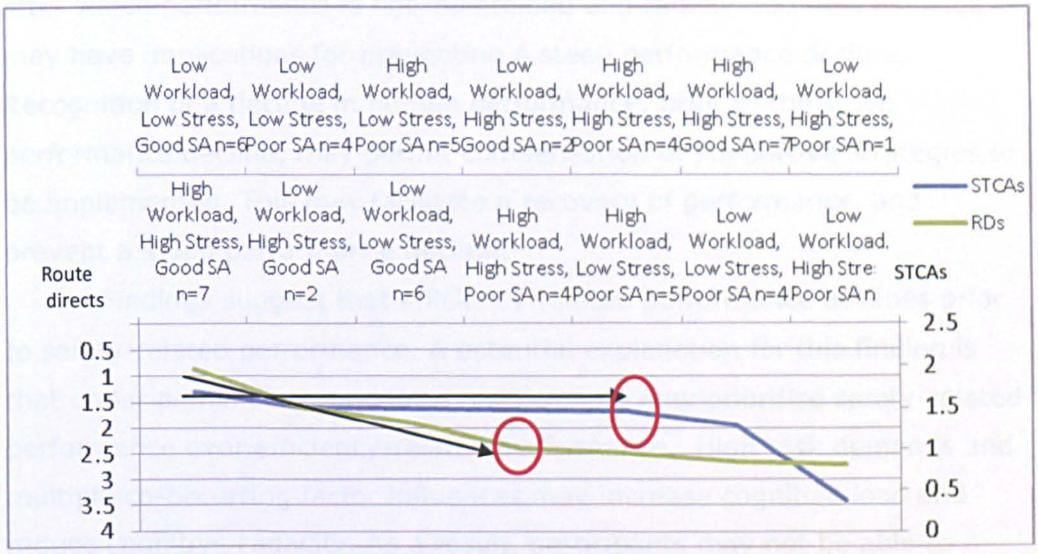
Figure 9.55. Average performance (frequency of STCAs) under different levels of workload, stress and SA on frequency of STCAs, high taskload 1



9.6.3 Safety-related performance and efficiency-related performance may be prioritised differently

Findings showed that declines in efficiency –related performance measures (frequency of route directs, time to assume aircraft, time to respond to offered aircraft) were associated with more factor groupings than the safety-related performance measure (STCAs). In other words, efficiency-related measures appear to be more vulnerable to associations with multifactor combinations. Figure 9.56 presents both frequency of STCAs (safety-related) and frequency of route directs (efficiency-related) in association with workload, stress and SA.

Figure 9.56. Average performance (frequency of STCAs, frequency of route directs) under different levels of workload, stress and SA on frequency of STCAs and route directs, high taskload 2



Three factor combinations (low workload, low stress and poor SA; high workload, low stress, and poor SA; low workload, high stress, and good SA) appear to be associated with a relatively steep decline in route direct frequency, prior to a more gradual decline. This is in contrast with STCA frequency, which is similar when associated with five separate multifactor variations, after which a gradual performance decline is recorded. The difference between the least STCAs (high workload, high stress, good SA, M=1.31, SD=0.63) and the most STCAs (low workload, high stress, poor SA, M=3.4, SD=0) approached significance, W=28, p<0.1, r=-0.29.

9.6.4 Discussion of the shape of performance decline in association with multiple factors

The second and third hypothesised shapes of performance decline were similar to trends identified in the data. Data trends that were closely aligned to the first hypothesised performance shape of a continuous performance decline were infrequently observed. Performance rarely declined in a purely linear fashion although some data trends were more linear with less periods of stable performance.

The most frequent trend of performance decline in association with multiple factors was periods of gradual performance decline interspersed with periods of performance maintenance (the third hypothesised shaped of performance decline), frequently followed by a final, steep performance decline in association with change to a specific multifactor group. This sudden decline in performance may represent the edge of performance, after which performance is not maintained and rapidly declines. Findings may have implications for preventing a steep performance decline. Recognition of a decline in human performance, prior to the steep performance decline, may permit compensation or supportive strategies to be implemented. This may facilitate a recovery of performance, and prevent a steep performance decline.

Findings suggest that efficiency-related performance declines prior to safety-related performance. A potential explanation for this finding is that under demanding conditions, participants may prioritise safety-related performance over efficiency-related performance. High task demands and multiple co-occurring factor influences may increase cognitive load and reduce cognitive capacity. As a result, participants may not be able to maintain high performance on multiple tasks (Schneider & Detweiler 1988). Participants shed or delay a lower priority task to enable reallocation of resources to a higher priority task. Prioritisation of tasks is recognised as an effective strategy to maintain performance, and in this way "experienced operators can maintain performance under stress by establishing [task] priorities" (Kontogiannis, 1999, p9). As safety was the primary priority of the study task, safety-related tasks were prioritised over efficiency-based tasks. This data trend was identified more regularly during the second high taskload period, supporting the notion that this effect occurs most frequently under high task demands, potentially as a strategy to maintain safety-related performance.

9.7 The association between posture and measured factors

The association between participants' posture and measured factors was investigated using Spearman's' correlation coefficient analysis. Table 9.7 summarises results of the association between posture and other factors.

Table 9.7. Spearman's correlation coefficient results for posture in association with measured factors.

Factor 1	Factor 2	Correlation coefficient and significance value
Posture	Workload	0.17, p=0.0005
Posture	Fatigue	0.1, p=0.16 NS
Posture	Stress	0.21, p=0.003
Posture	Arousal	0.14, p=0.059 NS

A significant positive relationship between posture and workload was reported (Figure 9.57), $r_s=0.17$, $p<0.001$. As workload increases, participants sit increasingly forward. In addition, stress and posture significantly positively correlated (Figure 9.58) ($r_s=0.21$, $p<0.005$).

Figure 9.57. Scatterplot of posture against workload

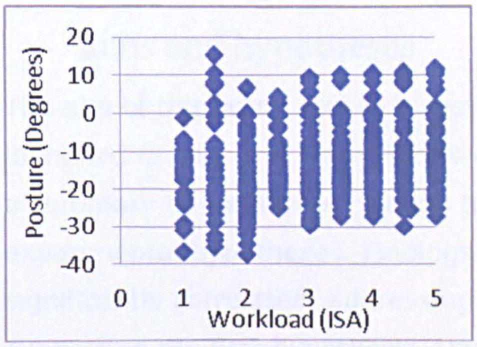
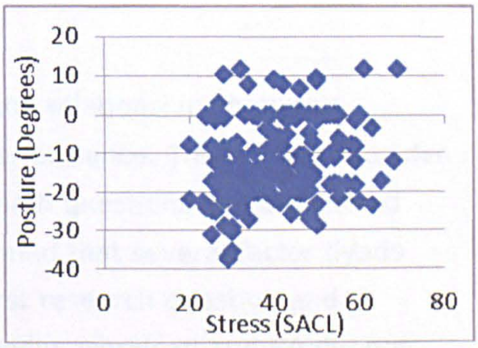
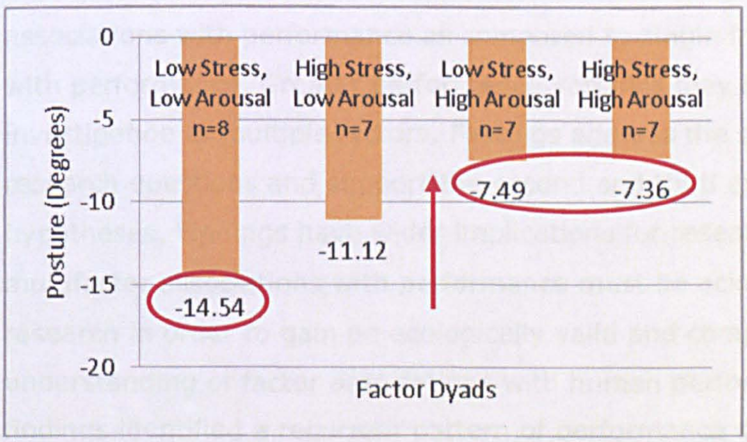


Figure 9.58. Scatterplot of posture against stress



A median split analysis was applied to the measure of participant posture to investigate posture changes in association with multiple factor groups (Figure 9.59) in high taskload 1. Mean posture was significantly more forward when associated with high stress and high arousal (M=-7.36, SD=9.34) than when associated with low stress and low arousal, W=43, $p<0.05$, *r*= -0.63.

Figure 9.59. Impact of stress and arousal on posture, high taskload 1



9.7.1 Discussion of the association between posture and measured factors

Significant, positive correlations were reported between posture and workload and posture and stress. Findings suggest that posture may be used as an observable indicator of experienced workload and stress.

9.8 Overall discussion of findings in association with research aims and hypotheses

The aim of this study was to investigate the relationships between identified factors and associations with performance. This section provides a summary of findings in relation to research questions and associated experimental hypotheses. Findings confirmed that several factor dyads significantly correlated, addressing the first research question and supporting the first hypothesis. Unexpectedly, workload and SA did not significantly relate. This finding may be due to challenges with the SPAM measures, discussed later in section 11.8. Findings also indicated that co-occurring factor dyads and triads may interact to have a cumulative association with performance. A greater performance decline was associated with specific factor dyads as compared to an association with only one of the factors in the dyad. This result was robust, occurring across a range of performance measures. In addition, more significant differences in performance were identified in analyses of factor dyad and triad associations with performance as compared to single factor associations with performance. Greater performance variance may be explained by the investigation of multiple factors. Findings address the second and third research questions and support the second and third experimental hypotheses. Findings have wider implications for research; it is argued that multifactor associations with performance must be acknowledged in future research in order to gain an ecologically valid and comprehensive understanding of factor associations with human performance. Finally, findings identified a recurrent pattern of performance decline that closely resembled the third hypothesised shape of performance decline. Performance frequently appeared to gradually decline in association with specific multifactor groups, interspersed with periods of maintenance, until a steep decline occurred. This shape may reflect participants' active management of performance, until the edge of performance is reached and performance rapidly declines. Implications of this finding are important for operational centres; if gradual performance decline are identified, supportive strategies may be able to be implemented to prevent a steep performance decline. Findings supported the fourth research aim and experimental hypothesis.

9.9 Chapter summary

This chapter presented results from an experimental study, outlined in the previous chapter (chapter eight). Naive participants took part in a computer-based cognitive task with en-route ATC elements. Taskload was manipulated as the independent variable to create variability in the data. The selected subgroup of factors (workload, fatigue, stress, arousal and SA) was measured through self-report scales. Performance was the dependent variable and measured in terms of safety and efficiency. Safety performance was measured by the frequency of short-term conflict alerts (STCAs) and efficiency was measured by the frequency of route directs, time to assume aircraft and time to respond to offered aircraft. Results are presented in accordance with research questions. Descriptive data is first presented which provides an overview of measures across the simulation. Findings on associations between each factor and performance, using correlation analyses, are subsequently presented. Findings of the covariance between multiple factors, and interactions with performance are then presented. Research findings of the nature of performance decline around the edge of performance are described. Differences in safety and efficiency-related performance are presented. The chapter concludes by stating that each research question was addressed. In spite of some experiment and statistical analyses limitations, results suggest interactions between factors may occur to have a greater negative association with performance. The next chapter (Chapter 10) continues the presentation of experimental results by presenting findings of participant behaviours in association with performance.

Chapter 10. Indicators of potential performance decline: Findings from an experiment study and interview study

10.1 Chapter Overview

This chapter presents findings collected during the previous experiment (Chapter 8) and an interview study with en-route air traffic controllers that investigate indicators of potential performance decline. Findings from the experiment study are presented first. Findings support an association between specific participant behaviours and the potential for participant performance decline. Findings were extended with an interview study conducted with en-route ATCOs, which is subsequently presented in section 10.3. The study aimed to investigate the use of indicators in ATC, and identify specific indicators of performance decline. Findings confirmed that controllers use both internal, subjective indicators and overt, objective indicators as markers of potential performance decline, for their own performance and for colleagues' performance.

10.2 Continuation of experimental study findings: Observed participant behaviours

10.2.1 Observed participant behaviours: Method

Data was recorded as part of the experiment trial as previously described in Chapter 8.

10.2.2 Observed participant behaviours: Process to refine observed behaviours as indicators of potential performance decline

Behaviours were observed throughout the experiment trial. For analysis, the observed behaviours were summed for each 20 minute taskload period (excluding transitions). A total of 137 participant behaviours were recorded (Appendix 15). It was not practical to investigate the association between 137 behaviours and five single factors (workload, fatigue, stress, arousal, SA) and four performance measures (frequency of STCAs, frequency of route directs, time to assume aircraft, time to respond to offered aircraft). The behaviour set was therefore reduced through a refinement process, documented in sections 10.2.2.1. and 10.2.2.2.

10.2.2.1 Refinement consideration 1: Sensitivity to changes in the experienced level of each factor and changes in performance

Previous findings indicated that an association existed between taskload and self-reported factors (section 9.2.2). Therefore if participant behaviours were indicative of experienced factors, it was expected that the frequency of the observed behaviours will also vary in association with taskload periods. The discrepancy in behaviour frequency between high and low taskloads was calculated. The range of frequency differences was suggested to reflect the sensitivity of the marker - a larger difference may indicate a large association between the behaviour and factor.

Any marker that had a total difference of 10 points or less between taskloads was removed. This low score suggested that indicators did not vary with the taskloads, and were therefore not sensitive to subjective experience. This cut score was arbitrary in that the number 10 only represented a low variation in behaviour frequency. However, the cut score was supported by a visual examination of the data. Frequency patterns of behaviours with a total discrepancy between taskloads of 11 or more were more consistent and observable.

A total of 82 behaviours were removed, leaving 55 behaviours. The number of participants that demonstrated the removed behaviours ranged from 1-16 although the majority of behaviours (89%) were demonstrated by less than six participants. Behaviours that were less sensitive also appeared to be less common between participants. Behaviours recorded for 6 or more participants (14 indicators, 17%) were reviewed in case the arbitrary cut point had excluded factors incorrectly. However, behaviour frequencies did not vary in association with taskload, and so were excluded from further analysis.

10.2.2.2 Refinement consideration 2: Commonality of indicators between participants

Data were examined for the frequency of participants exhibiting observed behaviours. Only indicators that were common between individuals, and not idiosyncratic, were of interest. Indicators that were exhibited by three or less individuals were excluded from analysis. The cut point was relatively arbitrary, but was supported by visual review of the data. Behaviours exhibited by four or more individuals became more consistent in associations with taskload phases. Three additional behaviours of the remaining 55 (9.09%) were excluded from further analysis.

10.2.3 Refined set of behavioural indicators

After applying the refinement criteria, 52 of the original 137 behaviours were selected analysis. Table 10.1 presents the summed discrepancy in behaviour frequency between taskload periods, indicating sensitivity to taskload variation, and the number of participants that demonstrated the behaviour. Results are ordered by the summed discrepancy in behaviour frequencies between taskload periods.

Table 10.1. List of behavioural indicators included in analysis, ordered by the summed difference between taskloads

	Summed frequency of occurrence per 20 minute taskload phase						
Behavioural indicators	1-20m LTL1	25-44m HTL1	49-68m LTL2	73-92m HTL2	97-116m LTL3	summed difference	Participant 'n'
Sat forward towards screen	55	178	43	161	36	501.00	29.00
Sat back	36	21	71	12	71	183.00	27.00
Itch face	88	29	76	32	58	176.00	22.00
Mouth open	44	56	30	72	26	126.00	22.00
Hand off mouse	25	4	25	3	57	118.00	17.00
Forgetting	5	45	12	21	19	84.00	27.00
Sigh	69	94	83	63	89	82.00	29.00
Little movement/still	29	4	21	10	17	60.00	27.00
Bang mouse	30	48	37	21	30	54.00	14.00
Mouthing' instructions under breath	15	37	20	17	22	47.00	15.00
Smile	9	10	4	22	2	45.00	14.00
Tapping fingers	29	5	11	6	15	44.00	14.00
Negative verbal words	3	14	2	11	1	42.00	12.00
Rub face/neck	13	26	18	22	40	42.00	6.00
Shift position/move in chair	27	37	32	25	44	41.00	28.00
Swearing	1	14	4	11	2	39.00	6.00
Glance away from screen	10	2	8	6	28	38.00	17.00
Shake head	6	20	9	11	2	36.00	20.00
Open hand	2	13	0	6	1	35.00	5.00
Cradle face	16	27	17	21	12	34.00	12.00
Worried – face tense	3	17	6	7	2	31.00	14.00
Drink	14	1	6	2	10	30.00	8.00
Itch head	14	20	20	9	22	30.00	12.00

Pull mouth	60	49	36	39	36	30.00	23.00
Eyebrows pulled together-frown	14	26	22	23	11	29.00	18.00
Grouped controlling	0	7	1	8	0	28.00	11.00
Slump down in seat	4	2	5	2	21	27.00	13.00
Yawn	1	0	5	1	18	27.00	9.00
Pout	28	33	23	29	15	25.00	18.00
Hmm'	0	5	2	9	0	24.00	6.00
Press lips together	54	45	34	30	30	24.00	21.00
Head down (chin towards chest)	1	5	7	2	14	23.00	13.00
Jerky and sudden movements	14	1	4	3	9	23.00	14.00
Lick lips	40	28	28	32	25	23.00	22.00
Slow, considered actions	10	0	5	0	3	23.00	12.00
Verbal expressions of panic/no idea	1	8	2	6	0	23.00	7.00
Face red	1	9	1	4	1	22.00	7.00
Suck in breath	1	7	1	6	1	22.00	11.00
Clicking inaccuracy/errors	5	14	12	11	19	20.00	24.00
Suck bottom lip	4	11	1	3	4	20.00	4.00
Squinting	21	10	12	10	14	19.00	16.00
Scrunch lips to side of face	21	22	10	12	15	18.00	15.00
Eyebrows together and up – puzzled?	6	10	5	7	1	17.00	7.00
Release/forceful blow of air	2	7	5	9	4	16.00	15.00
Itch neck	6	12	15	10	11	15.00	15.00
Negative verbal sounds	1	4	0	5	2	15.00	8.00
Teeth/jaw clenched	2	7	2	5	3	15.00	7.00
Negative verbal expressions	1	5	0	3	1	14.00	4.00
Tut	2	9	8	5	2	14.00	11.00
Chew inside cheek	0	4	2	7	6	12.00	6.00
Jerky head movements	3	5	2	5	1	12.00	11.00
Stretch	1	0	2	1	9	12.00	6.00

10.2.4 Observed participant behaviours: Statistical analysis approach

Correlation analyses were used to investigate the relationship between observed behaviours and measures of workload, fatigue, stress, arousal and SA as well as performance measures (frequency of STCAs, frequency of route directs, time to assume aircraft, time to respond to offered aircraft). Spearman's correlations were used as data violated the parametric assumption of independence.

10.2.5 Observed participant behaviours: Results and discussion

10.2.5.1 Overview

Table 10.2 presents Spearman's correlation coefficients for each behavioural marker correlated with factor and performance measures across five taskload periods. Correlation coefficients presented in bold are significant at a p<0.05 level. Because of the low n (5) sporadic results may have occurred. In addition, significance is only utilised here to indicate possible relationships and data trends and is not considered conclusive. Data trends of particular interest are presented below.

Table 10.2. Spearman's Correlation coefficient for behavioural indicators, self reported factors and performance measures across 5 taskload periods

Marker	Workload	Fatigue	Stress	Arousal	SA	Posture	STCA	RD	Time to respond to offered aircraft	Time to assume aircraft
Sat forward	**0.9**	-0.2	**1**	**1**	0.5	**0.9**	0.5	-0.6	0.88	0.66
Sat back	**-0.97**	-0.05	-0.87	-0.87	-0.21	**-0.97**	-0.67	0.82	-0.82	-0.67
Itch face	-0.50	-0.60	-0.60	-0.60	0.30	-0.50	**-0.90**	0.80	-0.60	-0.80
Mouth open	**1.00**	-0.10	**0.90**	**0.90**	0.30	1.00	0.60	-0.70	**0.90**	0.70
Hand off mouse	**-0.97**	0.05	-0.87	-0.87	-0.21	**-0.97**	-0.67	0.67	**-0.97**	-0.82
Forget aircraft	0.50	0.60	0.60	0.60	-0.30	0.50	**0.90**	-0.80	0.60	0.80
Sigh	-0.4	0.2	0.0	0.0	0.0	-0.40	0.0	0.1	-0.3	-0.1
Still	-0.50	-0.60	-0.60	-0.60	0.30	-0.50	**-0.90**	0.80	-0.60	-0.80
Bang mouse	-0.21	-0.31	0.21	0.21	0.41	-0.21	-0.21	0.36	-0.05	-0.05
Mouthing instructions	-0.20	0.50	0.10	0.10	-0.30	-0.20	0.40	-0.20	0.00	0.30
Smile	**1**	-0.1	**0.9**	**0.9**	0.3	1	0.6	-0.7	**0.9**	0.7
Tap fingers	-0.6	-0.3	-0.7	-0.7	0.1	-0.6	-0.8	0.6	-0.8	**-0.9**
Negative words	**0.9**	-0.2	1	1	0.5	**0.9**	0.5	-0.6	0.8	0.6
Rub face	-0.2	**0.9**	-0.1	-0.1	-0.7	-0.2	0.6	-0.5	-0.1	0.3
Shift position	-0.70	0.4	-0.4	-0.4	-0.4	-0.7	-0.1	0.2	-0.6	-0.3
Swearing	0.6	0.3	0.7	0.7	-0.1	0.6	0.8	-0.6	0.8	**0.9**
Glance away	-0.80	0.10	**-0.90**	**-0.90**	-0.30	-0.80	-0.60	0.50	**-0.90**	-0.80
Shake head	0.8	-0.1	**0.9**	**0.9**	0.3	0.8	0.6	-0.5	**0.9**	0.8
Open hand	0.8	0.1	**0.9**	**0.9**	0.3	0.8	0.6	-0.8	0.6	0.5
Cradle face	0.80	-0.10	**0.90**	**0.90**	0.30	0.80	0.60	-0.50	**0.90**	0.80
Worried	0.8	-0.1	**0.9**	**0.9**	0.3	0.8	0.6	-0.5	**0.9**	0.8
Drink	-0.60	-0.30	-0.70	-0.70	0.10	-0.60	-0.80	0.60	-0.80	**-0.90**
Itch head	-0.82	0.36	-0.56	-0.56	-0.36	-0.82	-0.21	0.36	-0.67	-0.36
Pull mouth	0.56	-0.56	0.67	0.67	0.82	0.56	-0.15	-0.21	0.21	-0.15
Frown	0.80	-0.10	**0.90**	**0.90**	0.30	0.80	0.60	-0.50	0.90	0.80
Grouped controlling	0.82	0.21	0.72	0.72	-0.10	0.82	0.82	-0.67	**0.97**	**0.97**
Slump	**-0.98**	0.15	**-0.98**	**-0.98**	-0.41	**-0.98**	-0.56	0.67	-0.87	-0.67
Yawn	-0.82	0.36	**-0.98**	**-0.98**	-0.67	-0.82	-0.31	0.46	-0.67	-0.41
Pout	**0.9**	-0.2	1	1	0.5	**0.9**	0.5	-0.6	0.8	0.6
Hmm	0.82	0.21	0.72	0.72	-0.10	0.82	0.82	-0.67	**0.97**	**0.97**
Press lips	0.1	-0.87	0.36	0.36	**0.96**	0.1	-0.62	0.41	-0.1	-0.46
Head down	-0.70	0.60	-0.60	-0.60	-0.70	-0.70	0.10	0.20	-0.40	0.00
Jerky	-0.60	-0.30	-0.70	-0.70	0.10	-0.60	-0.80	0.60	-0.80	**-0.90**

movements										
Lick lips	0.62	-0.67	0.46	0.46	0.67	0.62	-0.21	-0.05	0.36	-0.05
Slow actions	-0.56	-0.67	-0.56	-0.56	0.41	-0.56	**-0.98**	0.87	-0.67	-0.87
Verbal panic	0.8	-0.1	**0.9**	**0.9**	0.3	0.8	0.6	-0.5	**0.9**	0.8
Face red	0.78	0.22	0.89	0.89	0.11	0.78	0.78	-0.78	0.78	0.78
Suck in breath	0.78	0.22	0.89	0.89	0.11	0.78	0.78	-0.78	0.78	0.78
Clicking inaccurate	-0.50	0.70	-0.30	-0.30	-0.60	-0.50	0.30	-0.10	-0.30	0.10
Suck lip	0.1	0.1	0.41	0.41	0.31	0.1	0.1	-0.36	-0.15	-0.15
Squint	-0.67	-0.36	-0.67	-0.67	0.21	-0.67	-0.87	0.67	-0.87	**-0.98**
Scrunch lips	0.2	-0.1	0.5	0.5	0.5	0.2	0.0	-0.3	-0.1	-0.2
Puzzled	**0.90**	-0.20	1.00	1.00	0.50	**0.90**	0.50	-0.60	0.80	0.60
Release air	0.7	0.4	0.6	0.6	-0.3	0.7	**0.9**	-0.7	**0.9**	**1**
Itch neck	-0.30	0.10	-0.10	-0.10	-0.20	-0.30	0.10	0.30	0.10	0.30
Negative verbal sounds	0.7	0.6	0.6	0.6	-0.3	0.7	**0.9**	-1	0.6	0.7
Jaw clenched	0.56	0.56	0.67	0.67	-0.21	0.56	0.87	-0.87	0.56	0.72
Negative verbal expressions	0.72	0.31	0.82	0.82	0.1	0.72	0.72	-0.87	0.56	0.56
Tut	0.41	-0.1	0.62	0.62	0.21	0.41	0.41	-0.15	0.67	0.67
Chew inside cheek	0.30	**0.90**	0.10	0.10	-0.80	0.30	**0.90**	-0.80	0.40	0.70
Jerky head movements	**0.97**	-0.15	**0.97**	**0.97**	0.41	**0.97**	0.56	-0.67	0.87	0.67
Stretch	-0.82	0.36	**-0.98**	**-0.98**	-0.67	-0.82	-0.31	0.46	-0.67	-0.41

10.2.5.2 The relationship between observed participant behaviours and self-reported factors

Jerky and rapid head movements are significantly correlated with workload, possibly because participants need to scan faster with the presence of more aircraft. Negative verbal statements are also significantly positively correlated with workload. Fatigue is significantly related to only two indicators. There is no clear indication of why these relationships have occurred and they may be spurious. Unexpectedly, fatigue did not significantly correlate with yawning. The relationship was in the expected direction, although weak. This may be a result of low n(5) affecting statistical power. The findings for stress and arousal are identical. This was not expected and the reasons are unclear. It may be that the reduction of the data created the same pattern of variation occurred between stress and arousal. When measures were averaged across 20 minute taskload periods, correlation findings may have co-varied to a similar extent. Alternatively, it may be that observable behaviours may not be sensitive enough to differentiate between the related concepts of stress and arousal.

Stress and arousal significantly positively correlated with several indicators, again in the direction expected. For example, glancing away from the screen is significantly negatively correlated with stress, suggesting that if stress is high participants are more focused on the screen. If stress/arousal is low, participants may glance from the screen more often. Finally, yawning was significantly negatively associated with stress and arousal.

10.2.5.3 Relationships between participant behavioural indicators and measures of performance

STCAs are significantly positively correlated with observed instances of forgetting aircraft. In addition, STCAs are also significantly positively correlated with negative verbal sounds which may be expected. Frequency of route directs do not significantly relate with any marker. This may be because this efficiency-related action is a lower priority and may correlate more with workload than behavioural indicators or underlying cognitive state. Time to respond to offered aircraft is related to several indicators. Some relationships appear counter-intuitive. For example, glancing away from screen and frequency of participant taking their hand off of the mouse are both significantly negatively associated with time to respond to offered aircraft. If participants have a lower workload, which is also significantly associated with glancing away from the screen, participants may also have the capacity to respond to aircraft faster. It is suggested that higher demands on the participant may lead to negative expressions such as swearing, and efficiency tasks such as time to respond to offered aircraft are not prioritised.

The investigation of indicators of performance decline had both theoretical and practical motivations. Identification of behavioural indicators that may be associated with performance will contribute to the relatively sparse literature on behavioural indicators of performance (Sharples et al., 2012). A practical application of the findings is a contribution to identification of indicators of potential performance decline.

10.3 Interview study with en-route air traffic controllers

10.3.1 Interview study: Aims

The aim of this study was to generate expert opinion regarding the indicators of potential performance decline in an ATC setting. An additional aim was to identify indicators that were commonly associated with specific factor influences on performance.

10.3.2 Pilot study: Focus groups

A focus group study was conducted to investigate if indicators of potential performance decline were used in an ATC setting. It was necessary to gain support for this concept from a sample of ATC professionals prior to investing additional time and resources into a detailed investigation. In addition, the focus group served as a pilot study.

10.3.2.1 Pilot study: Aim and research questions of the focus group study

The aim of the pilot study was to investigate the concept of indicators of performance decline within an ATC setting.

10.3.2.2 Pilot study: Method of focus groups

10.3.2.2.1 Design

One semi-structured focus group interview, lasting a total of 160 minutes, including a 20 minute refreshment break, was conducted as a pilot study to investigate expert opinion on the use of indicators of potential performance decline in ATC settings. The focus group interview, defined as an interactive, discussion-based interview with a small group of participants (Millward, 2006) was selected as the expert knowledge elicitation method for the pilot study as it "stimulates memories, discussion, debate and disclosure in a way that is less likely in a one-to-one interview" (Millward, 2006, p279). Participants were three ex-controllers. The focus group took place in a large meeting room at the EUROCONTROL Experimental Centre. Participants were fully informed about the research aims. To facilitate disclosure, confidentiality was emphasised. An interview schedule guided the progression of discussion topics. Participants were asked a total of 15 lead, open-ended questions (e.g. "What is your understanding of indicators of potential performance decline?"). The interview schedule was reviewed independently by two human factors' professionals prior to use. Probing questions were used to follow up participant responses. The focus group was recorded via two dictaphones, and the moderator made written notes. The recordings were transcribed and a thematic analysis was conducted. The focus group used an essentialist position approach and focused on the intensity and frequency of themes as opposed to the "processes of social interaction" (Millward, 2006, p279) which is a priority in the social constructivist approach.

10.3.2.2.2 Selection of factors for inclusion

Participants were asked to specify indicators of potential performance decline in relation to a selection of human factors: Workload, fatigue, stress, SA, communications, teamwork. This factor set was identified for inclusion in studies during the second research stage (Chapters 5-7). There are some differences to this factor set compared to the factors included in the experimental study. Teamwork and communications were reintroduced in this interview study as it was feasible to do so. Arousal is no longer included. Arousal was specifically included in the experimental study only as Cox and Mackay (1985) recommend to measure stress and arousal concurrently.

10.3.2.2.3 Participants

Participants were three ex-ATCOs based at EUROCONTROL experimental centre (one female and two males). An opportunity sample was used to select participants. Participants were required to have previous experience as an en-route controller. Participants' age ranged from 51-60. Participants responded to grouped age ranges and so an average cannot be determined. Experience in en-route ATC ranged from 14 years – 27 years, with an average of 20.33 years. Participants controlled in different countries: Ireland, Sweden and the UK. Participants knew each other from the same work place, and were role-homogenous.

10.3.2.2.4 Materials

The focus group was conducted using a question schedule. Topics were selected to address the research questions and in addition, explore related topics to gain a wider understanding of the concept and use of indicators of performance in an ATC setting. The question categories were designed to begin with general questions relating to experience of performance limits and indicators, and narrowing focus to specific indicators and the meanings of those indicators. The focus group was semi-structured and participant responses to lead questions were followed with appropriate probes; participants were also encouraged to discuss other topics which they felt were related but had not been addressed in the lead questions.

Other materials included an introduction to the focus group, an informed consent form, a demographic questionnaire and a debrief. The session was recorded using two Olympus DSS Standard digital recorders.

10.3.2.2.5 Procedure

Ex-controllers based at the EUROCONTROL Experimental Centre (EEC) were identified by the industrial sponsor and were invited to take part in the study. On the day of the session, as per Breen's (2006) recommendations, participants were welcomed into the room and offered refreshments. Participants were asked to read the Introduction to the Session document and sign the informed consent form if they were happy to continue. Participants then completed the demographic questionnaire. The session was then structured according to the interview schedule. A process-facilitation style of moderation was selected which advocates low control over what is discussed, but control over the process and interactions between participants. This moderator style ensured that all topics of interest were discussed, and maximised involvement from each participant. After 80 minutes participants had a 20 minute refreshment break. The session was reopened with a recap of discussion points. The focus group lasted for a total of 160 minutes. Once the question schedule was complete participants were asked if they had any further comments. The session was then closed. Participants received a debrief and were then thanked for their time. The session was recorded with a digital recorder and was transcribed for analysis.

10.3.2.3 Pilot study: Strategy of analysis

The session recording was transcribed orthographically. A thematic analysis was selected to identify meaningful themes.

10.3.2.4 Pilot study: Focus group results and discussion

All participants agreed with the concept of a performance 'edge' or 'limits' and suggested that controllers instinctually sense when they have the potential for performance decline. A distinction was made between indicators that were internal to the controller (e.g. feeling nervous or uncomfortable with the traffic situation) and indicators that were overt (e.g. changing voice pitch and speed). All participants agreed that both internal and external indicators are used by controllers to determine when they or colleagues are susceptible to potential performance decline. All participants agreed that some indicators were specific to experienced factor influences. For example, participants identified that if a colleague was fatigued, indicators of a potential performance decline may be slower reactions or falling behind traffic. Agreement with these concepts provides support for further investigation of the use of indicators of potential performance decline in ATC.

Participants agreed that the factor set included for discussion was meaningful. However, all participants recommended a separate category for vigilance. It was expressed that different indicators were associated with vigilance issues as compared to SA issues. Therefore, SA and vigilance will be included as separate categories in the next study. Vigilance was combined with attention and presented to participants as one category, for completeness. Participants had the option of responding to vigilance and attention separately, although based on previous findings (see Chapter 6) many controllers do not colloquially differentiate between attention and vigilance.

Overall, participants agreed that the questions were meaningful and presented in a logical order. However it was identified that participants found it difficult to respond to direct requests to specify indicators. Asking participants to share their experience of specific situations which included indicators elicited more information. This will influence the creation of the design of future questions. It is possible that this effect arose from the use of indicators becoming 'instinctual' with experience and therefore used automatically with less conscious awareness.

The group dynamic may have influenced participant responses. One participant forcefully emphasised that indicators, although used in ATM settings, cannot be indicative of specific issues; *"Looking for handy indicators is kind of like taking the easy way out"*. Other participants initially disagreed, and gave several examples of indicators having clear meanings. For example, one participant stated *"When you get to the 'err...err...' then you really are in a problem"*. However, after several discussions participants began to moderate personal views to suggest that indicators may or may not be indicative of specific issues. A motivation bias to not be associated with reaching performance limits when working as a controller may have influenced participant responses. To control for this, an interview method will be used in the subsequent study.

10.3.3 Semi-structured Interviews

10.3.3.1 Semi-structured interviews: Method

10.3.3.1.1 Semi-structured interviews: Design

A total of 22, one hour semi-structured interviews were conducted with en-route ATCOs using a face-to-face medium to gain an understanding of the use of indicators of reaching performance limits in ATC. The semi-structured interview enabled topics of interest to be investigated whilst providing the flexibility to investigate relevant topics raised by the participant. The sample was purposive, and the number of interviews was based on pragmatic considerations such as time and the number of ATCOs for which shift cover could be arranged. Participants were selected based on group characteristics including age, experience and nationality. The interviews took place in the Maastricht Upper Area control centre (MUAC) in an office opposite the operations room. The location was familiar and convenient to participants. An interview schedule was developed to guide the semi-structured interview; participants were asked pre-designed lead questions which were then followed by probes. A protocol was used to standardise the interview method procedure. Interviews were recorded with two dictaphones, with the prior informed consent of participants, and the researcher took written notes. The interviews were then orthographically transcribed and thematic analysis was applied as the analysis strategy.

10.3.3.1.2 Semi-structured interviews: Factors -specific indicators of performance decline

Participants were asked to list indicators of potential performance decline that were perceived to be the associated with a specific factor (e.g. "What indicators of potential performance decline are associated with the influence of fatigue on performance?"). The factors included in the interview study were: workload, fatigue, stress, attention/vigilance, communications, and teamwork.

10.3.3.1.3 Participants

In total 22 en-route controllers were interviewed. The majority of participants were male (17, or 77.27%), compared to female participants (5, or 22.73%). All participants worked as en-route controllers in the Maastricht Upper Airspace control (MUAC) centre. Participants' ages ranged from 21-60. Participants responded to grouped age ranges and so an average age cannot be calculated. A total of five participants (22.72%) were in the 21-30 ages range, a majority of nine participants (40.9%) were in the 31-40 age range. A total of seven participants (31.81%) responded to the 41-50 age range and one participant was in the 51-60 age range (0.05%). All participants were qualified ATCOs who had completed training. Years of experience as an ATCO (excluding training) ranged from 1.5-31 (M=14.55, SD=8.68). A total of 15 participants had worked as an on the job training instructor (OJTI). Years of experience as an OJTI ranged from 2-25 years (M=10.93, SD=7.11). In total six participants were also supervisors. Experience as a supervisor ranged from 1.5 to 11 (M=6.08 years, SD=3.56). Participants were of eight nationalities: Austrian (two participants, 9.09%), Belgian (four participants, 18.18%), Bulgarian (one participant, 4.55%) English (five participants, 22.73%), Denmark (one participant, 4.55%), Dutch (three participants, 13.64%), German (four participants, 18.18), Irish (two participants, 9.09%). Participants were recruited by MUAC centre managers and were selected to represent several sub-groups of controllers, based on age, sex, experience, role and nationality. The sample was therefore a non-probability purposive sample.

10.3.3.1.4 Semi-structured interviews: Materials and equipment

An interview schedule was designed to structure the interview. The interview comprised of 11 lead, open-ended questions which related to five areas of interest:

1. Current use of indicators in ATC settings
2. Internal and external indicators of performance limits
3. Indicators associated with specific factors
4. Levels of awareness of own indicators and colleagues' indicators
5. Generalisation of indicators between controllers

The interview schedule was reviewed and approved by two human factors experts and two ex-controllers. The interview began with an open question which asked the participant to talk about a time when they experienced themselves or a colleague reaching the edge of their performance. This was designed to enable the participant to share their own experience easily and permit further follow-up questions regarding the indicators that told them they were reaching the edge of performance. The lead questions were arranged from general topics (e.g. "Could you please tell me about a time in the recent past when you identified that either yourself or a colleague was nearing the edge of your performance?") to more specific questions (e.g. "To what extent are the indicators you've specified common between controllers"). This format was selected to lead participants through the topics in a logical progression, without unnecessary 'jumps' between topics (Millward, 2006). The question wordings were similar to the pilot study based on the previous positive feedback. Examples of indicators were use in the lead question to facilitate participants' understanding. The same indicators were used in examples for all participants (Millward, 2006).The interview was recorded on two Olympus DSS Standard digital recorders.

10.3.3.1.5 Semi-structured interviews: Procedure

All interviews were conducted in a quiet office next to the MUAC operations room, which was convenient for participants. Interviews lasted for one hour. This period of time was allocated by the centre managers, although was sufficient to discuss the topics of interest.

A standardised protocol was followed for each interview. The participant was welcomed and offered refreshments. The participant read the standardised introduction and was then asked to sign an informed consent form if she/he was happy to continue with the interview. The participant then completed a demographic questionnaire. The participant was asked for permission to record the interview session and the digital recorders were started. The interview schedule was then followed. After the questions had been completed, the participant was asked if she/he had any other comments. The participant was then given a paper copy of the standardised debrief which contained the researcher's contact details. The audio recording was subsequently transcribed for analysis.

10.3.3.2 Semi-structured interviews: Strategy of analysis

Interviews were transcribed orthographically. A thematic analysis was selected as the analysis strategy. A quantitative content analysis was not considered appropriate due to the implicit assumption that more frequent themes are more important than others, which may not be applicable to the current data. Indicators may not have been raised for several reasons, including motivation biases. No identifying information is stored in the transcription, and any data used in analysis was anonymous. Where it is necessary to use quotations from the session, participants will remain anonymous.

10.3.3.3 Semi-structured interviews: Results

A total of 22 one-hour interviews were orthographically transcribed and analysed using thematic analysis. Recurrent and relevant themes are presented below with illustrative quotes from participants. The presentation of results is organised by the order of research aims and topics of interest included in the question schedule. Other relevant themes that emerged are subsequently presented.

10.3.3.3.1 Controllers' understanding of indicators of potential performance decline

All participants (22/22) were familiar with the concept of indicators and agreed that they occurred in the ATC operations room. In general, participants characterised indicators as indicators that a controller was not feeling comfortable with the control task, and indicated when a controller was moving towards the edge of performance: *"The indicators are part of losing the control or going towards the limits or crossing the limits [of performance]. So it's not like the limit is here and you see the indicators, and then suddenly bang, you run over. The indicators are part of it on the way down to losing control" (Participant 21).* Indicators cannot be conceptualised strictly as indicators of performance. Performance may not change in the presence of negative influences or controller discomfort due to adaptive mechanisms that protect performance. Rather, indicators indicate that the controller may not be controlling comfortably, and may be experiencing negative influences from factors.

10.3.3.3.2 Use of indicators of potential performance decline in air traffic control

All controllers stated indicators are commonly used in ATC to provide information regarding when a controller may not be controlling optimally, or a factor (such as fatigue, stress) is negatively influencing performance. All controllers monitor their own personal indicators as well as colleagues' indicators: *"...We work close together, we monitor each other you would be very aware of the person sitting beside you whether they're on the ball or whether they're slightly less, whether they're tired, whether they're distracted by whatever or something, it's part of the job and you do, you make allowances" (Participant 2)*. This was perceived as a natural process that *"you don't think about...I just do it like it's a brain process that isn't conscious" (Participant 2)*. Another controller stated *"I think it's a natural thing to look for signs" (Participant 11).* Controllers used indicators for the primary functions of gaining information which subsequently led to supporting performance.

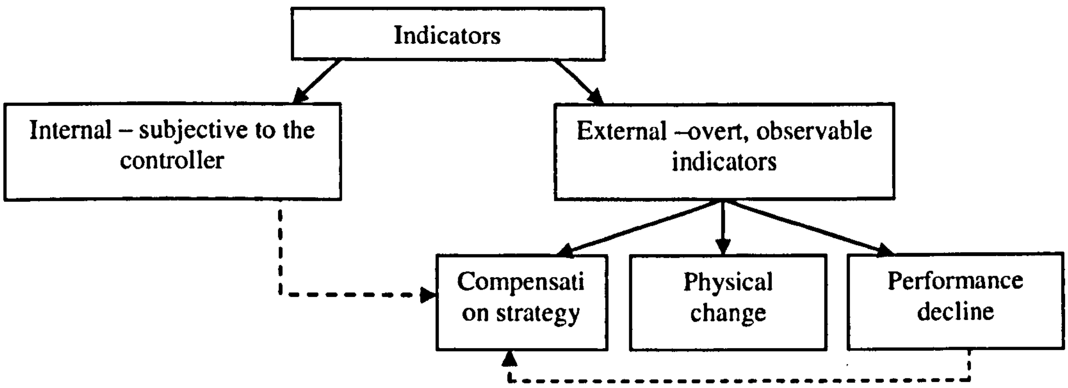
After identification of a marker, controllers interpreted the meaning based on previous experience and frequently applied a supportive mechanism such as a change in control strategy to mitigate the issue that was negatively influencing the controller: *"...it's that point [of recognising something is wrong] where you have to, well in my opinion you have to change the way that you're controlling the traffic" (Participant 10)*. This process occurs both for controllers to support their own performance, and controllers who apply adaptive strategies to support their colleagues' performance: *"If someone's getting stressed they can get louder or sit closer to the screen or something so if you see these things then you pay more attention yourself." (Participant 20)*. The perception and use of indicators in ATC is a critical element in maintaining a consistently high task performance.

The application of the compensation strategy can result in the maintenance of performance even when associated with negative factor influences. The experienced negative influence may therefore not be reflected in the controllers' performance even though the influence is present. Therefore, some indicators will not strictly associate with ATCO performance, but rather the ATCO's subjective state.

10.3.3.3.3 Categorisation of indicators used by air traffic controllers

Figure 10.1 provides an initial broad categorisation of indicators based on qualitative data from controllers. It should be noted that the categories are not mutually exclusive. A marker can be both experienced internally and also overtly reflected in performance, such as a feeling of being 'slow' and falling behind with traffic. Participants distinguished between internal, subjectively experienced indicators and external, observable indicators.

Figure 10.1.Categorisation of indicators produced from qualitative data



Internal indicators

Internal indicators may alert the controller to specific state or negative influence on performance: *"I know that when I start thinking, 'Oh it's going fine' I've learned that I force myself to tighten the bolts and to really pay extra attention" (Participant 1)*. Another said that they change their control strategy *"when I start getting a little bit nervous" (Participant 2)*.

External indicators

By contrast, external indicators are overt and observable. Three broad sub-categories of external indicators emerged from participant responses (Figure 10.1). Changes to a controller's performance, such as a performance decline, serve as an external marker to the controller his/herself and their colleagues that the controller may not be comfortable. One participant explained: *"When people are controlling you expect a specific performance meaning that they are not going to give too many unnecessary clearances to the aircraft...if you have people doing, this giving an alternative level for no reason then you just start to wonder,* *'Why is he doing this?' Okay, he does it once. He was not paying attention on this one. He does it twice and then you start wondering, 'Well it's not his day'" (Participant 1)*. Another sub-category of external indicators is behavioural and physical changes in a controller. Examples include a face becoming red, or fidgeting, which provide information to other controllers: *"You see it coming, you see them getting nervous, you see them talking faster" (Participant 2)*.

Adaptive changes to the control strategy to mitigate negative influences on performance are a sub-category of external indicators. Compensation strategies as indicators indicate that a controller is feeling uncomfortable, but is aware of the potentially negative influence, and is attempting to protect and maintain performance. As one controller summarised *"When somebody is just extra careful, I suppose that it's because they feel that they have to be extra careful" (Participant 1)*. If a controller is aware of internal indicators, a compensation strategy may be selected and applied. This is represented in Figure 10.1 by an arrow with a dashed line connecting the internal marker to the compensation strategy. This is then observable in the method of controlling. Alternatively, a decline in performance may alert the controller that a compensation strategy is required to protect performance. This is represented by an arrow with a dashed line connecting performance decline and compensation strategy. In addition, colleagues may observe the controller's performance decline and apply their own compensation strategy to support the controller's performance.

10.3.3.3.4 Sub-categories of external indicators may provide distinct information

Performance declines or errors may provide a more serious indication that a controller is experiencing difficulties with the task. Controllers appear to place weight on this category of indicator and provide support in response to these indicators: *"If I see that someone is correcting themselves very often then I would pay a lot of attention to what he's actually doing or a lot more let's say...I start looking out for things where I really follow every single clearance. I will try to focus more on what my controller is doing and try to support as well like giving hints" (Participant 11)*.

A physical change (e.g. red face, yawning, laid back posture) may indicate a change in controllers' cognitive state (Sharples, Edwards, Balfe, Wilson & Kirwan, 2012), although may not be related to feelings of discomfort. Controllers suggest that the meanings of indicators are dependent on the context.

Adaptive changes in control strategy inform colleagues that the executive controller (EC) is experiencing discomfort with the control task (the reason for discomfort may not be observable), although the EC is aware of this and is attempting to protect and maintain performance with the application of a compensation strategy.

10.3.3.3.5 External indicators may mean different things depending on context

Indicators may mean different things depending on the control context. Participant 1 suggested: *"As a coordinator controller you follow what the executive is doing and there is a variety of complexity levels for situations and if it's an easy situation, a very crystal clear solution to a problem and then you see that the person is not applying it straightaway it triggers maybe a little alarm in your head"*. This may have been interpreted differently during a high taskload. Controllers use experience and knowledge of the control situation to interpret the meaning of the indicator.

10.3.3.3.6 Indicators of specific factor influences

Participants were presented with a list of factors [workload, fatigue, stress, vigilance, SA, teamwork] accompanied by standardised definitions, the same as those that were used in the expert knowledge elicitation study (Chapter 6). Participants were asked to identify internal or external indicators that they believed to be associated with a specific influencing factor. Although not contained in the study questions, all participants naturally reported adaptive compensation strategies that were applied in response to the detection of potential performance decline. These strategies can also serve as observable indicators. Therefore compensation strategies that controllers use in response to factor influences are also listed.

10.3.3.3.7 Workload

Controllers differentiated between high workload, low workload, and transitions between workload extremes. Each form of workload was reported to be associated with different indicators.

High workload

Participants reported internal (Table 10.3) and external (Table 10.4) indicators of potential performance decline that were associated with high workload. Findings were grouped into suggested categories. Changes to subjective feelings and performance changes were reported as important indicators that a controller may be reaching the edge of performance: *"If you start to miss the things that you should be doing at certain times, it gets exponentially busier and then you can't catch up anymore" (Participant 4)*. In comparison, physiological change and visible cues indicators were not interpreted to indicate that a controller was reaching the edge of performance or that a potential performance decline was likely.

Table 10.3. Indicators internal to the controller

Proposed category	Marker
Cognitive changes	Don't know the next steps
	Increased focus
	Calls are a surprise
	Reduced self-awareness
Changes to control	Reactive
	No back-up plan
	No space for unexpected event/ working to capacity
	Future plan reduces in minutes
Physiological changes	Heart beat faster
	sweat
	Red cheeks
Subjective feeling	Feeling of losing control
	More traffic than can handle
	Panic and uncertainty
	Not comfortable

Table 10.4. Observed indicators

Proposed category	Marker
Perception changes	Can't talk to executive/ executive doesn't hear you
Visible cues	Fidgety
	Move closer to screen
	Colleagues not talking to one another
Changes to voice	Talking faster/ more "say again"s (from pilots)
	Tone of voice
Verbal cues	Swearing
	Blaming others
Performance changes	Miss actions
	Mixing call signs
	Can't see simple solution
	Overlook aircraft

Controllers reported using specific compensation strategies in high taskload periods if they were aware of potential performance decline (Table 10.5). These were primarily control strategies such as reducing efficiency to ensure safety, or going 'back to basics' to ensure all aircraft are safe. Several respondents reported that ECs became less self aware under periods of high workload and therefore more reliant on the CC to apply compensation strategies: *"They start to swim... the planner next to them is very much paying attention and they tell them 'Okay now you do this, now* *you do this, now you do this'" (Participant 14)*. Preparation for a high taskload was reported to be the most effective strategy.

Table 10.5. Compensation strategies which are also indicators

Proposed category	Compensation strategy
Control strategy	Less prioritisation on efficiency and more on safety
	Back to basics
	Defensive controlling
	Keep talking so pilots cannot interrupt
	Quicker decisions but less considered
Verbal changes	No pleasantries
	Speak slowly
Support from CC	Seek guidance from CC
Increase field of awareness	Sitting back
Emotion regulation	Deep breath

Low workload

Table 10.6, Table 10.7, Table 10.8 list the internal and external and compensation strategy indicators of reaching the edge of performance during low workload. In comparison to high workload, the indicators reflect a potential influence on performance through potential boredom or relaxation, leading to distraction: *"In low workload, there's nothing to do so you start doing other things, boredom becomes an issue and then you start talking or having a chat or doing whatever and it's, yeah, you can miss things" (Participant 10)*. One particularly interesting marker during low workload is that controllers report leaving a problem develop for longer or creating complex situations to reduce boredom. Controllers report attempting to compensate for the influence of low workload by maintaining conscious awareness.

Table 10.6. Indicators internal to the controller

Proposed category	Marker
Cognitive changes	Pay less attention
	Easily distracted
	Reduced awareness
	Reduced self-awareness
Changes to control	Leave situations develop for longer
	Trying to create more complex situations
	Less safety buffer
Subjective feeling	Boredom
	Relaxed

Table 10.7. Observed indicators

Proposed category	Marker
Perception changes	Incorrect assessment of a situation
Visible cues	Sit back in chair
	Away from radar screen
	Talking to colleague
Performance changes	Overlooking aircraft
	Forgetting aircraft
	Repeated 'sloppy' mistakes
	Fall behind traffic due to distraction

Table 10.8. Compensation strategies which are also indicators

Tell self to pay attention
Repeatedly check situation
Sitting forward in low workload – trying to concentrate on problem

Workload transitions

Transitions between taskload extremes (low-high and high-low) were associated with specific indicators (Table 10.9, Table 10.10 and Table 10.11). Indicators were different depending on the direction of transition. A transition from low to high taskload required controllers to change 'state' in order to meet the speed and demands of the traffic, known as a *"gear shift" (Participant 4)*. Indicators that controllers may not be performing optimally during this transition included falling behind the traffic and losing awareness. Indicators associated with high to low taskload transitions were mostly characterised as emerging from a feeling of relaxation after the traffic peak and a resulting loss of concentration: *"When you said to the edge of your performance, that's probably the reason why things go wrong, just after a busy period because people start relaxing and the adrenalin goes away and you lose your concentration" (Participant 16)*.

Table 10.9. Indicators internal to the controller

Potential category	Marker	Transition direction
Cognitive changes	Fall behind	Low - high
	No plan	Low - high
	Lack of awareness	Low - high
	Gear shift	Low - high
Subjective feeling	Relax	High - low
	Perception of tiredness	High - low

Table 10.10. Observed indicators

Performance changes	Overlooking aircraft	Low - high High-low
Visible cues	One controller at position	High-low

Table 10.11. Compensation strategies also indicators

Potential category	Marker	Transition direction
Change in control style	Lower complexity in preparation	Low – high
	'Relax' between busy periods	High - low
Subjective experience	More effort to concentrate	High - low
	Conscious internal reminder to focus	High - low

Several distinct types of performance decline are associated with workload, such as overlooking aircraft (vigilance issues) and mixing call signs (communications issues). Workload may therefore negatively influence other factors such as vigilance, fatigue, and awareness which are then observed to be a causal factor of performance decline. This is important for understanding underlying causes of performance decline that may manifest as a different factor.

10.3.3.3.8 Fatigue

Several sub-categories of internal (Table 10.12) and external (Table 10.13) indicators of fatigue were reported, as well as indicators that arose from applications of compensation strategy (Table 10.14). Most indicators were identified as specific to fatigue. However, some participants reported that performance changes, such as overlooking aircraft, as indicators were not specifically associated with fatigue and needed to be interpreted in context. For example: *"If there is a busy situation with high traffic if you overlook something there then it doesn't necessarily need to be because you are too tired...If it is quiet I've overlooked some traffic know it is because I'm tired probably" (Participant 11)*. Therefore, the influence of fatigue may be represented in performance indirectly. Most controllers felt that consciously maintaining attention is an effective compensation strategy for feeling fatigued. In addition, several controllers reported control changes, such as increasing safety buffers, to mitigate the influence of fatigue and protect performance: *"You can be very tired and work very correct because you know you have to perform better because you feel tired" (Participant 13)*.

Table 10.12. Indicators internal to the controller

Potential category	Marker
Cognitive changes	Slower
	Not as sharp
	'Mild confusion'
	Extra time thinking about task
	Reduced awareness
	Concentration issues: Not paying as much attention
	Increased assumptions
	Distracted
Physiological changes	Feeling cold
Internal perception, feeling	Not controlling as expected
	Feel tired
	Not looking forward to shift
	Not on top of things
	Not comfortable
	More effort to control
	Have to push self
	Don't want to work busy traffic
	Forcing to pay attention
Changes to control	Less flexible
	Don't see, or longer to see, a solution
	Lower motivation to control efficiently
	Slow reactions
	Slower to solve problems
	Reactive control

Table 10.13. Observed indicators

Potential category	Marker
Visible cues	Yawning
	Laid back
	Eyes closed
	Falling asleep
Verbal	Slower speech
Teamwork	More discussion with CC
Physical appearance	'Looks tired'
	Colour of face
Demeanour	Less active
	Quieter
	Not as confident
Performance changes	Multiple small mistakes, 'sloppy'
	Check frequency
	Overlooking aircraft
	Mixing up call signs
	Don't hear read back
	Incorrect plan without realisation
	Inappropriate reactions
	'Running behind traffic'
	Forgetting/ Surprise

Table 10.14. Compensation strategies also indicators

Potential category	Compensation mechanisms
'Force' conscious attention	Pay attention during session that are known to be prone to fatigue issues i.e. early morning shift
	Consciously think about controlling
	Be alert and focused
Role change	Ask to start or sit on the planning position next session
	Ask to swap with the planner /planner offers during the current session
EC – change control strategy	Conservative control
	Simple controlling, Easy solutions
	Defensive control
	Simple instructions
	Increase safety buffer

	'Relax' between busy periods
CC- change strategy to support EC	More proactive – solve issues prior to reaching EC
	Pay more attention, more double-checking of clearances
Discussion between EC and CC	Inform CC and ask for extra attention
	More discussion with CC regarding solutions, double-checking
	Discussion regarding who is paying attention to the radar
Reduce fatigue	Take a break, away from radar screen
	Nap during breaks
Do not control	Call in sick

10.3.3.3.9 Stress

Respondents differentiated between stress resulting from personal situations and task-related stress, which were both reported to negatively influence performance. Respondents suggested that the indicators and effects of stress were the same regardless of cause. Respondents also differentiated between positive, or 'excited', stress and stress which results in negative feelings and potentially performance change. Participant 11 explained: *"It's almost excited because there is more traffic coming. It's a different situation if someone is already in a complex situation, you realise he is falling behind then it's a different impression you get from the person"*.

Only indicators of stress that influenced controllers negatively were discussed. Respondents emphasised changes in subjective feeling, such as feeling tense, uncomfortable and anxious, as unambiguous indicators of stress (Table 10.15). This suggests that stress may affect subjective experience and associated cognitive changes rather than performance directly. Several observable indicators (Table 10.16) were manifestations of emotional responses, such as frustration and demonstrations of anger, and associated physiological changes such as vocal changes, shaking and fidgeting. Compensation strategies (Table 10.17) were designed to counteract the influences of stress on the controller, such as emotion regulation and practical strategies such as reducing rate of speech. Support was sought from the CC to further protect performance.

Table 10.15. Indicators internal to the controller (negative stress)

Proposed category	Marker
Cognitive changes	Start to think slower
Physiological changes	Heartbeat
	Sweat
Subjective feeling	Not coping
	Feeling doing badly/ uncomfortable (negative)
	Anxious (negative)
	Nervous
	Tense

Table 10.16. Observable indicators

Proposed category	Marker
Visible cues	Fidgeting
	Red cheeks/neck, flushed
	flustered
	Sit closer to screen
	shaking
Changes to voice	Speaks faster (negative)
	Speaks higher (negative)
	Speaks louder
	Speaks quieter
Demeanour	Easily frustrated
	Angry/ confrontational
	sad, unmotivated
	Blame others
Verbal cues	Ask to open a sector
	Communication changes
	swearing
	Shouting
Performance changes	Falling behind
	incorrect instructions

Table 10.17. Compensation strategies also indicators

Proposed category	Compensation strategy
Verbal changes	Speak slower
	More authoritative in instruction
Support from CC	Pay more attention to EC's actions
Emotion regulation	Reduce stress
	Sit back, reduce anxiety
	Relax

10.3.3.3.10 Attention/Vigilance

Indicators of negative influences of vigilance and SA were very similar, possibly due to vigilance being an integral aspect of SA. Cognitive perception changes were primarily described as indicators of reduced vigilance (Table 10.18). However, the consequences of these perception changes were observable, such as overlooking aircraft (Table 10.19). Compensation strategies (Table 10.20) included changes to control strategy, such as changing the scanning strategy to accelerate perception of issues. Coordinating controllers (CCs) also supported executive controllers (ECs) to protect performance. Performance may be particularly vulnerable to vigilance issues as the controller would not be aware of an issue unless brought to his/her attention.

Table 10.18. Indicators internal to the controller

Proposed category	Marker
Cognitive/ perception changes	Not as 'sharp'
	Surprised
	Assume more
	Focused, 'tunnel vision'
	Donut effect – focus on edges of sector only
	Focusing on one area of sector and not scanning others
	Not aware
Changes to control	Scan differently
	Not leaving a problem

Table 10.19. Observable indicators

Proposed category	Marker
Performance changes	Overlook aircraft
	Don't hear/see

Table 10.20. Compensation strategies also indicators

Proposed category	Compensation strategy
Change scanning pattern	Speed up scanning
Force' conscious vigilance	Focused, conscious to remain vigilant
Support from CC	CC to instruct to focus on something else

10.3.3.3.11 SA

Controllers referred to a decline or loss of SA as 'losing the picture'. The loss of SA was reported to be progressive and occur in stages which were associated with different indicators: *"It starts off by just falling behind a bit. So you might just be a few steps behind what you're supposed to be doing and if that builds up too much then you will get to the point where you start to lose the picture" (Participant 20)*. Therefore, the internal and observable indicators for SA were categorised into indicators which indicate a controller is progressing to losing the picture, or that a controller has lost the picture, and therefore SA (Table 10.21, Table 10.22, Table 10.23, Table 10.24). The context of high or low taskload was reported to influence SA, and the associated indicators of SA, differentially. The progressive decline of SA was only reported under conditions of high taskload. In low traffic the loss of awareness was more instantaneous: *"We sort of relaxed, 'Oh, it's done now', eating a sandwich and the fourth both of us had forgotten about it or not assessed it, but suddenly it's flashing and we're, "How did we miss that?" (Participant 4)*. Controllers felt that recovery of SA was relatively easy in periods of low traffic as compared to high traffic.

Compensation strategies (Table 10.25) protect performance when a controller is losing the picture. It was reported to be difficult to rebuild awareness after losing the picture. The compensation strategies from the EC attempt to make the situation safe when awareness is degraded. Conversely, compensation strategies by the CC are tactical and appear to facilitate the EC in rebuilding the picture. For example, CCs will change control strategy to reduce complexity and/or traffic frequency to allow the EC to catch up and rebuild the picture. In addition, CCs will monitor the EC's instructions and step in if necessary until the EC has recovered the picture *"They [CC] tell them 'Okay now you do this, now you do this, now you do this'" (Participant 14)*. The more degraded awareness is, the more reliant the EC may be on the CC to protect performance and rebuild the picture.

Table 10.21. Indicators internal to the controller when losing the picture

Proposed category	Marker
Cognitive changes	Difficulty selecting priorities
	Thinking whilst giving the clearance
	Tunnel vision/hearing
Subjective feeling	Under confident

Table 10.22. Indicators internal to the controller having lost the picture

Proposed category	Marker
Cognitive changes	Lose awareness
	Everything a surprise
	No plan
	Cannot see a solution
Changes to control	Reactive control
Subjective feeling	Panic

Table 10.23. Observable indicators of losing the picture

Proposed category	Marker
Visible cues	Slow at task
Performance changes	Running behind
	Time working ahead degrades – less awareness?
	Missing calls

Table 10.24. Observable indicators of having lost the picture

Proposed category	Marker
Visible cues	Zig-zagging head movement of where to look
	'Blacked out'/ silent
Verbal cues	Asking for confirmation
Performance changes	Unsafe clearance
	Unexpected decisions
	Jumping from one aircraft to another
	Don't know who's calling
	Don't react correctly

Table 10.25. Compensation strategies also indicators

Proposed category	Compensation strategy
Control strategy	Keep static traffic
	Build plan as go
	Conservative clearances
	Reduce complexity
Prevention	Prevention – freeing up space
Support from CC	Get CC to decrease traffic load to allow to build up picture again – to catch up
	CC to monitor controllers' actions
	CC provides instructions
	Ask for help and be aware

10.3.3.3.12 Inadequate communications

As communication is observable no internal indicators were reported. (Table 10.26). Controllers described inadequate communications in relation to causes and contributory factors such as fatigue, lack of attention, or stress (Table 10.27). One controller explained: *"It [mixing call signs] happens more if someone's tired or under pressure than if they're normal" (Participant 20)*. No compensation strategies were reported. Controllers instead emphasised the causes of communication mistakes in terms of underlying factors and the need to address those factors.

The impact of communications on overall task performance was perceived to be influenced by taskload. In low taskload, inadequate communications influences can be addressed: *"I'm not saying if you have two aircraft that communication will never play a role, it could, but in general if there's not too many aircraft you can work around it."*

In contrast, in high taskload *"If you have aircraft that aren't listening and you're busy...maybe the extra thing that sends you over"*.

Table 10.26. Observable indicators

Proposed category	Marker
Situational issues	Inadequate communications with aircraft
	Equipment failures
Performance changes	Mixing call signs
	Slip of the tongue

Table 10.27. Contributory factors

Lack of attention
Stress
High workload

10.3.3.3.13 Teamwork

Controllers did not provide indicators of inadequate teamwork per se as teamwork issues were considered to overt and easily identifiable. Controllers described different forms of inadequate teamwork (Table 10.28) and the potential negative consequences of inadequate teamwork on performance (Table 10.29). Inadequate teamwork was reported to increase workload, potentially resulting in the controller falling behind traffic. In addition, inadequate teamwork between the EC and CC resulted in controllers in the EC position feeling a loss of a safety net: *"Once you start losing the safety net you're definitely approaching some dangerous areas" (Participant 18)*. No compensation strategies were reported. Infrequently, controllers stated they would ask the CC to support specific tasks.

Table 10.28. Team member and issue creating inadequate teamwork

Colleague	Issue
Pilot	Not listening
	Not responding
	Not following instructions
Supervisor	Manage sectors for controllers
Coordinating controller	Proactive
	Negative attitude
	Not interested
	Not monitoring
	Lack of understanding

Table 10.29. Inadequate teamwork associated with performance issues

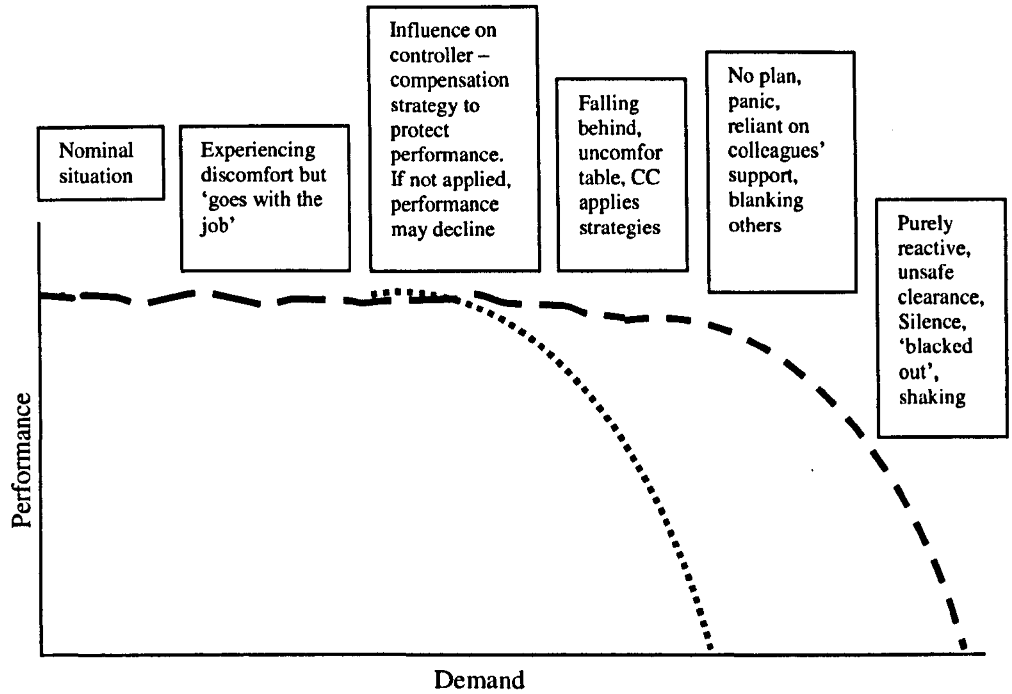
Category	Outcome
Task-related	Increased workload
	Loss of safety net (Relevant to CC)
	Falling behind traffic
Subjective feeling	Tension
	Stress

10.3.3.3.14 Progression to the edge of performance

Progression to the edge of performance was spoken about in terms of 'stages' and associated experiences. Figure 10.2 provides a representation of the controllers' experience at each stage, developed from participant responses. Performance is first represented as an uneven line; there will often be minor changes in performance although overall performance is maintained to a consistently high standard.

Within the region of safe performance, controllers experience nominal situations daily and are addressed with relative comfort. Performance is maintained. If demand increases the controller may experience subjective discomfort with the task. However, respondents suggested that these experiences are seen as 'part of the job' and something that all controllers should be able to deal with. Although experiencing subjective discomfort, controllers still complete the control task with a high level of performance. If demand increases further, performance may begin to be negatively affected by factor influences such as workload and fatigue. Here, performance may decline. Alternatively, if the controller identifies the threat to performance, a compensation strategy can be applied and performance can be maintained. The compensation strategy may not be sufficient to protect and maintain performance if task demands increase. The controller may begin to fall behind the traffic: *"It's something that will build up and you miss one...and then okay maybe you miss another one or two or you're confused as to who called you. Sometimes that happens and it'll go back down again and there's no problems and sometimes it will keep rising, starting to lose the picture" (Participant 2)*. Control may become reactive and controllers may rely on colleagues' support for maintenance of performance. If task demands are reduced, it is possible that performance can be recovered. However, if demand is not reduced at this point, the so-called 'edge of performance' may be reached. Control becomes reactive, and controllers may experience panic. Unsafe clearances may be given. Severe negative reactions may occur, such as a controller shaking or becoming silent. The controller has reached performance limits and is operating outside of safe performance.

Figure 10.2. Diagram of performance and demand with associated indicators and controllers' subjective experience



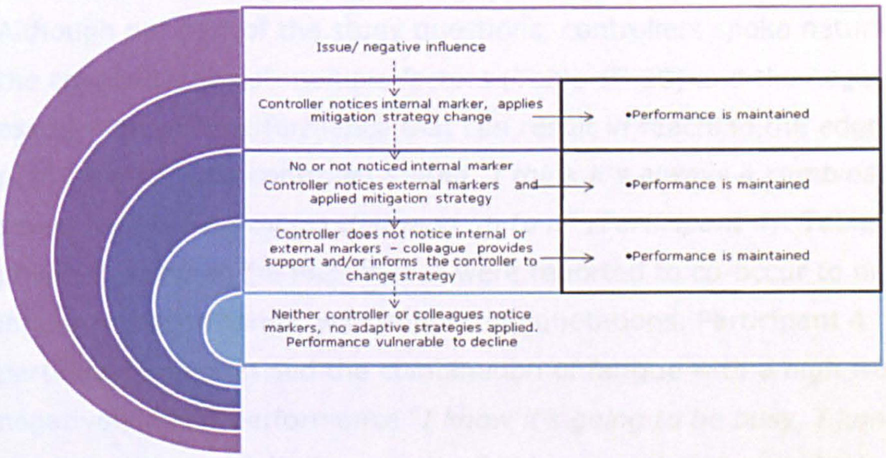
10.3.3.3.15 Awareness of indicators

Compensation strategies are dependent on awareness

Controllers emphasised that awareness of indicators was critical to employing a compensation strategy. One participant summarised: *"I'd say 300%, if you know that you're not being top performing today then that's fine, just adapt your working style and you'll get through the day. It doesn't really matter but if you don't know it and you're still trying to do the same then it might end in tears" (Participant 12).*

When an influencing factor is present, performance may be protected by several 'barriers' (created from awareness and compensation strategies) before becoming vulnerable to factor influences. Figure 10.3 represents the interplay between awareness and compensation strategy. If an influencing factor occurs (e.g. fatigue) internal indicators such as feelings of discomfort may alert the EC and trigger the application of a compensation strategy. Performance may then be maintained. If an internal marker did not occur or was not detected, another opportunity to detect the issue may occur through observable indicators. For example: *"It's getting busy… you start speaking fast and then somebody says "Say again" and then that's it, you have a hint. 'Okay good, I have to slow down* *because I was not aware that I was speeding up my transitions because of the amount of traffic'. You slow down and everything's fine again"* *(Participant 1)*. However, if the EC is not aware of indicators, protection of performance is dependent on a colleague's (i.e. the CC's) awareness: *"You're not aware that you're working to the edge of your performance then you need to rely on other people to tell you or people to remind you of how you are working" (Participant 15)*. If neither controller notices an issue, participants suggested that performance is more likely to decline than if a compensation strategy was applied. The progression presented in Figure 10.3 may not be applicable in all situations, although captures many elements of controllers' answers.

Figure 10.3. Representation of a barrier model of performance protection in association with marker awareness and compensation strategy



Individual differences in awareness

Participants differed in the extent of conscious awareness of personal indicators. A minority of controllers (3/22) suggested that they personally 'sense' or 'just know' when they are reaching a performance limit but could not identify how they knew. In contrast, most controllers could identify personal indicators.

Individual differences in observable indicators

There was an overall consensus that in general, indicators were generic and common between controllers. However, some indicators appeared to depend on the individual. For example, a change in voice pitch was seen as a general indication that a controller may be finding a situation difficult, but whether the pitch rose or fell would depend on the individual.

10.3.3.3.16 Indicators are learned through experience

Indicators of potential performance decline are not formally taught but are learned through experience. One respondent explained *"You start to know that you've been burning your fingers before on this kind of situation that you really have to pay attention" (Participant 1)*. This has implications for trainees and newly qualified controllers. Respondents suggested that inexperienced controllers will be more vulnerable to performance decline as *"they don't know how to protect themselves" (Participant 18)*.

10.3.3.3.17 Multiple factor co-occurrence and association with performance: the controllers perspective

Although not part of the study questions, controllers spoke naturally about the co-occurrence of multiple factors (Table 10.30) and the negative association with performance that can result in reaching the edge of performance. One controller stated *"I think it's always a combination of seven, eight, nine things that lead up to it" (Participant 4)*. Table 10.30 presents some of the factors that were reported to co-occur to negatively influence performance, with supporting quotations. Participant 4 particularly emphasised the combination of fatigue with a high workload to negatively affect performance *"I know it's going to be busy, I know I'm tired. Just be careful"*. The relationship between fatigue and high workload appeared to be bi-directional (Table 10.30). Controllers frequently reported the influence of indirect factors such as workload and fatigue on more outcome-based factors such as communications and vigilance.

Table 10.30. Quotations relating to multiple factor influences

Factors	Supporting quotations
High workload and fatigue	If somebody's been running for a whole hour of really busy traffic, then just at the end, you can feel really tired or they can look really tired (Participant 9)
	You think it's going to affect your workload because you're tired because you don't feel comfortable (Participant 10)
High workload, vigilance, teamwork	Sometimes these people who are so focused on the situation... it's very helpful for them to give them an idea. I think that's the point where teamwork is very important (Participant 11)
Fatigue, stress, low workload	[Talking about a near miss in low workload] I could definitely say that I was fatigued in that moment, I was very stressed (Participant 11)
High workload	And stress has to do with the workload ... For me with the workload as

and stress	well, you get more stressed when you, when you work higher amounts of traffic (Participant 3)
Low workload, vigilance	I've not much to do so you're chatting and you might miss the moment when it's actually getting busy (Participant 5)
High workload, stress and communications	That happens sometimes in busy traffic. You want to say something and you said it the wrong way...you can actually start mixing up call signs, and I've noticed that that's a first indicator of you're starting to become a little bit more stressed (Participant 7)

10.3.3.4 Semi-structured interviews: Discussion

Expert opinion regarding indicators of potential performance decline was generated by conducting one hour face-to-face interviews with 22 en-route controllers from MUAC. Interviews were orthographically transcribed and analysed using thematic analysis. Results revealed that indicators were used in an ATC setting by all respondents, as indication of when a controller was reaching the edge of performance, or a factor was negatively influencing performance. It was considered a natural process that all controllers used. Participants differentiated between internal indicators, representing a subjective experience, and external indicators, which were observable. Three sub-categories of external indicators were identified: changes in performance, physical signs and application of a compensation strategy.

Participants confirmed that specific factor influences on performance were associated with specific internal and external indicators. Indicators were identified for the factors of workload, fatigue, stress, vigilance, SA, communications and teamwork. Participants also reported adaptive changes in control strategy that were applied to maintain performance when the influencing factor was present which resulted from the identification of indicators. Compensation strategies are therefore an integral aspect of the use of indicators in ATC. In addition, compensation strategies were also identified to be used as external indicators themselves of controller discomfort.

Specific factors influenced performance differentially, which in turn influenced the associated indicators. The factors of workload fatigue and stress can influence other factors (e.g. communications, teamwork, SA, vigilance) and the subsequent association with performance. The influences of workload, fatigue and stress may not be visible in performance but manifest as other factor influences, such as overlooking aircraft (a vigilance issue) due to fatigue. It is therefore important for aviation professionals to acknowledge the underlying issues of performance declines to gain a valid and comprehensive understanding about factor influences and to understand how to best protect performance. Factors such as communications, vigilance, teamwork and SA influence performance directly.

A progression to the edge of performance was developed based on participant responses. The representation describes the subjective experience of controllers at each stage, and the indicators associated with the edge, and moving over the edge of performance. Although this may not be applicable in all control situations, the representation of a move to the edge of performance may provide a standardised understanding of the indicators and control situations to monitor and contributes understanding to the wider human performance field.

Awareness emerged as an integral element in the use of indicators; controllers needed to be aware of their own or colleagues' indicators in order to apply a compensation strategy. It was suggested that there were individual differences in overall levels of awareness. In addition, controllers suggested that it was harder to be self-aware than aware of colleagues' indicators. This was especially true for inexperienced controllers who were perceived to not have the experience in order to identify indicators and apply adaptive strategies. Awareness is critical in the identification of indicators and subsequent application of adaptive strategies to protect performance. Supervisors and CCs may benefit from a more standardised list of generic indicators, and in addition, possibly learn different indicators to monitor from each other. Workshops that provide standardised indicators for which to monitor, and support development of awareness of indicators for the self and colleagues', may support controllers in protecting and maintaining performance in the presence of negative influences. This may also support trainees in protecting performance whilst developing the required experience to identify their own indicators.

Although not in the study aims, it was interesting to note that controllers naturally raised the issue of multiple factor occurrences and the influence on performance. One controller suggested that it is often a combination of seven or more things that add up to result in a performance decline. To gain a comprehensive understanding of factor influences on performance and the progression to the safe edge of performance, multiple factor combinations must be acknowledge both in research and in practical applications such as near-miss and incident investigations.

The advantage of the interview study is that rich, qualitative data was generated from ATC experts to provide comprehensive information in the investigation of indicators in an ATC setting. The broad ranges on participants in role, age, experience, and control sector ensured that views were representative across several subgroups in the control centre. Further research may confirm the stages of progression towards the edge of performance and investigate validity and reliability in generalisation to other control centres. In addition, further research may investigate the use of standardised indicators in facilitating supervisors and controllers in identifying potential performance decline and subsequently applying compensation strategies to prevent performance decline.

10.4 Chapter summary

This chapter presented findings from an experiment study and an interview study that investigated the concept of indicators of potential performance decline. Findings from the experimental study confirmed that associations between participant behaviours and factors were in the direction expected and supported the potential association between participant behaviours and performance.

An interview study was then described, which aimed to investigate the use of indicators of performance decline by en-route ATCOs, and identify specific indicators. A total of 22 en-route ATCOs from MUAC participated in one hour face-to-face semi-structured interviews. Results supported that indicators are used by ATCOs to inform potential performance decline. Indicators that were associated with specific factor influences were identified. Finally, a visual representation of the progression to the edge of performance was developed from participant responses. It was concluded that the use of indicators in ATC facilitate the protection and maintenance of performance.

Chapter 11. Discussion

11.1 Chapter overview

This final chapter demonstrates how each research aim was achieved by the work presented in this thesis, and discusses the significant contributions and implications of this research to understanding human performance in air traffic control. The thesis was concerned with investigating the existence of human factor interactions and the subsequent association with human performance in air traffic control. For the study to have practical relevance, the thesis investigated the use of internal and external indicators to facilitate the implementation of supportive strategies to prevent controllers experiencing reduced performance due to an interaction of multiple factors. This research was essential to address previous research gaps in human factors literature, and develop a comprehensive understanding of the occurrences of factors in an ATC setting and the associated influences on controller performance. In addition, it was important to investigate potential strategies that may mitigate factor influences and prevent performance decline. This chapter discusses the main research findings in relation to each study aim. Different research studies contributed to different aims. The contributions of this thesis to understanding human performance in air traffic control are emphasised and discussed. An acknowledgement of research limitations, and attempts to control for the limitations, is outlined, followed by suggestions for future research. The thesis concludes with practical recommendations and a summary of the main findings and contributions of the thesis.

11.2 The changing landscape of human factors included for consideration in different research stages

An initial set of nine factors (workload, fatigue, stress, attention, vigilance, SA, communications, teamwork, trust) that were provided by EUROCONTROL provided the scope for this research. Throughout the development of the thesis, the factors included for investigation in individual research studies were adjusted as necessary, informed by aviation-expert recommendations and pragmatic considerations.

Table 11.1 summarises the factors that were included for consideration for each research study.

Table 11.1. Human factors included for investigation for each research study

<table>
<tr><th>Factor</th><th>Literature analysis</th><th>Incident report analysis</th><th>Expert knowledge elicitation</th><th>Experiment</th><th>Indicators of potential performance decline: interview study</th></tr>
<tr><td>Workload</td><td>√</td><td>√</td><td>√</td><td>√</td><td>√</td></tr>
<tr><td>Fatigue</td><td>√</td><td>√</td><td>√</td><td>√</td><td>√</td></tr>
<tr><td>Stress</td><td>√</td><td>√</td><td>√</td><td>√</td><td>√</td></tr>
<tr><td>Attention</td><td>√</td><td>√</td><td rowspan="3">√</td><td rowspan="3">√</td><td rowspan="2">√</td></tr>
<tr><td>Vigilance</td><td>√</td><td>√</td></tr>
<tr><td>Situation awareness</td><td>√</td><td>√</td><td>√</td></tr>
<tr><td>Communications</td><td>√</td><td>√</td><td>√</td><td></td><td>√</td></tr>
<tr><td>Teamwork</td><td>√</td><td>√</td><td>√</td><td></td><td>√</td></tr>
<tr><td>Trust</td><td>√</td><td>√</td><td></td><td></td><td></td></tr>
<tr><td>(Arousal)</td><td></td><td></td><td></td><td>√</td><td></td></tr>
</table>

Overall, Table 11.1 presents the progressive refinement of the factors selected for inclusion in research investigations. For pragmatic reasons, teamwork and communications were excluded from the experimental study but are reintroduced for the interview study. Findings confirmed the importance of these factors within an ATC environment and the association with performance.

11.3 Reflections on research aims

The achievement of each aim is first described, followed by a discussion of main findings. The contribution to the overall thesis is then emphasised, and the implications of the results are discussed.

11.3.1 Identify a set of human factors that influence air traffic controller (ATCO) performance

The first research step was to identify a set of human factors that were present in the ATC environment, and influenced air traffic controller (ATCO) performance. Human factors and aviation experts from EUROCONTROL provided an initial set of nine factors (workload, fatigue, stress, attention, vigilance, SA, communication, teamwork, trust) for consideration. A literature review of peer-reviewed conference and journal papers confirmed that each factor was reported to be present in the control environment, or part of the control task, and was found to be associated with controller performance. An analysis of European aviation performance-related incident reports in which ATCOs were reported to have caused or contributed to the incident confirmed the occurrence of each of the nine factors in an ATC environment.

All nine factors were supported in the literature to associate with ATCO performance although the relationship between some factors and performance are more well-documented that others. Within the literature, the relationship between workload and controller performance had been frequently identified, both in expert and non-expert samples. Similarly, stress, attention, vigilance, situation awareness, communications and teamwork have all been repeatedly confirmed to associate with controller performance, from findings from experimental analyses as well as incident report data. The incident report data collected as part of the present research supports these literature findings, providing further confirmation that these factors are also associated with controller performance within ATC settings.

Fatigue was noted in the literature to negatively associate with human performance, primarily through findings utilising experimental studies. Investigations that analysed incident reports to investigate fatigue within ATC identified that fatigue was not frequently reported to contribute to performance-related incidents (Della Rocca, 1999). A similar result was identified in the present research findings; fatigue was only reported in 6/272 incidents (2%). These findings are contrary to experimental data reporting an association between fatigue and performance (e.g. Williamson et al., 2011). An interpretation of these findings is supported by the literature. Wickens et al. (2004) suggests that the indirect relationship between fatigue and performance may inhibit a reliable and consistent demonstration of the association between fatigue and performance as fatigue may manifest, and therefore be observed, as different issues. In addition, fatigue is also believed to be underreported in incident reports due to reporting biases (Edwards et al., 2011; Johnson, 2001; Kirwan et al., 2001). Implications for wider research are a possible re-examination of the incident reporting process, or methods of incident analysis, to capture this complex data within the ATC domain, and advancement of methodologies to support the assessment of fatigue in association with controller performance during offline simulations.

Similarly, stress is repeatedly documented to associate with ATCO performance within the reviewed literature. Incident report findings identified that stress was only reported to contribute to 3/272 incidents (1%). This result is surprising, but may result from the same biases that are suggested to influence the reporting of fatigue. Stress has an indirect relationship with performance and so may manifest as different, observable issues. In addition, it is hard to retrospectively confirm, without assumption, that stress contributed to an incident.

Finally, the findings related to the factor of trust require some discussion. Literature findings report an association between trust (interpersonal and trust in machines) and performance (e.g. Erdem and Ozen, 2003; Muir & Moray, 1996). In addition, Mosier et al. (1994) reported that over-trust in technology was reported as a contributor in aviation incident reports. This finding is in contrast to the incident report findings generated as part of this PhD research; trust was only reported in nine/272 incidents (3%). It is important to note that several studies report an indirect association between trust and performance. For example, Muir and Moray (1996) reported that over-trust in technology negatively correlated to monitoring behaviours, whilst Mosier et al. (1994) reported that over-trust in technology was associated in monitoring failures in the sample of incident reports reviewed. Therefore, as with fatigue and stress, the indirect relationship between trust and performance may have influenced the identification of trust in performance-related incidents. This finding has wider implications. It is suggested that if trust is associated with performance, and is therefore a factor of concern in ATC, methods of capturing this data are required in order to comprehensively generate a valid understanding of the influence of trust in association with ATCO performance.

The incident report data extends previous incident report analyses reported in the literature sample. Several studies used incident report data to investigate the association between factors and controller performance, although the majority of studies restricted the focus of analysis to data from the US (e.g. Della Rocca, 1999, Mosier et al., 1994) or the UK (e.g. Shorrock, 2007). Findings from the current research therefore provide confirmation that the considered set of nine factors is also reported to be associated with performance decline throughout European ANSP centres. In addition the similarity between international incident report data suggests that these factor associations with ATCO performance may not be specific to individual cultures, but pervasive human factor issues that are a significant concern within the ATC domain. Research must continue to advance in order to mitigate the association of these specific factors with controller performance.

In summary, findings confirmed that the set of nine human factors occur in an ATC setting and are associated with controller performance. Findings suggest that these factors are appropriate to be included in future research, providing the initial foundations of the research.

Findings have implications for wider research. Literature reporting factor influences in association with controller performance was sporadic for certain factors, (e.g. Matthews & Davies, 2001) and often resulted from experimental studies (Wickens at al., 1997) which were potentially not transferable to an ATC setting. Findings support previous research by providing confirmation of the factors that are reported to occur specifically within ATC settings and are associated with controller performance. One practical implication of the findings is that it may be useful for ATC supervisors to be aware of the factors that are negatively associated with controller performance to facilitate monitoring and supporting controllers.

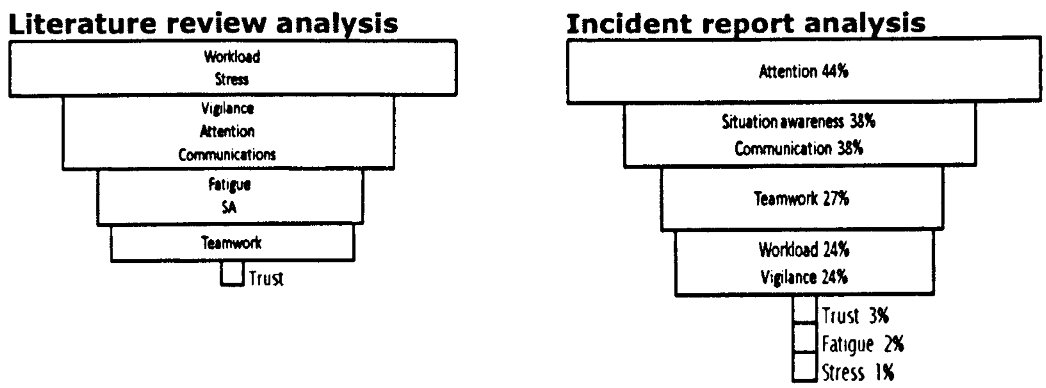
11.3.2 Select a sub-group of factors that may be included in further studies

It was impractical to include all nine factors in further research. It was therefore necessary to select a subset of factors. It was intended that the factors most frequently negatively associated with controller performance, as well as the most frequently considered factors in previous multifactor investigations, were selected so that the most critical factors in relation to ATCO performance were included in the next research stage.

Three separate studies contributed to achieving the second study aim: a literature review analysis of the frequency of factors included in peer-reviewed papers that investigated the relationship between at least two human factors, a performance-related incident report analysis and a questionnaire of air traffic professionals. Each methodology resulted in a ranked hierarchy of the recorded frequency of the nine factors that negatively influenced performance. It was also necessary to ensure that factors were reported to co-occur with other factors in an ATC setting to fulfil the thesis aims. Therefore, findings relating to the frequency of the co-occurrence of factors were also considered.

A discrepancy existed between the literature review analysis and incident report analysis regarding the frequencies with which factors were reported to negatively associate with performance. Figure 11.1 presents an overview of the relative frequencies from the literature analysis (on the left-hand side) and incident report analysis (on the right hand side). The diagrams are intended for facilitation of comparison only. The length of the boxes reflect more frequent inclusion of the factor in research findings; the longer the boxes the higher the frequency, but are not to scale.

Figure 11.1. A representation of the findings from the literature review and incident report analysis relating to relative factor frequencies



It is possible that the reported frequencies may have been influenced by the motivations and resources underlying the different methodologies. Factors that are easily measurable may have been prioritised in research studies, and may not reflect the most important factors in the ATC environment. Alternatively, biases in the incident report data may have contributed to the discrepancy, as factors which are difficult to record retrospectively (such as fatigue) may be underreported. A questionnaire of air traffic professionals was conducted to contribute to resolving the discrepancy between the previous studies. Findings identified a hierarchy of single factors and factor dyads that were most frequently, negatively influenced performance. Findings resolved the discrepancy by confirming a similar hierarchy to the incident report analysis. The findings from the three studies were compared and informed the selection of a subgroup of factors, achieving the second study aim.

The contribution of these findings to the thesis is the selection of a sub-group of factors for use in future research, facilitating progression to the next research stage. Selected factors are supported by three methodologies to be most frequently and negatively associated with controller performance. The reasons for the discrepancy may be similar to the interpretation outlined above for the discrepancy between the literature analysis and incident report analysis. Further research should be considered to investigate and address this discrepancy.

Findings also have implications for the wider ATC domain. Both incident report data and aviation expert opinion confirmed the co-occurrence of human factors in ATC. This is an important finding. There is a relative lack of research on multifactor influences on ATCO performance. It is therefore suggested that literature findings are out of step with real ATM domains. In order to gain an ecologically valid and comprehensive understanding of the current 'threats' to performance in the ATC domain, research needs to acknowledge and develop further understand of multifactor influences in ATC and the associated influence on controller performance. Findings also contribute to a more detailed understanding of the factors that most frequently are negatively associated with controller performance.

11.3.3 Investigate the relationships and potential interactions between multiple, selected human factors

An important expectation of the thesis was to investigate the relationship and possible interactions between multiple factors; previous research of these topics was sparse, especially specific to the ATC domain. Both experimental and field-based studies contributed to achieving this research aim, summarised in Table 11.2.

Table 11.2. Contribution of findings to thesis aim three resulting from multiple studies

Findings	Setting	
	Laboratory	Field
Multiple factors co-occur in ATC		Incident report analysis Questionnaire Interview study
Multiple factors covary	Literature review analysis Experiment study	
Multiple factors interact	Experiment study	

Three studies using separate methodologies (literature review analysis, incident report analysis, and questionnaire) confirmed that multiple factors co-occur in an ATC environment and are associated with negative influences on performance. An experiment using a computerised task with ATC elements was then conducted to investigate and extend knowledge of the relationships between multiple factors. Several findings that are pertinent to the study aim are discussed.

Experimental findings contributed to previously identified literature (section 2.3). Several factor dyads were identified to significantly relate which were in line with previously-identified relationships in the literature. For example, workload and stress (Glaser et al., 1999), workload and fatigue (Corrandini & Cacciari, 2002), fatigue and stress (Park et al., 2006) and arousal and SA (Taylor & Selcon, 1991) were identified to significantly, positively correlate. Findings from the questionnaire also supported these findings; workload and stress, and fatigue and workload were both rated by aviation professions to frequently co-occur to negatively influence controller performance.

An unexpected finding from the experimental study was a positive relationship between fatigue and SA; when participants reported higher fatigue, responses to SA questions became quicker. Previous literature has identified a negative relationships between fatigue and SA (Matthews, 2002), although few studies were identified to have investigated this relationship in the literature sample. In addition, findings from the questionnaire indicated that aviation experts perceived a relationship between fatigue and inadequate awareness. Several interpretations may account for this unexpected finding. A general lethargy may impact on participants' motivation to answer accurately. Alternatively, the relationship may be mediated by a third factor, supported by the low shared variance between fatigue and SA. In addition, the result may be an artefact of the limitations of the SA measure. Further research should be completed to gain a further understanding of this relationship. In addition, a non-significant relationship was reported between workload and SA which conflicts with previous research (e.g. Wickens, 2002). In addition, stress and SA also did not correlate significantly. Again, this is contrary to expectations (e.g. Endsley, 1995) although this relationship is in general underreported (Perry et al., 2008). Findings may be due to the potential inaccuracies of the SA measure.

The relationship between arousal and SA was observed to be potentially curvilinear. Arousal is a U-shaped performance driver (i.e. not monotonic) and may be negatively associated with performance at either extreme of under-arousal and over-arousal. A scatter graph appeared to show that response times to SA questions became faster with experienced arousal reported to be in the mid-range. U shaped factors may have influenced the statistical analysis. Stress is also a U-shaped performance driver. A potential curvilinear relationship was identified between stress and workload although this was not analysed further.

Overall, findings therefore supported the covariance between multiple factors, and partially confirmed previous research findings. Findings contribute to previous research by confirming that multiple factors do co-occur in ATC. Experimental findings confirm relationships between factor dyads. Findings therefore add to the understanding of the co-occurrence and covariance of factors, both to general human performance literature, and specifically within the ATC domain. Findings also have practical implications; it is suggested that it is necessary to acknowledge the co-occurrence of multiple factors within the ATC domain to achieve an ecologically valid understanding of the influences on controller performance.

11.3.4 Investigate the association of multiple factor relationships with human performance

Three studies using separate methodologies (literature review analysis, incident report analysis, and questionnaire) confirmed that multiple factors co-occur in an ATC environment and are associated with negative influences on performance and the subsequent association with performance.

The association between covarying factors and performance was investigated using a median split approach. An important finding is that factor dyad groupings appear to cumulatively associate with both safety-related and efficiency-related performance measures; performance decline was greater when associated with two or more negatively influencing factors than when associated with a single negatively influencing factor. For example, a low workload and poor SA were associated with a higher frequency of STCAs than either of these factors that appeared alone (for example, low workload and good SA, or poor SA and high workload). This analysis extended previous research and addressed a gap in previous research of the investigation of multifactor combinations in association with performance. In addition, the use of a median split technique contributes to an additional research gap in which the majority of studies investigating factor relationships used correlation analyses only. Findings contribute further understanding to the research domain.

Importantly, greater performance variance was explained by factor triads as opposed to single factors or factor dyads. This result may be interpreted in the context of 'Limited Resources' (Wickens, 1984). An accumulation of negatively-influencing factors may demand more resources to support performance. When a task is cognitively demanding, control strategies are utilised to support performance (Sperandio, 1971). However, if factor co-occurrences continue to negatively influence performance, and/or resources become substantially depleted, the remaining cognitive resources and control strategies may not be sufficient to meet the demands of the task, resulting in reduced performance. Therefore, it may be hypothesized that under some circumstances, it is not necessarily the extent of a single factors' influence on performance (unless in an extreme form, such as overload), but the number of interacting factors which when combined have a negative influence on performance, that determines the overall association with performance.

Results from an interview study with active en-route controllers further confirmed the co-occurrence of multiple factors in ATC and an association with performance decline, based on their own experience. Participants naturally spoke of multiple factor occurrences, and suggested that performance declines do not often result from the influence of a single factor in current operations environments. ATCO opinion therefore supports experimental findings.

The achievement of this aim contributed to the thesis by investigating the relationship between multiple factors and the subsequent association with performance. The implication of this finding is the importance of considering multiple factors when investigating human performance in safety critical situations. Findings also have implications for ATC. It may be suggested that incident investigations are facilitated by encouraging a focus on the co-occurrence of multiple factors.

11.3.5 Inform fundamental understanding of ATCO behaviour at the edge of performance

This thesis aim was necessary to extend understanding of the nature of behaviour at the edge of performance. It was important to understand the association of multiple factors with controllers reaching the edge of performance, and the progression from a safe to an unsafe region of performance.

Experimental results specific to periods of high taskload were analysed to investigate participants' reaching the edge of performance. The most frequently identified performance shape consisted of several periods of small performance declines occurring in association with multifactor influences interspersed with periods of maintenance. It was only when negative performance-influencing factors combined (i.e. high stress in combination with poor situation awareness) that performance declined steeply, indicating that the combined influence may push participants to the edge of performance.

Findings from an interview study with qualified en-route ATCOs expanded on experimental findings by providing an ATC-specific perspective of controller behaviour around the edge of performance. Participant responses were used to develop of a representation of the progression from safe performance to the edge of performance. Findings suggested that when controllers experienced negative factor influences (such as feelings of fatigue or discomfort during a high taskload), strategies are applied to mitigate the influence of the factor; this may be sufficient to maintain performance. Controllers may also use observable, small declines in performance, such as communications mistakes, overlooking an aircraft, or falling behind traffic, to indicate that a change in control strategy is required. The application of a compensation strategy may maintain performance until factor influences change or task demands increase, at which point performance may again decline. This finding therefore indicates that the shape of performance most frequently identified in the experimental results may result from small performance declines interspersed with changes in control strategy to support performance. The research aim was therefore achieved with a combination of experiment data which was supported and further informed by qualitative data from en-route ATCOs.

The contribution of these findings to the thesis is a more detailed understanding of the manifestation of multifactor influences on performance. Findings confirmed that the concept of an edge of performance is applicable to human performance in ATC. In addition, findings indicated that performance can be protected and maintained by the application of supportive strategies prior to reaching the edge of performance.

Findings also contribute to wider research, providing further understanding of the edge of performance and a foundation for future research to build upon, and further develop the understanding of the progression of performance decline and behaviour at the edge of performance. Findings also have important practical implications for ATC. Findings extended knowledge of the compensation strategies used to protect and maintain performance. If indicators can be identified to highlight when a supportive strategy is needed, one of the potential outcomes of this finding is that it may be possible that performance can be maintained and steep performance declines may be prevented.

11.3.6 Identify indicators of potential performance decline

Previous findings confirmed the nature of performance around the edge of safe performance. It was essential to build on these findings and investigate if indicators may indicate when a controller was reaching the edge of performance so that supportive strategies may be implemented to support controllers' performance when influenced by multifactor combinations, and therefore prevent performance decline.

Participant behaviours were observed throughout experiment trials. Correlation analyses were applied to investigate the association between behaviours and self-reported factors and performance measures. Findings revealed significant relationships between several participant behaviours and self-reported factors as well as measures of performance. Initial findings therefore supported that observable behaviours may be associated with participants' internal state and performance. However, the data was limited as only observable behaviours were recorded.

An interview study with 22 active en-route ATCOs extended the findings. All participants confirmed that internal (subjectively experienced) and external (overt, observable) 'indicators' of controllers' reaching the edge of performance were utilised in ATC operations rooms. Internal and external indicators that were reported to be associated with a specific factor were recorded.

A total of 15 (out of 52) indicators that were identified in the experimental trials were confirmed as indicators also identified in the interviews. There are several possible explanations for this marginal overlap. The researcher was not familiar with the indicators that may suggest when a participant is reaching the edge of performance, and so all observed behaviours were recorded. However, with experience, controllers are familiar with the behaviours that may indicate potential performance decline as opposed to idiosyncratic behaviours. Alternatively, it is possible that the behaviours observed in the experiment also do occur in the control environment, although more subtle indicators may not be consciously taken notice of by controllers, potentially resulting in underreporting.

A point of interest was that participants behaviours observed in the experiment appeared to be of finer detail that indicators reported in the interview study. For example, behaviours such as frowning, clenching jaw and shifting position were observed during the experiment. Indicators reported by controllers appeared to focus on more easily perceived observable indicators such as performance changes (e.g. overlooking aircraft) and physiological changes such as a red face, or verbalisations of feelings. One interpretation of this finding is that controllers may focus more on easily observable indicators for efficiency purposes; controllers monitoring colleagues often have little time to spare.

Controllers confirmed that indicators are used to inform them when a change in control strategy is needed. An integral concept to these findings was awareness - if controllers were not aware of indicators, supportive strategies were not implemented and performance became vulnerable to decline. A final point of note is that indicators are learned through experience and are not standardised; each controller has their own set of internal and external indicators.

This aim contributed to the thesis by identifying specific indicators than can be utilised to inform the controller or colleagues when a supportive strategy is needed to maintain performance.

Findings contribute to the wider research area of the association between indicators and subjective reports and cognitive state. "Anecdotally, many industries and work activities have reported that it is possible to 'see' how well a person is coping with their work" (Sharples et al., 2012, p2). However, little research has investigated the association between indicators and subjective report (Sharples et al., 2012). Findings contribute to enhanced understanding of the use of indicators, and provide a foundation for future work.

Findings relating to indicators that facilitate the implementation of supportive strategies are an essential output from the research contained in this thesis and have important implications for the operations room. Distribution of the indicators to ATC centres may promote an initial standardisation of knowledge. A total of 19/22 controllers supported the concept of sharing indicators. Findings may also support less experienced controllers whilst building their own indicators through experience. Supervisors may also benefit from a generic list of indicators, facilitating monitoring of ATCOs to support decisions of implementation of mitigation strategy.

11.4 Other findings pertinent to this thesis: Similarities and differences between factors

Throughout the thesis, it was identified that the factors included for investigation could be categorised differently. An initial categorisation of factors was suggested resulting from the literature review. Factors of workload, fatigue and stress were grouped as factors resulting from interactions between the individual and environment and were reported to have an indirect relationship with performance, influencing other factors such as vigilance or SA which then negatively influenced performance. Vigilance, attention and SA were grouped as factors referring to cognitive processes, and were widely reported in the literature to be influenced by the factors of workload fatigue and stress. Communications, teamwork and trust were categorised as factors resulting from individuals acting within a team environment. These factors can also be classified as elements of controller task performance and were reported to be influenced by factors such as workload and fatigue. Incident reports confirmed that the different factor groups influenced performance differentially. Workload and fatigue were not classified in any of 272 analysed incidents as a main cause of an incident. Fatigue was only recorded as a contributory or possible factor, implying the difficulty of detecting fatigue as a contributor to an incident. Conversely, attention and SA were dominantly recorded as main causes of an incident. Findings support the more contributory, indirect role of workload and fatigue to influencing performance. Findings from an interview study with 22 en-route ATCOs contributed to interpretation of these findings. The factor influences of workload and fatigue manifest in performance differentially, through other factors, such as overlooking aircraft (vigilance issues) or falling behind traffic (inadequate SA).

An important implication of this finding is that multiple factors must be considered within research studies and the ATC environment in order to gain a comprehensive understanding of the different forms of factor influences on controller performance. A comprehensive and accurate understanding is essential for development and application of appropriate compensation strategies. In addition, supervisors and controllers must be aware that an apparent error, or cause of performance decline, may be motivated by underlying causes, and apply appropriate supportive strategies to the influencing factor rather than the manifestation. Finally, findings also have implications for data collection and investigations. Several European centres have daily reporting processes which capture daily data and 'near-misses'. It is essential that such tools facilitate recording of suspected underlying causes or multiple factor co-occurrences in order to comprehensively capture accurate information relating to performance decline in ATC. Data can be utilised to inform appropriate compensation strategies that address any underlying causes that may not be observable in performance. In addition, incident investigators must be provided with the appropriate tools to examine multiple factor occurrences and their contribution to incidents in order to collect accurate data that will support the development of compensation technologies.

11.5 Progression of validation

The process of validation differed for the findings of factor relationships and interactions and the indicators of the edge of performance. External validity was first established for multifactor relationships; data supporting this research aim was initially gathered from the field through a combination of a literature review, incident report analysis and a questionnaire of air traffic control experts. Once initial support for the concept had been established, the internal validity of the concept was then supported through experimental findings. Conversely, the concept of behavioural indicators of potential performance decline was first internally validated by identification of indicators in an experimental study. The results were then externally validated by findings from interview studies with ATCOs investigating the use of behavioural indicators in the field.

11.6 Reflections on approach and methods

The literature review and analysis provided an informative and comprehensive overview of the field of interest. A summary of previous findings supported the development of research hypotheses and designs for later research stages and identified gaps in research. As with any review, there is the possibility that relevant research findings or articles may not be identified in the search process; however this concern was attempted to be at least partially controlled for by the use of a structured literature search with comprehensive and literature-guided search terms. Findings provided a comprehensive overview of the research areas of interest, which was particularly beneficial for the early stages of research.

An aviation incident report analysis provided valuable data on the factors that were reported to contribute to ATCO performance-related incidents. The incident report data was only possible to access through industry contacts. This may indicate a need for more open data reporting in Europe, similar to the NASA Aviation Safety Reporting System (ASRS). Several potential issues exist with incident report data, which have been highlighted throughout this thesis. However, the incident reporting process provides ATC-specific data which is beneficial to gain an ecologically valid understanding of performance in ATC.

Questionnaire data generated findings which were specific to ATC, and reflected the current ATC environment. The development of the questionnaire demanded a great deal of time; for example, exercises were required that were meaningful to aviation professionals but that could be distributed via an online medium without the presence of the researcher. In addition, natural language had to be used in the questionnaire so that the questionnaire was meaningful and had face validity.

The experimental method was complex and required several pilot studies for the integration of several measures and decisions of measure periodicity. However the data that was generated was detailed, and permitted an exploration of multifactor covariances and associations with performance. An experiment with numerous concurrent measures in a controlled setting was the only pragmatic way to investigate multifactor co-occurrences and associations with performance. The experimental design that was selected (low-high-low-high-low taskload) was used to create variability in the data. Each taskload section lasted 20 minutes in total. However, it is probable that some of the results (for example, fatigue) may differ compared to a design using longer sections, for example low taskload, high taskload and low taskload. With only one high workload peak, stress and fatigue, as well as perception of workload may differ. Performance may also be expected to differ with less STCA errors. Therefore, it is important for future research to investigate multifactor associations with performance in ATC with different experimental designs. It is suggested that although the factor rating and performance measures may change, the association between the factors and performance will be similar to those identified in the current study; it is the association between factors and performance that was the focus of the experimental findings and so the results may be transferrable to different situations (i.e. only one high workload period).

Experimental measures included both self-report measures (such as ISA) and a psychophysiological measure of heart rate. Heart rate was found to vary with taskload in the expected direction, although average HR across participants was only marginally different between taskload periods. Heart rate variability may have resulted in more sensitive data. However, the calculation and analysis of HR variability was outside the scope of this research. It is feasible to conduct this analysis to target other objectives outside of this research. However, currently, due to the low rate of variation with taskload, HR data was excluded from further analysis.

Finally, the focus group and interview study generated rich data of ATCO experiences regarding the mitigation of factor influences on performance. A pilot study consisting of a focus group with ex-controllers enabled the refinement of meaningful language to be included in the interview study, therefore potentially increasing face validity. Access to run interviews with controllers was complex. Analysis was also lengthy. However, the contribution of the data may have significant implications for the maintenance and improvement of safety in ATC.

11.7 Contributions resulting from this thesis

This thesis provides several contributions to the existing literature. A triangulation of methods confirmed a set of factors that influence controller performance specifically within an ATC setting, and proposed an initial hierarchy of factors that were reported to most frequently, negatively influence controller performance. In addition, data from several sources (incident reports, expert knowledge elicitation questionnaire) confirmed the co-occurrence of multiple factors in an ATC setting, and provided a suggested hierarchy of the most frequently occurring multifactor relationships to negatively influence controller performance. Findings provide an initial foundation, to be developed by future studies.

The thesis also contributed findings that addressed several previously identified research gaps in the literature. This included the investigation of factor relationships in both experimental and ATC field settings, an interaction analysis which extended findings beyond correlation designs, analysis of the relationship between more than two factors, and an investigation of the association of multiple factors with performance. The number of factors included for measurement in the experimental trials was novel, and so findings extend existing knowledge.

An additional contribution of this thesis was the novel investigation of multifactor interactions and the subsequent association with performance. Results suggest that co-occurring factors interact to create a cumulative negative association with performance, although findings need further research for validation within an ATC environment.

The investigation of the nature of performance at the edge of performance is a novel contribution resulting from this thesis. A representation of the progression of controllers' performance from safe performance to the edge of performance was developed. Findings contribute to understanding the manifestation of controller performance when associated with multiple factor influences.

This thesis also extends existing research by confirming the use of internal and external indicators in ATC operations rooms to inform controllers when supportive strategies are required to prevent performance decline. Indicators that are reported to be associated with specific factor influences were identified. Findings provide the contribution of a potential method of protecting performance from multiple factor influences and potentially preventing a performance decline. The recorded indicators are an outcome of the thesis which may facilitate a standardisation of knowledge between operational personnel.

11.8 Limitations of the research

Limitations to the research described in this thesis are acknowledged. It was necessary to restrict the number of factors that influenced controller performance to an initial set of nine factors. It is therefore possible that other factors also occur in ATC settings which were not included for consideration in this research. However, this was attempted to be controlled by using multiple methods, including aviation expert opinion, to confirm that the factor set included the factors that most frequently negatively influenced controller performance. For pragmatic reasons, the factor set was further refined to a set of six factors. Findings will therefore not reflect any other factors that may be important within an ATC setting. This was again attempted to be controlled by selecting the most frequent factors to negatively influence performance.

Several challenges were encountered during the experimental trials. Self-report measures are vulnerable to biases or participant deception (Dane, 1990). This was attempted to be controlled by emphasising confidentiality and anonymity of results. The situation-present assessment method (SPAM) was selected to measure SA for its low intrusion qualities and the potential to generate data frequently. The SPAM method assesses time of participant response to the SA question to infer the level of SA. However, during high taskload periods, participants were responding faster to SA questions with lower levels of accuracy. A post-trial interview revealed that participants were answering as quickly as possible without considering accuracy in order to get back to the task, even though participants were explicitly asked to answer as quickly and accurately as possible. The measure of SA was therefore limited in reliability. In addition, findings from the experimental trials may not be able to be generalised to ATC settings due to the use of naive participants and a low-fidelity task. However, working within these constraints, several experimental findings (co-occurrences of factors, performance at the edge of performance and indicators of the edge of performance) were supported through the qualitative data generated in an interview study with active en-route controllers. The median split analysis that was utilised to investigate interactions between factors reduced statistical power and did not acknowledge individual differences. Although this is a controversial method, it was the most practical option available to investigate the interaction of factors and the association with performance.

Observation of participants' behaviours during the experimental trial was challenging. It was difficult to record all behaviours accurately. Only one researcher identified and coded behaviours, increasing the risk of reporting errors. However, findings may be supported by similar findings generated from an interview study with en-route controllers.

Incident reports, questionnaire and interview studies were vulnerable to various biases. This research attempted to control for limitations by using multiple methods. Each research aim was informed by at least two studies that provided data to address the same research aim, although from differing perspectives. For example, although there were biases associated with incident reports, similar data was also found using a literature review analysis and questionnaire data, increasing confidence in the accuracy of the findings.

It was outside of the scope of this thesis to investigate if the representation of the progression to the edge of performance extends to other domains. Further research is required to investigate the validity of the generalisation of the findings in this research to other safety-critical domains.

11.9 Suggestions for future research

Future research may investigate the association between other factors that may be present in an ATC environment that were not included in this research, and the subsequent association with performance. Future research may also extend findings by including the factors of communications and teamwork in experimental investigations of multifactor relationships. By building on the findings in this thesis, a more comprehensive understanding of the factors that influence controller performance, and the association with performance, can be developed.

Due to time and resource limitations, multifactor interactions and the resulting cumulative influence on performance were not validated in an ATC simulation. It is proposed that future research use high fidelity simulations to confirm and extend findings. In addition, future research can extend the current findings by including both male and female ATCOs as participants. A larger number of participants will be beneficial to increase statistical power, and additional analyses may be then appropriately applied to the data.

It is suggested that future research examine the relationship and association with performance of more than three factors. The present research identified that more performance variance is explained with the association of more factors and so it is important to investigate the performance variance accounted for by different numbers of factors in typical and non-typical control situations. Future research may also establish if a point of saturation exists over which more performance variance would not be explained by considering the co-occurrence of more factors.

Another potential avenue of future research is to investigate the causal relationship between factors and performance. This remains a gap in the literature and may further inform the process by which controller performance is negatively influenced by multiple factors.

The design of the taskload manipulation (low-high-low-high-low) may have influenced results as discussed in section 11.5. It is therefore suggested that further research conduct a similar experiment, but with variations in the taskload manipulation, for example longer periods of taskload or beginning with a high taskload. Results may contribute to understanding the association with workload and performance under difference circumstances. This research would build on current findings and have a practical application to control rooms, to further inform likely associations with performance under specific circumstances.

Future research will also examine the heart rate variability in association with self-reported measures collected throughout this task. Heart rate variability information may further support self-reported workload.

In order to comprehensively investigate potential interaction relationships between factors, and cumulative associations with performance, it is essential that future research develop more appropriate research methods and statistical analyses to facilitate the investigation of multiple factors. The statistical analyses available are not sufficient to reliably, statistically analyse factor interactions. Analyses require an impractical number of participants or have severe limitations (Maccallum et al., 2002). In order to fully support multifactor interaction research, more suitable of analysis must be developed.

Future research may build on the findings of indicators of potential performance decline, and develop further methods to protect performance from multifactor influences and prevent performance decline. This may encourage increased focus on research regarding the proactive prevention of performance decline as opposed only retrospective guidance.

Future research may investigate the application of the findings of the present research, and validate the generalisation of findings, to other safety-critical domains. The present research focuses on human factor influences on human performance. Therefore, it may be hypothesised that the results of the present research may be transferable to other safety critical domains that rely on human performance, such as transport, manufacturing, nuclear and oil and gas. The representation of the progression to the edge of performance (section 10.3.3.3.14) and the associated indicators, as well as the representation of the awareness of indicators (section 10.3.3.3.15) may inform performance decline in these safety critical domains, and in addition, provide initial mitigation strategies, and a foundation for further research in the mitigation of performance decline.

The present research suggests that multifactor associations occur and possibly cumulatively, negatively influence performance. It is noted that the present research was carried out in the context of ATC, a domain in which a large amount of research has already been conducted relating to the compensation of single factor influences on performance. Other safety-critical domains may first need to establish a body of research on these single factor influences on performance prior to researching multifactor influences. However, it is reasonable to assume that multiple factors co-occur in other safety-critical domains, and so future research may use the present research findings as a foundation from which to investigate the occurrence of multiple factors and cumulative, negative, associations with performance. In addition, further research may subsequently investigate strategies to mitigate negative influences on human performance, which may be domain-specific. Methods and analyses outlined in the present research may be replicated and adapted as appropriate to the specific domain. It is therefore strongly encouraged that other safety-critical domains investigate multifactor associations with performance in order to identify proactive strategies to prevent performance decline, and ultimately, support human performance and enhance safety.

11.10 Recommendations

Recommendations may be made as a result of the research findings of this thesis:

- Future research in the human performance domain should consider multifactor interactions and the resulting impact on performance to produce a more ecologically valid and comprehensive picture of factor influences and human performance in air traffic controllers.
- Future research should conduct experimental studies with qualified ATCOs in a high-fidelity simulation; findings may build on and extend the research findings in this thesis.
- Knowledge of the particular factors or indicators to monitor should be provided to operational staff, in particular, supervisors. An awareness of the interactions of these factors and subsequent effects on performance may help support performance prior to decline.
- Operational staff should receive an opportunity to discuss and share indicators that indicate when a controller is reaching the edge of performance and when a supportive strategy is required.
- Trainees may be supported by facilitating learning of standardised internal and external indicators in order to make performance less vulnerable to factor influences whilst developing personal indicators from experience.
- Awareness of self and others' indicators should be emphasised and discussed. Awareness training relating to topics such as: the interaction of multiple factors, the cumulative impact on performance and indicators that highlight the need for supportive

strategies may further contribute to preventing performance declines.

- Day-to-day reporting procedures, or near-miss reporting, may incorporate space for users to discuss or record the occurrence of multiple factors, or perceived underlying factors leading to the situation of concern.
- Incident investigations may include the opportunity to explore the contribution of interacting factors, as well as underlying factors such as fatigue and workload, to incidents via interviews with personnel.

11.11 Concluding statement

The research presented in this thesis has addressed long-standing research gaps within human performance literature, and reported findings which support a move towards consideration of multiple-factor interactions and the associated influence on performance in ATC settings. Findings suggest that factors do co-occur in ATC, and interact to negatively influence performance, pushing controllers to the edge of performance. This research therefore provides a foundation from which to develop an ecologically valid and comprehensive understanding of multifactor occurrences and associated implications for controller performance in current ATC environments. In addition, findings will contribute to a greater understanding of the edge of performance in association with multiple factors.

Finally, the current research has contributed critical knowledge to the initial understanding of strategies to prevent performance declines in a safety critical industry. This thesis has also achieved a novel and important practical outcome by identifying indicators that indicate when a supportive strategy must be implemented to protect and maintain performance. It is now essential that future research contribute to further understanding of multiple factor interactions and the association with performance within ATC and other safety critical domains. By developing a comprehensive and ecologically valid understanding of multifactor interactions and the cumulative association with controller performance, active compensation strategies can be developed and a move from retrospective techniques to proactive prevention of performance decline can be achieved with important implications for the improvement of safety within air traffic control.

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Appendices

Appendix 1. Example of de-identified SAFLearn report

SAF XXXXX Year-Month-Date Time of Incident — 1) Unique report identifier

ATCO forgot action — 2) Error classification

RiskCat>[B]* — 3) Severity category

ANSP Provider XXXXX
A/C:ARR1 WakeCat>M IFR Alt: FL:92 Descending Approach
FType:Air transport Aircraft identifier XXXXX
A/C:DEP1 WakeCat>M IFR Alt: FL:74 Climbing Departure
FType:Air transport Aircraft identifier XXXXX

— 4) Incident overview

OVERVIEW>ATCO descended arriving aircraft to the same level as he had cleared departing traffic. MSep:1.3Nm 800ft
DETAILS> At 15H22:25 just before the aircraft's tracks had crossed the controller transferred DEP1 to the departures frequency in accordance with normal practice.
In the next transmission at 15H25:32, he instructed ARR1 to descend to FL80, a level that put it in conflict with DEP1.
As the two aircraft converged to 2.3 miles the controller advised ARR1 that there was departing traffic climbing to "one level below in your 12 o'clock now at a range of 2nm" and instructed it to turn right onto 050. There had been a TCAS warning.

— 5) Full text description

Main factors:
The controller prematurely descended ARR1.
FACTOR: ACAS - TA only source: SAFLearn Impact: Possible factor TCAS warning, no details
FACTOR: DescFactors - ATMService - Handing over/taking over - Transfer of traffic [HEIDI Contrib.]
FACTOR: ExplFactors - Hum - Psyc - Slips - Response errors - Timing - Too early [HEIDI Contrib.]
FACTOR: DescFactors - ATMService - OpsCommunications - Ground/ground - Phraseology - Standard phraseology [HEIDI Contrib.] non-standard
FACTOR: ExplFactors - Hum - Psyc - Lapses - Forgetting [HEIDI main cause]
FACTOR: ExplFactors - Hum - Psyc - Lapses - Loss of Awareness - Of traffic [HEIDI main cause]

— 6) Classification

Appendix 2. Search terms

1. **Attention**

Attention, notice, aware, pay attention, watching, distracted, concentration, interest, inattention, attend, process, attention, distraction, fixation

2. **Communication**

Communication, data-link, text, radio, speaking, coordination, instructions, phone call, planner, discussion, read back, corrections, message, transmission, vhf, uhf, frequency, listening, talking, noise level, interference, channel quality, broadcast channel, slips, response errors, language, accent, high R/T workload, misunderstanding, misinterpretation, handwriting, marking of strips

3. **Fatigue**

Fatigue, tired, tiredness, sleep loss, sleep disturbance, weary, long shift, sleepy, drained, lack of concentration, exhaustion, sleep deprived, time of day, weakness, drowsy, lethargy, sluggish, worn-out, drained, shattered

4. **SA**

Situation awareness, attention, memory, lost the picture, didn't see, filtration, forgot, planning, mental capacity

5. **Stress**

Stress, stressor, emergency, conflict, pressure, strain, time pressure, backlog, busy, anxiety, tension, demands, difficulty, colleague disputes, anger

6. **Teamwork**

Teamwork, cooperation, group, team, collaboration, support, help, assistance, relationship, colleague, working together, coordination, planner, timing, transition, transfer, handover/takeover

7. **Trust**

Trust, confidence, expectation, reliance, dependence, distrust, rechecking, assumes, uncertainty, automation, lack of trust,

8. **Vigilance**

Vigilance, watch, observe, monitor, scan, prioritise, sequencing, alert, notice, concentrate, missed, filtration, late detection, no detection

9. **Workload**

Workload, overload, underload, transition, taskload, busy, quiet, too much, too little, unfamiliar task, traffic load, excessive load, fluctuating load, unexpected demands, emergency, complex mix, abnormal time pressure.

Appendix 3. HEIDI (2001) lower-level classification terms mapped to the higher-level factor

Heidi Categories	Category Examples
Attention	Distraction: over long time, over short time, Fixation on important information, Complacency
Communication	1. Slips, Response errors, Slip of tongue/pen 2. Communications, Spoken communications; Call-sign confusion, Ground-ground communication; 3. Written communication: Data link, Handwriting, Marking of strips
Fatigue	Sleep loss, Sleep disturbance, Tiredness, acute, chronic, other fatigue issues
Loss of awareness (Situation awareness)	Of traffic, Mental Capacity, Loss of picture, Loss of SA
Coordination (Teamwork)	1. Team Skills: Transfer of responsibility, Handover/takeover, Poor/Unclear/No coordination, Inadequate transfer 2. Poor communication: Pilot, colleagues 3. Team Management: Returning to sector after break, Temporary unmanned position, Poor splitting/collapsing sectors 4. Timing: too early, late, long, short, transition
Trust	1. Confidence, in automation, complacency 2. Trust in others & automation: Over, Under, Mistrust
Detection (Vigilance)	Late detection, No detection, Monitoring
Workload	1. Workload issues: Too much, Too little, Task shedding, Unfamiliar task/novel situation, underload, complexity, changes 2. Traffic and airspace: Traffic load/complexity, Excessive load, Fluctuating load, Unexpected demands, Complex,, Unusual situations

Welcome

Welcome!

You are invited to participate *in a study that aims to examine the effects of multiple human factors on air traffic* controller performance. The study is conducted by Tamsyn Edwards at the University of Nottingham, UK, in collaboration with EUROCONTROL. The results of this survey will contribute to identifying the human factors that most negatively impact controller performance.

This survey is directed at air traffic controllers and aviation safety/incident investigators.
This survey contains 21 questions and should take no more than 20 minutes to complete. At the completion of these questions, you will have the option to exit the survey or provide responses to an additional 7 questions. This will take a further 15 - 20 minutes.

You do not need to identify yourself in this survey - you can choose to remain anonymous, and all responses are confidential.

Once the research findings are available, a summary will be provided to all respondents who provide a valid email address at the end of the survey.

After completing the survey, please feel free to pass on the survey link to interested parties. If you have any questions or comments about this survey, please don't hesitate to contact Tamsyn Edwards, epxte@nottingham.ac.uk or phone +44(0)115 9514033

Thank you in advance for your help. If you agree to participate in this research having read the above information, please select 'Next'

Occupation

*** 1. Please select your current occupation:**

○ Controller

○ Safety/incident investigator

○ Controller AND safety/incident investigator

Instructions

You are about to see 21 pairs of performance influences, such as stress and fatigue, that may impact a controller's ability to provide a safe service. Based on your previous experience, please rate the frequency that each combination occurs in cases where controller performance has contributed to a loss of separation incident.

Factor pairs

The following define the factors that are being considered. These definitions were created with a small group of expert controllers. You may want to print out these definitions to use with the remainder of the survey.

Factor Definitions:
Fatigue: Feelings of tiredness or weariness caused by prolonged activity. E.g. Wanting to handover although it's not yet time. Making errors that don't normally happen. Missing more calls than normal. Asking for repeats

Inadequate Communications: Problems in the exchange of verbal information, including timeliness, accuracy, clarity and receptiveness. E.g. Not professional or focused language. Not in control of the communication pattern

Stress: Pressures imposed by the situation which challenge the controller's ability to cope. E.g. Extended decision making & re-planning. Perceiving traffic situations normally set up are now getting too risky. Questioning own ability to cope

Inadequate Situation Awareness: Problems with the maintenance of a coherent mental picture for current and future controller performance. E.g. Lack of alternatives if plans change. Lack of awareness of what is coming and what is needed

Inadequate Teamwork: Controllers not working together effectively. E.g. Poor sector-to-sector coordination between controllers or between tactical and planner controllers

High Workload: High demand (amount and complexity) imposed by ATC tasks. E.g. Insufficient process time to refine and prioritise actions. Communications moving beyond capabilities

Underload: Very low demand (amount and complexity) imposed by ATC tasks. E.g. Boredom due to little traffic on frequency. Becoming inattentive or distracted during very quiet periods

*** 1. In your experience as an incident investigator, how frequently does the following combination lead to controller-related loss of separation incidents?**

	Very rarely	Rarely	Sometimes	Often	Very often
Inadequate situation awareness AND High workload	○	○	○	○	○

*** 2. In your experience as an incident investigator, how frequently does the following combination lead to controller-related loss of separation incidents?**

	Very rarely	Rarely	Sometimes	Often	Very often
Fatigue AND Inadequate teamwork	○	○	○	○	○

*** 3. In your experience as an incident investigator, how frequently does the following combination lead to controller-related loss of separation incidents?**

	Very rarely	Rarely	Sometimes	Often	Very often
Inadequate communication AND Fatigue	○	○	○	○	○

*4. In your experience as an incident investigator, how frequently does the following combination lead to controller-related loss of separation incidents?**

	Very rarely	Rarely	Sometimes	Often	Very often
Underload AND Inadequate communication	○	○	○	○	○

***5. In your experience as an incident investigator, how frequently does the following combination (one following the other) lead to controller-related loss of separation incidents?**

	Very rarely	Rarely	Sometimes	Often	Very often
High workload AND Underload	○	○	○	○	○

***6. In your experience as an incident investigator, how frequently does the following combination lead to controller-related loss of separation incidents?**

	Very rarely	Rarely	Sometimes	Often	Very often
Fatigue AND High workload	○	○	○	○	○

Factor pairs (cont.)

Factor Definitions:

Fatigue: Feelings of tiredness or weariness caused by prolonged activity. E.g. Wanting to handover although it's not yet time. Making errors that don't normally happen. Missing more calls than normal. Asking for repeats

Inadequate Communications: Problems in the exchange of verbal information, including timeliness, accuracy, clarity and receptiveness. E.g. Not professional or focused language. Not in control of the communication pattern

Stress: Pressures imposed by the situation which challenge the controller's ability to cope. E.g. Extended decision making & re-planning. Perceiving traffic situations normally set up are now getting too risky. Questioning own ability to cope

Inadequate Situation Awareness: Problems with the maintenance of a coherent mental picture for current and future controller performance. E.g. Lack of alternatives if plans change. Lack of awareness of what is coming and what is needed

Inadequate Teamwork: Controllers not working together effectively. E.g. Poor sector-to-sector coordination between controllers or between tactical and planner controllers

High Workload: High demand (amount and complexity) imposed by ATC tasks. E.g. Insufficient process time to refine and prioritise actions. Communications moving beyond capabilities

Underload: Very low demand (amount and complexity) imposed by ATC tasks. E.g. Boredom due to little traffic on frequency. Becoming inattentive or distracted during very quiet periods

***1. In your experience as an incident investigator, how frequently does the following combination lead to controller-related loss of separation incidents?**

	Very rarely	Rarely	Sometimes	Often	Very often
Inadequate teamwork AND Inadequate situation awareness	○	○	○	○	○

***2. In your experience as an incident investigator, how frequently does the following combination lead to controller-related loss of separation incidents?**

	Very rarely	Rarely	Sometimes	Often	Very often
Inadequate teamwork AND Underload	○	○	○	○	○

***3. In your experience as an incident investigator, how frequently does the following combination lead to controller-related loss of separation incidents?**

	Very rarely	Rarely	Sometimes	Often	Very often
Inadequate teamwork AND Stress	○	○	○	○	○

***4. In your experience as an incident investigator, how frequently does the following combination lead to controller-related loss of separation incidents?**

	Very rarely	Rarely	Sometimes	Often	Very often
Inadequate communication AND High workload	○	○	○	○	○

***5. In your experience as an incident investigator, how frequently does the following combination lead to controller-related loss of separation incidents?**

	Very rarely	Rarely	Sometimes	Often	Very often
Inadequate situation awareness AND Fatigue	○	○	○	○	○

***6. In your experience as an incident investigator, how frequently does the following combination lead to controller-related loss of separation incidents?**

	Very rarely	Rarely	Sometimes	Often	Very often
Inadequate communication AND Inadequate teamwork	○	○	○	○	○

Factor pairs (cont.)

Factor Definitions:

Fatigue: Feelings of tiredness or weariness caused by prolonged activity. E.g. Wanting to handover although it's not yet time. Making errors that don't normally happen. Missing more calls than normal. Asking for repeats

Inadequate Communications: Problems in the exchange of verbal information, including timeliness, accuracy, clarity and receptiveness. E.g. Not professional or focused language. Not in control of the communication pattern

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Underload: Very low demand (amount and complexity) imposed by ATC tasks. E.g. Boredom due to little traffic on frequency. Becoming inattentive or distracted during very quiet periods

***1. In your experience as an incident investigator, how frequently does the following combination lead to controller-related loss of separation incidents?**

	Very rarely	Rarely	Sometimes	Often	Very often
Fatigue AND Stress	○	○	○	○	○

***2. In your experience as an incident investigator, how frequently does the following combination lead to controller-related loss of separation incidents?**

	Very rarely	Rarely	Sometimes	Often	Very often
Stress AND Underload	○	○	○	○	○

***3. In your experience as an incident investigator, how frequently does the following combination lead to controller-related loss of separation incidents?**

	Very rarely	Rarely	Sometimes	Often	Very often
High workload AND Stress	○	○	○	○	○

***4. In your experience as an incident investigator, how frequently does the following combination lead to controller-related loss of separation incidents?**

	Very rarely	Rarely	Sometimes	Often	Very often
High workload AND Inadequate teamwork	○	○	○	○	○

*** 5. In your experience as an incident investigator, how frequently does the following combination lead to controller-related loss of separation incidents?**

	Very rarely	Rarely	Sometimes	Often	Very often
Stress AND Inadequate situation awareness	○	○	○	○	○

*** 6. In your experience as an incident investigator, how frequently does the following combination lead to controller-related loss of separation incidents?**

	Very rarely	Rarely	Sometimes	Often	Very often
Underload AND Fatigue	○	○	○	○	○

Factor pairs (cont.)

Factor Definitions:

Fatigue: Feelings of tiredness or weariness caused by prolonged activity. E.g. Wanting to handover although it's not yet time. Making errors that don't normally happen. Missing more calls than normal. Asking for repeats

Inadequate Communications: Problems in the exchange of verbal information, including timeliness, accuracy, clarity and receptiveness. E.g. Not professional or focused language. Not in control of the communication pattern

Stress: Pressures imposed by the situation which challenge the controller's ability to cope. E.g. Extended decision making & re-planning. Perceiving traffic situations normally set up are now getting too risky. Questioning own ability to cope

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Underload: Very low demand (amount and complexity) imposed by ATC tasks. E.g. Boredom due to little traffic on frequency. Becoming inattentive or distracted during very quiet periods

*** 1. In your experience as an incident investigator, how frequently does the following combination lead to controller-related loss of separation incidents?**

	Very rarely	Rarely	Sometimes	Often	Very often
Inadequate situation awareness AND Inadequate communication	○	○	○	○	○

*** 2. In your experience as an incident investigator, how frequently does the following combination lead to controller-related loss of separation incidents?**

	Very rarely	Rarely	Sometimes	Often	Very often
Underload AND Inadequate situation awareness	○	○	○	○	○

*** 3. In your experience as an incident investigator, how frequently does the following combination lead to controller-related loss of separation incidents?**

	Very rarely	Rarely	Sometimes	Often	Very often
Stress AND Inadequate communication	○	○	○	○	○

4. Please use this space to share any comments you may have regarding this exercise

Options

Thank you for answering these questions. You now have an option to leave the survey or continue to an additional 7 questions.

These additional questions focus on the impact of performance influences on controller performance. Findings will be used to identify the most critical factors that negativly impact controller performance. It will take approximately 10-15 minutes to answer these additional questions.

*** 1. Please choose an option below:**

○ I am happy to respond to the additional questions

○ I would not like to respond to the additional questions (proceed to optional demographic information and survey exit)

Instructions

You are about to see 7 questions which explore the impact of performance influences, such as stress and fatigue together, on controller performance.

Each question will present one performance-related factor. Please think of the factor as present in a controller's performance. You will also see 5 or 6 additional factors in a table. Based on your previous experience, please select the top three factors that would most negatively impact controller performance if they co-occurred with the initial factor.

Rank 1 represents that factor you believe would have the most negative impact on performance if combined with the initial factor. You may only place one factor in one ranking position. A full example of this exercise is presented below.

Each factor is defined at the top of each page, with accompanying examples of the negative implications of the factor in an ATC environment.

This is a completed example of the questions you are about to see. Please note that one factor is presented in the question. The 6 additional factors are presented in a ranking table.

In the example, 3 of the 6 factors have been ranked acccording to its impact on controller performance, assuming the factor were to co-occur with the initial factor of "inadequate teamwork".

Please note that only one factor per rank is permitted. For example, two factors could not both be placed in Rank 1. These two factors must be assigned separate ranks.

31. Which of the following performance influences would have the most negative effect on controller pe was already experiencing "inadequate teamwork"

	Inadequate teamwork AND Inadequate communication	Inadequate teamwork AND Fatigue	Inadequate teamwork AND Stress	Inadequate teamwork AND High workload
1 (Most impact)	○	○	○	✓
2	○	○	○	○
3	○	○	✓	○

Relationship impact

Factor Definitions:

Fatigue: Feelings of tiredness or weariness caused by prolonged activity. E.g. Wanting to handover although it's not yet time. Making errors that don't normally happen. Missing more calls than normal. Asking for repeats

Inadequate Communications: Problems in the exchange of verbal information, including timeliness, accuracy, clarity and receptiveness. E.g. Not professional or focused language. Not in control of the communication pattern

Stress: Pressures imposed by the situation which challenge the controller's ability to cope. E.g. Extended decision making & re-planning. Perceiving traffic situations normally set up are now getting too risky. Questioning own ability to cope

Inadequate Situation Awareness: Problems with the maintenance of a coherent mental picture for current and future controller performance. E.g. Lack of alternatives if plans change. Lack of awareness of what is coming and what is needed

Inadequate Teamwork: Controllers not working together effectively. E.g. Poor sector-to-sector coordination between controllers or between tactical and planner controllers

High Workload: High demand (amount and complexity) imposed by ATC tasks. E.g. Insufficient process time to refine and prioritise actions. Communications moving beyond capabilities

Underload: Very low demand (amount and complexity) imposed by ATC tasks. E.g. Boredom due to little traffic on frequency. Becoming inattentive or distracted during very quiet periods

1. Which of the following performance influences would have the most negative effect on controller performance if the controller was already experiencing a *high workload*

	High workload AND Fatigue	High workload AND Inadequate communication	High workload AND Inadequate situation awareness	High workload AND Inadequate teamwork	High workload AND Stress
1 (Most impact)	○	○	○	○	○
2	○	○	○	○	○
3	○	○	○	○	○

2. Which of the following performance influences would have the most negative effect on controller performance if the controller was already experiencing *underload*

	Underload AND Stress	Underload AND Inadequate communications	Underload AND Inadequate situation awareness	Underload AND Inadequate teamwork	Underload AND Fatigue
1 (Most impact)	○	○	○	○	○
2	○	○	○	○	○
3	○	○	○	○	○

3. Which of the following performance influences would have the most negative effect on controller performance if the controller was already experiencing *fatigue*

	Fatigue AND Stress	Fatigue AND High workload	Fatigue AND Inadequate situation awareness	Fatigue AND Underload	Fatigue AND Inadequate teamwork	Fatigue AND Inadequate communications
1 (Most impact)	○	○	○	○	○	○
2	○	○	○	○	○	○
3	○	○	○	○	○	○

4. Which of the following performance influences would have the most negative effect on controller performance if the controller was already experiencing *stress*

	Stress AND High workload	Stress AND Underload	Stress AND Inadequate communications	Stress AND Fatigue	Stress AND Inadequate situation awareness	Stress AND Inadequate teamwork
1 (Most impact)	○	○	○	○	○	○
2	○	○	○	○	○	○
3	○	○	○	○	○	○

5. Which of the following performance influences would have the most negative effect on controller performance if the controller was already experiencing *inadequate situation awareness*

	Inadequate situation awareness AND Underload	Inadequate situation awareness AND Inadequate teamwork	Inadequate situation awareness AND Stress	Inadequate situation awareness AND Inadequate communications	Inadequate situation awareness AND Fatigue	Inadequate situation awareness AND High workload
1 (Most impact)	○	○	○	○	○	○
2	○	○	○	○	○	○
3	○	○	○	○	○	○

6. Which of the following performance influences would have the most negative effect on controller performance if the controller was already experiencing *inadequate communication*

	Inadequate communication AND Fatigue	Inadequate communication AND Inadequate teamwork	Inadequate communication AND Stress	Inadequate communication AND Inadequate situation awareness	Inadequate communication AND Underload	Inadequate communication AND High workload
1 (Most impact)	○	○	○	○	○	○
2	○	○	○	○	○	○
3	○	○	○	○	○	○

7. Which of the following performance influences would have the most negative effect on controller performance if the controller was already experiencing *inadequate teamwork*

	Inadequate teamwork AND Inadequate communication	Inadequate teamwork AND Fatigue	Inadequate teamwork AND Stress	Inadequate teamwork AND High workload	Inadequate teamwork AND Underload	Inadequate teamwork AND Inadequate situation awareness
1 (Most impact)	○	○	○	○	○	○
2	○	○	○	○	○	○
3	○	○	○	○	○	○

Demographic information

Below are some demographic questions. Please note that questions are optional

1. Please select your age group:

- ○ 20 or younger
- ○ 21-30
- ○ 31-40
- ○ 41-50
- ○ 51-60
- ○ 60+

2. Gender

- ○ Male
- ○ Female

3. Please select your country of work

4. How many years of experience do you have in this occupation?

5. Are you currently a trainee?

- ○ Yes
- ○ No

Controllers: Instructions

You are about to see 21 pairs of performance influences, such as stress and fatigue, that may impact a controller's ability to provide a safe service. Based on your previous experience, please rate the frequency that each combination has negatively affected your ability to provide a safe service.

Controllers: Factor pairs

The following define the factors that are being considered. These definitions were created with a small group of expert controllers. You may want to print out these definitions to use with the remainder of the survey.

Factor Definitions:
Fatigue: Feelings of tiredness or weariness caused by prolonged activity. E.g. Wanting to handover although it's not yet time. Making errors that don't normally happen. Missing more calls than normal. Asking for repeats

Inadequate Communications: Problems in the exchange of verbal information, including timeliness, accuracy, clarity and receptiveness. E.g. Not professional or focused language. Not in control of the communication pattern

Stress: Pressures imposed by the situation which challenge the controller's ability to cope. E.g. Extended decision making & re-planning. Perceiving traffic situations normally set up are now getting too risky. Questioning own ability to cope

Inadequate Situation Awareness: Problems with the maintenance of a coherent mental picture for current and future controller performance. E.g. Lack of alternatives if plans change. Lack of awareness of what is coming and what is needed

Inadequate Teamwork: Controllers not working together effectively. E.g. Poor sector-to-sector coordination between controllers or between tactical and planner controllers

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Underload: Very low demand (amount and complexity) imposed by ATC tasks. E.g. Boredom due to little traffic on frequency. Becoming inattentive or distracted during very quiet periods

*** 1. In your experience as an air traffic controller, how frequently has the following combination negatively affected your ability to provide a safe service?**

	Very rarely	Rarely	Sometimes	Often	Very often
Inadequate situation awareness AND High workload	○	○	○	○	○

*** 2. In your experience as an air traffic controller, how frequently has the following combination negatively affected your ability to provide a safe service?**

	Very rarely	Rarely	Sometimes	Often	Very often
Fatigue AND Inadequate teamwork	○	○	○	○	○

*** 3. In your experience as an air traffic controller, how frequently has the following combination negatively affected your ability to provide a safe service?**

	Very rarely	Rarely	Sometimes	Often	Very often
Inadequate communication AND Fatigue	○	○	○	○	○

*** 4. In your experience as an air traffic controller, how frequently has the following combination negatively affected your ability to provide a safe service?**

	Very rarely	Rarely	Sometimes	Often	Very often
Underload AND Inadequate communication	○	○	○	○	○

*** 5. In your experience as an air traffic controller, how frequently has the following combination (one following the other) negatively affected your ability to provide a safe service?**

	Very rarely	Rarely	Sometimes	Often	Very often
High workload AND Underload	○	○	○	○	○

*** 6. In your experience as an air traffic controller, how frequently has the following combination negatively affected your ability to provide a safe service?**

	Very rarely	Rarely	Sometimes	Often	Very often
Fatigue AND High workload	○	○	○	○	○

Controllers: Factor pairs (cont.)

Factor Definitions:
Fatigue: Feelings of tiredness or weariness caused by prolonged activity. E.g. Wanting to handover although it's not yet time. Making errors that don't normally happen. Missing more calls than normal. Asking for repeats

Inadequate Communications: Problems in the exchange of verbal information, including timeliness, accuracy, clarity and receptiveness. E.g. Not professional or focused language. Not in control of the communication pattern

Stress: Pressures imposed by the situation which challenge the controller's ability to cope. E.g. Extended decision making & re-planning. Perceiving traffic situations normally set up are now getting too risky. Questioning own ability to cope

Inadequate Situation Awareness: Problems with the maintenance of a coherent mental picture for current and future controller performance. E.g. Lack of alternatives if plans change. Lack of awareness of what is coming and what is needed

Inadequate Teamwork: Controllers not working together effectively. E.g. Poor sector-to-sector coordination between controllers or between tactical and planner controllers

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Underload: Very low demand (amount and complexity) imposed by ATC tasks. E.g. Boredom due to little traffic on frequency. Becoming inattentive or distracted during very quiet periods

*** 1. In your experience as an air traffic controller, how frequently has the following combination negatively affected your ability to provide a safe service?**

	Very rarely	Rarely	Sometimes	Often	Very often
Inadequate teamwork AND Inadequate situation awareness	○	○	○	○	○

*** 2. In your experience as an air traffic controller, how frequently has the following combination negatively affected your ability to provide a safe service?**

	Very rarely	Rarely	Sometimes	Often	Very often
Inadequate teamwork AND Underload	○	○	○	○	○

*** 3. In your experience as an air traffic controller, how frequently has the following combination negatively affected your ability to provide a safe service?**

	Very rarely	Rarely	Sometimes	Often	Very often
Inadequate teamwork AND Stress	○	○	○	○	○

*** 4. In your experience as an air traffic controller, how frequently has the following combination negatively affected your ability to provide a safe service?**

	Very rarely	Rarely	Sometimes	Often	Very often
Inadequate communication AND High workload	○	○	○	○	○

*** 5. In your experience as an air traffic controller, how frequently has the following combination negatively affected your ability to provide a safe service?**

	Very rarely	Rarely	Sometimes	Often	Very often
Inadequate situation awareness AND Fatigue	○	○	○	○	○

*** 6. In your experience as an air traffic controller, how frequently has the following combination negatively affected your ability to provide a safe service?**

	Very rarely	Rarely	Sometimes	Often	Very often
Inadequate communication AND Inadequate teamwork	○	○	○	○	○

Controllers: Factor pairs (cont.)

Factor Definitions:

Fatigue: Feelings of tiredness or weariness caused by prolonged activity. E.g. Wanting to handover although it's not yet time. Making errors that don't normally happen. Missing more calls than normal. Asking for repeats

Inadequate Communications: Problems in the exchange of verbal information, including timeliness, accuracy, clarity and receptiveness. E.g. Not professional or focused language. Not in control of the communication pattern

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Underload: Very low demand (amount and complexity) imposed by ATC tasks. E.g. Boredom due to little traffic on frequency. Becoming inattentive or distracted during very quiet periods

*** 1. In your experience as an air traffic controller, how frequently has the following combination negatively affected your ability to provide a safe service?**

	Very rarely	Rarely	Sometimes	Often	Very often
Fatigue AND Stress	○	○	○	○	○

*** 2. In your experience as an air traffic controller, how frequently has the following combination negatively affected your ability to provide a safe service?**

	Very rarely	Rarely	Sometimes	Often	Very often
Stress AND Underload	○	○	○	○	○

*** 3. In your experience as an air traffic controller, how frequently has the following combination negatively affected your ability to provide a safe service?**

	Very rarely	Rarely	Sometimes	Often	Very often
High workload AND Stress	○	○	○	○	○

*** 4. In your experience as an air traffic controller, how frequently has the following combination negatively affected your ability to provide a safe service?**

	Very rarely	Rarely	Sometimes	Often	Very often
High workload AND Inadequate teamwork	○	○	○	○	○

*** 5. In your experience as an air traffic controller, how frequently has the following combination negatively affected your ability to provide a safe service?**

	Very rarely	Rarely	Sometimes	Often	Very often
Stress AND Inadequate situation awareness	○	○	○	○	○

*** 6. In your experience as an air traffic controller, how frequently has the following combination negatively affected your ability to provide a safe service?**

	Very rarely	Rarely	Sometimes	Often	Very often
Underload AND Fatigue	○	○	○	○	○

Controllers: Factor pairs (cont.)

Factor Definitions:

Fatigue: Feelings of tiredness or weariness caused by prolonged activity. E.g. Wanting to handover although it's not yet time. Making errors that don't normally happen. Missing more calls than normal. Asking for repeats

Inadequate Communications: Problems in the exchange of verbal information, including timeliness, accuracy, clarity and receptiveness. E.g. Not professional or focused language. Not in control of the communication pattern

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Underload: Very low demand (amount and complexity) imposed by ATC tasks. E.g. Boredom due to little traffic on frequency. Becoming inattentive or distracted during very quiet periods

*** 1. In your experience as an air traffic controller, how frequently has the following combination negatively affected your ability to provide a safe service?**

	Very rarely	Rarely	Sometimes	Often	Very often
Inadequate situation awareness AND Inadequate communication	○	○	○	○	○

*** 2. In your experience as an air traffic controller, how frequently has the following combination negatively affected your ability to provide a safe service?**

	Very rarely	Rarely	Sometimes	Often	Very often
Underload AND Inadequate situation awareness	○	○	○	○	○

*** 3. In your experience as an air traffic controller, how frequently has the following combination negatively affected your ability to provide a safe service?**

	Very rarely	Rarely	Sometimes	Often	Very often
Stress AND Inadequate communication	○	○	○	○	○

4. Please use this space to share any comments you may have regarding this exercise

Controllers: Options

Thank you for answering these questions. You now have an option to leave the survey or continue to an additional 7 questions.

These additional questions focus on the impact of performance influences on controller performance. Findings will be used to identify the most critical factors that negativly impact controller performance. It will take approximately 10-15 minutes to answer these additional questions.

* 1. Please choose an option below:

○ I am happy to respond to the additional questions

○ I would not like to respond to the additional questions (proceed to optional demographic information and survey exit)

Controllers: Instructions

You are about to see 7 questions which explore the impact of performance influences, such as stress and fatigue together, on controller performance.

Each question will present one performance-related factor. Please think of the factor as present in a your performance. You will also see 5 or 6 additional factors in a table. Based on your previous experience, please select the top three factors that would most negatively impact your performance if they co-occurred with the initial factor.

Rank 1 represents that factor you believe would have the most negative impact on performance if combined with the initial factor. You may only place one factor in one ranking position. A full example of this exercise is presented below.

Each factor is defined at the top of each page, with accompanying examples of the negative implications of the factor in an ATC environment.

This is a completed example of the questions you are about to see. Please note that one factor is presented in the question. The 6 additional factors are presented in a ranking table.

In the example, 3 of the 6 factors have been ranked acccording to its impact on controller performance, assuming the factor were to co-occur with the initial factor of "inadequate teamwork".

Please note that only one factor per rank is permitted. For example, two factors could not both be placed in Rank 1. These two factors must be assigned separate ranks.

7. Imagine you are experiencing "inadequate teamwork". Which three of the following factors would hav on your ability to handle the traffic?

	Inadequate teamwork AND Inadequate communication	Inadequate teamwork AND Fatigue	Inadequate teamwork AND Stress	Inadequate teamwork AND High workload
1 (Most impact)	○	○	○	✓
2	○	○	○	○
3	○	○	✓	○

Controllers: Relationship impact

Factor Definitions:
Fatigue: Feelings of tiredness or weariness caused by prolonged activity. E.g. Wanting to handover although it's not yet time. Making errors that don't normally happen. Missing more calls than normal. Asking for repeats

Inadequate Communications: Problems in the exchange of verbal information, including timeliness, accuracy, clarity and receptiveness. E.g. Not professional or focused language. Not in control of the communication pattern

Stress: Pressures imposed by the situation which challenge the controller's ability to cope. E.g. Extended decision making & re-planning. Perceiving traffic situations normally set up are now getting too risky. Questioning own ability to cope

Inadequate Situation Awareness: Problems with the maintenance of a coherent mental picture for current and future controller performance. E.g. Lack of alternatives if plans change. Lack of awareness of what is coming and what is needed

Inadequate Teamwork: Controllers not working together effectively. E.g. Poor sector-to-sector coordination between controllers or between tactical and planner controllers

High Workload: High demand (amount and complexity) imposed by ATC tasks. E.g. Insufficient process time to refine and prioritise actions. Communications moving beyond capabilities

Underload: Very low demand (amount and complexity) imposed by ATC tasks. E.g. Boredom due to little traffic on frequency. Becoming inattentive or distracted during very quiet periods

1. Imagine you are experiencing a *high workload*. Which three of the following factors would have the most negative effect on your ability to handle the traffic?

	High workload AND Fatigue	High workload AND Inadequate communication	High workload AND Inadequate situation awareness	High workload AND Inadequate teamwork	High workload AND Stress
1 (Most impact)	○	○	○	○	○
2	○	○	○	○	○
3	○	○	○	○	○

2. Imagine you are experiencing *underload*. Which three of the following factors would have the most negative effect on your ability to handle the traffic?

	Underload AND Stress	Underload AND Inadequate communications	Underload AND Inadequate situation awareness	Underload AND Inadequate teamwork	Underload AND Fatigue
1 (Most impact)	○	○	○	○	○
2	○	○	○	○	○
3	○	○	○	○	○

3. Imagine you are experiencing *fatigue*. Which three of the following factors would have the most negative effect on your ability to handle the traffic?

	Fatigue AND Stress	Fatigue AND High workload	Fatigue AND Inadequate situation awareness	Fatigue AND Underload	Fatigue AND Inadequate teamwork	Fatigue AND Inadequate communications
1 (Most impact)	○	○	○	○	○	○
2	○	○	○	○	○	○
3	○	○	○	○	○	○

4. Imagine you are experiencing *stress*. Which three of the following factors would have the most negative effect on your ability to handle the traffic?

	Stress AND High workload	Stress AND Underload	Stress AND Inadequate communications	Stress AND Fatigue	Stress AND Inadequate situation awareness	Stress AND Inadequate teamwork
1 (Most impact)	○	○	○	○	○	○
2	○	○	○	○	○	○
3	○	○	○	○	○	○

5. Imagine you are experiencing *inadequate situation awareness*. Which three of the following factors would have the most negative effect on your ability to handle the traffic?

	Inadequate situation awareness AND Underload	Inadequate situation awareness AND Inadequate teamwork	Inadequate situation awareness AND Stress	Inadequate situation awareness AND Inadequate communications	Inadequate situation awareness AND Fatigue	Inadequate situation awareness AND High workload
1 (Most impact)	○	○	○	○	○	○
2	○	○	○	○	○	○
3	○	○	○	○	○	○

6. Imagine you are experiencing *inadequate communication*. Which three of the following factors would have the most negative effect on your ability to handle the traffic?

	Inadequate communication AND Fatigue	Inadequate communication AND Inadequate teamwork	Inadequate communication AND Stress	Inadequate communication AND Inadequate situation awareness	Inadequate communication AND Underload	Inadequate communication AND High workload
1 (Most impact)	○	○	○	○	○	○
2	○	○	○	○	○	○
3	○	○	○	○	○	○

7. Imagine you are experiencing *inadequate teamwork*. Which three of the following factors would have the most negative effect on your ability to handle the traffic?

	Inadequate teamwork AND Inadequate communication	Inadequate teamwork AND Fatigue	Inadequate teamwork AND Stress	Inadequate teamwork AND High workload	Inadequate teamwork AND Underload	Inadequate teamwork AND Inadequate situation awareness
1 (Most impact)	○	○	○	○	○	○
2	○	○	○	○	○	○
3	○	○	○	○	○	○

Controllers: Demographic information

Below are some demographic questions. Please note that questions are optional

1. Please select your age group:

- ○ 20 or younger
- ○ 21-30
- ○ 31-40
- ○ 41-50
- ○ 51-60
- ○ 60+

2. Gender

- ○ Male
- ○ Female

3. Please select your country of work

4. In which areas have you received training?

- ○ Tower
- ○ Approach/TRACON
- ○ En-route

5. In which area do you most frequently work?

- ○ Tower
- ○ Approach/TRACON
- ○ En-route

6. How many years experience do you have in air traffic control?

7. Are you currently a trainee?

- ○ Yes
- ○ No

Thank you!

Thank you for your time and participation in this survey. Your responses are much appreciated.
You have now completed the questionnaire.

Please enter a valid email adress below if you wish to receive the results of the survey. This is optional; however, if you do not provide a valid email address you will not receive any further information or results from this study.

If you provide an email address (below) please expect to receive feedback on the results within the next 2-3 months.

If you have any questions/comments, please contact Tamsyn Edwards
Email address: expte@nottingham.ac.uk
or call: +44(0)115 951 4033

1. Please enter a valid email address if you would like to receive feedback

Appendix 5. Instantaneous self assessment of workload

5. Excessive

4.5

4. High

3.5

3. Comfortable

2.5

2. Relaxed

1.5

1. Under-utilised

Appendix 6. Karolinska sleepiness scale

1. Extremely alert

2.

3. Alert

4.

5. Sleepy – but no difficulty remaining awake

6.

7. Extremely sleepy – fighting sleep

Appendix 7. Review of self-report measures of fatigue

Scale	Authors, papers used	Comments
Visual analog scales	Kabar. 100mm VAS, anchored with 'struggling to remain awake' on the left, and 'extremely alert and wide awake' on the right'.	
Karolinska sleepiness scale		Measures sleepiness rather than task related mental fatigue. May be considered in addition to fatigue scales.
Multidimensional fatigue inventory		Covers several scales of fatigue, including physical fatigue. More appropriate to measure mental fatigue.
Fatigue Symptom Checklist		Generally used in clinical samples. General fatigue rather than mental fatigue.
The Short Questionnaire for Current Strain	Müller & Basler, 1993	Used to measure fatigue and strain before and after exercise.
Activation–deactivation affect adjective check list (ADACL)	Thayer (1989)	Assesses tiredness, energy, calmness and tension. Possibly too wide a focus for this study.
The Swedish occupational fatigue inventory (SOFI)	Ahsberg et al., 1997. Developed for measuring work-related perceived fatigue.	25 expressions categorized into five latent subscales.
The Fatigue Severity Scale (FSS)	Krupp LB, LaRocca NG, Muir-Nash J, Steinberg AD. 1989;46:1121–3.	Has been previously used in clinical research.
SamnePerelli Fatigue Scale	Samn and Perelli (1982)	Used in fatigue measures of train controllers. 7-point scale with associated anchors

Appendix 8. Fatigue visual analogue scale

Not at all fatigued |————————————————| **Extremely fatigued**

Subject no. ______

Section 3: Stress Arousal Checklist

The adjectives below describe different feelings and moods. Please use this list to describe your feelings at this moment in time.

If the adjective *definitely describes your feelings* circle the:

(++) + ? -

If the adjective *more or less describes your feelings* circle the:

++ (+) ? -

If you do not understand the adjective, or you *cannot decide whether it describes how you feel* circle the:

++ + (?) -

If the adjective *does not describe the way you feel* circle the:

++ + ? (-)

Your first reactions will be the most reliable, therefore do not spend too long thinking about each adjective. Please be as honest and accurate as possible.

Tense	++ + ? -	Tired	++ + ? -
Relaxed	++ + ? -	Idle	++ + ? -
Restful	++ + ? -	Up tight	++ + ? -
Active	++ + ? -	Alert	++ + ? -
Apprehensive	++ + ? -	Lively	++ + ? -
Worried	++ + ? -	Cheerful	++ + ? -
Energetic	++ + ? -	Contented	++ + ? -
Drowsy	++ + ? -	Jittery	++ + ? -
Bothered	++ + ? -	Sluggish	++ + ? -
Uneasy	++ + ? -	Pleasant	++ + ? -
Dejected	++ + ? -	Sleepy	++ + ? -
Nervous	++ + ? -	Comfortable	++ + ? -
Distressed	++ + ? -	Calm	++ + ? -
Vigorous	++ + ? -	Stimulated	++ + ? -
Peaceful	++ + ? -	Activated	++ + ? -

Appendix 10. Situation present assessment questions

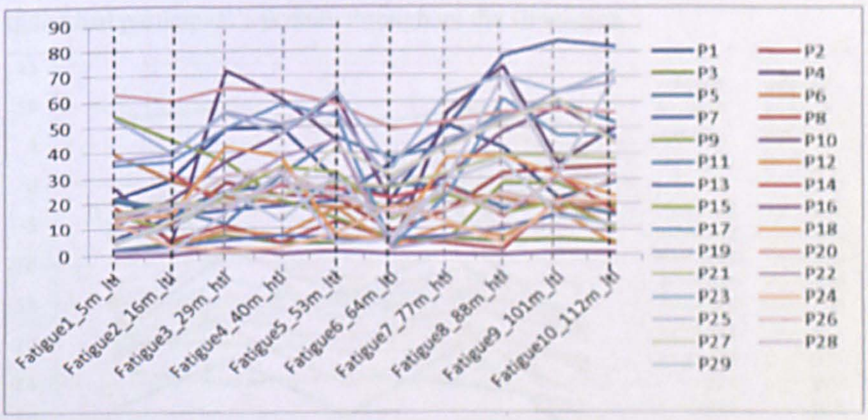
1. Are any aircraft about to come into your sector?
2. Will you need to transfer any aircraft soon?
3. Are any aircraft in conflict or about to be in conflict
4. Will you need to change the routing of any aircraft?
5. Are there any aircraft with crossing flight paths right now
6. What is the highest flight level an aircraft is currently occupying in your sector
7. Are any aircraft following each other on the same flight path

Appendix 11. Competency areas included in the competency test

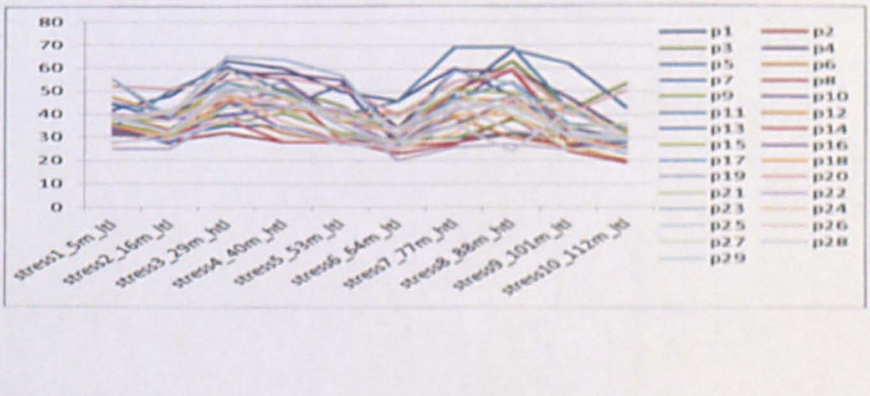
1. Flight level understanding
2. Heading
3. Communications
4. Control steps
5. How to control aircraft
6. Expedite rule
7. Route directs
8. Conflict detection
9. Conflict resolution
10. Sectors
11. Purpose and objectives of ATC
12. Coordination

Appendix 12. Individual differences in the measurements of fatigue, stress, arousal, SA and posture

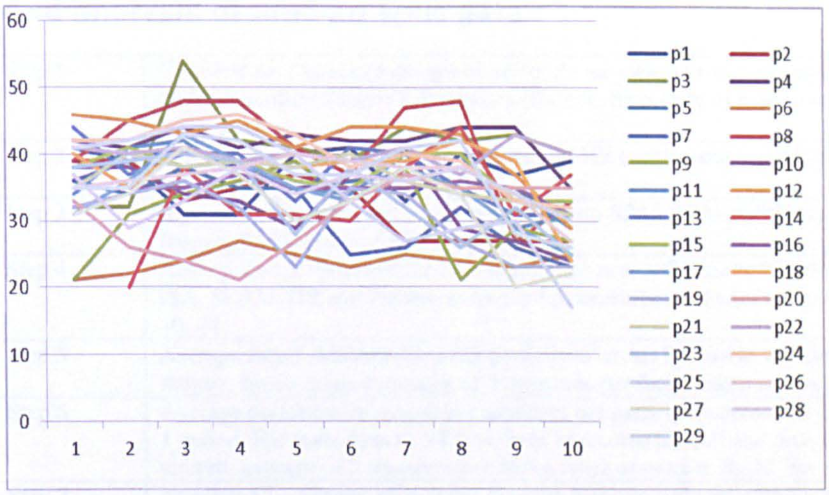
Individual participant fatigue ratings throughout the simulation



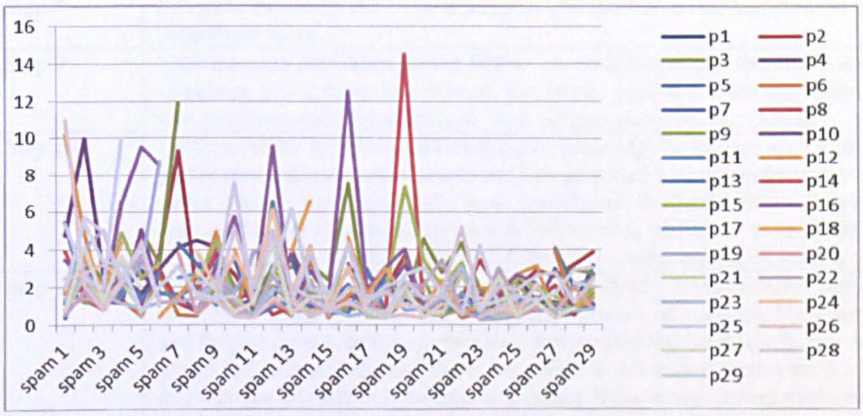
Individual participant stress ratings throughout the simulation



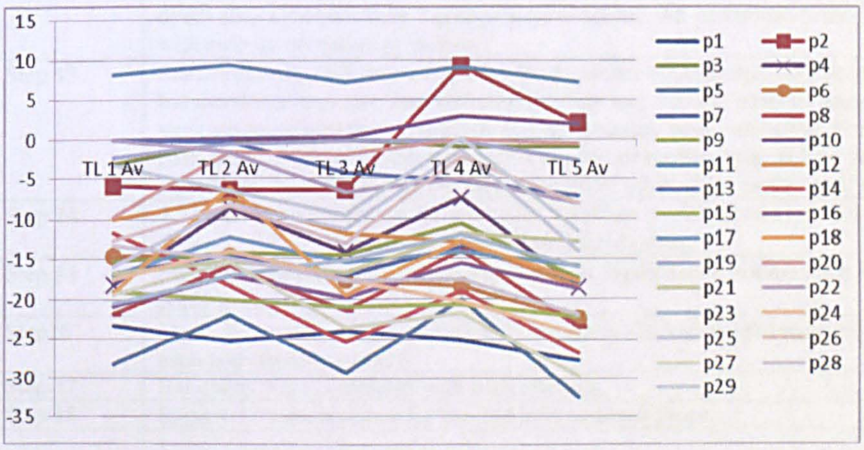
Individual participant arousal ratings throughout the simulation



Individual participant SA throughout the simulation



Individual participant's posture throughout the simulation



Appendix 13. Table of steps for applying median splits to data and analysis of median split data

Step 1	Calculate four minute averages of performance measures (time to assume aircraft, time to respond to offered aircraft, frequency of stcas, frequency of route directs) for each participant.
Step 2	Calculate 4 minute averages of posture and HR (continuous measurement) for each participant
Step 3	Input above data and self report measures into SPSS (ISA-workload; SPAM - SA; VAS-fatigue; SACL-stress; SACL-arousal)
Step 4	Average factor measures for each participant across 20minute high taskload 1 period. For ISA, SPAM, HR and Posture average of 5 measures per factor taken at minute 28, 32, 36, 40, 44.
Step 5	Average factor measures for each participant across 20minute workload period. For fatigue, stress, arousal average of 2 measures per factor taken at minute 29 and 40.
Step 6	Average performance measures calculated per participant across 20 minute high taskload 1 period. For route directs, STCAs, time to assume aircraft and time to respond to offered aircraft, average of 5 measures per factor taken at minute 28, 32, 36, 40, 44.
Step 7	Now have 1 score per participant for each measure and performance marker for high taskload 1.
Step 8	Frequencies conducted on each measure and marker to find midpoint in terms of participant score.
Step 9	Each measure regrouped within SPSS – those falling below the mid-point became low workload, low fatigue, low arousal, low stress, good SA. Each individual score above the mid-point became high workload, high fatigue, poor SA, high stress.
Step 10	Customs tables for each individual factor (now high or low for each individual) with each performance marker was completed. This provided a mean performance score for each factor group – for example, for those participants in workload low (14 participants) the average time to assume aircraft was 62.08 second, whilst the mean for all participants in group 2, or high workload was 69.77. this was conducted for all measures per marker
Step 11	Custom tables were then completed for factor dyads. So each factor group was recoded into SPSS, so that participants were grouped into 1 of 4 groups. For example if workload and fatigue were together, participants low in workload and low fatigue were placed in group 1. The rest of the variations became 2-4. All factors were paired with each other in this way for all performance markers. Again, the average performance for each group, i.e. participants with low workload and low fatigue, was calculated.
Step 12	Custom tables were then completed for factor Triads. This was a similar process to the dyads above, but this time 8 groups were available. All performance markers were paired with each combination of factors.
Step 13	Statistical tests were then conducted. First, parametric assumptions needed to be tested. Independence was met, interval/ratio data was met. Levene's test of homogeneity of variance and Kolmogorov-smirnov test of normality were conducted. For each performance marker within the context of a factor median split, at least one was significant. Non parametric tests were therefore selected for further analysis.
Step 14	All factor measure groups were recoded, so if low workload and low fatigue, this became group 1. each combination became a new, coded group.
Step 15	Mann-Whitney tests were conducted on each dyadic factor combination for each performance marker
Step16	Mann-Whitney tests were conducted on each triadic factor combination in relation to each performance marker.
Step 17	Bar charts were completed with each analysis
Step 18	Steps 4-17 were repeated for the 2nd high taskload phase.

Appendix 14. Results from statistical analyses of median split data for all factor dyads and combinations with performance

Significance results for dyad factor combinations, high taskload 1

Factor combination	STCAs	Time to assume aircraft	Time to respond to offered aircraft	Route directs	Posture
Workload & fatigue	low MWL, LF vs. High MWL, HF, p=0.07	NS	NS	Low MWL LF vs. High MWL LS p=0.01	NS
Workload & stress	NS	NS	NS	NS	NS
Workload & Arousal	NS	NS	NS	Low MWL LA vs. High MWL HA p=0.06	Low workload LA vs. Low MWL HA p=0.02
Workload & SA	low MWL, poor SA vs. High MWL, good SA – p=0.05	Low MWL, poor SA vs. High MWL, good SA, p=0.06	NS	NS	NS
Fatigue & Stress	NS	LF,LS vs. HF,LS p=0.08	NS	NS	NS
Fatigue & Arousal	LF,LA vs. LF, HA – p=0.02	NS	NS	HF LA vs. HF HA p=0.08	LF, LA vs. LF HA p=0.01
	LF,LA vs. HF,LA – p=0.03				LF LA vs. HF HA p=0.05
Fatigue & SA	NS	NS	NS	NS	NS
Stress & Arousal	LS,LA vs., HA – p=0.1	LS,LA vs. HS,LA p=0.04	NS	LS LA vs. LS HA p=0.05	LS LA vs. LS HA p=0.02
		HS,HA vs. HS,LA p=0.07			
Stress & SA	NS	HS good SA vs. HS poor SA p=0.05	NS	NS	NS
		LS good SA vs. HS poor SA p=0.1			
Arousal & SA	LA, poor SA vs. HA, good SA, p=0.07	NS	NS	LS SR vs. HA SR p=0.03	LA poor SA vs. HA good SA p=0.09
				LA SR vs. HA p<0.05	LA poor SA vs. HA poor SA p=0.09

Significant results for triad factor combinations, high taskload 1

Factor combination	Marker: STCAs	Reaction time to assume aircraft	Reaction time offered aircraft	Route directs for aircraft	Posture
Workload, fatigue, stress	NS	Low MWL LF HS vs. High MWL LF HS p=0.06	NS	NS	NS
		Low MWL LF HS vs. High MWL HF LS p=0.08			
Workload, fatigue, arousal	Low MWL, LF LA vs. Low MWL HF LA p=0.04	NS	NS	Low MWL HF LA vs. High MWL LF HA p=0.09	Low MWL LF LA vs. Low MWL LF HA p=0.02
	Low MWL LF HA vs. Low MWL LF LA p=0.02				Low MWL LF LA vs. High MWL LF HA p=0.03
	Low MWL LF LA vs. High MWL LF HA p=0.02				Low MWL LF LA vs. Low MWL HF LA p=0.02
					Low MWL LF LA vs. High

					MWL HF HA p<0.09
Workload, fatigue, SA	Low MWL LF Slow response vs. High MWL LF SR p=0.02 Low MWL LF SR vs. High MWL HF FR p=0.05 High MWL LF SR vs. High MWL HF SR p=0.9	Low MWL LF FR vs. High MWL HF FR p=0.04 Low MWL LF SR vs. High MWL HF FR p=0.05	NS	Low MWL LF SR vs. High MWL LF SR p=0.03	NS
Workload, stress, arousal	NS	NS	High MWL LS LA vs. High MWL HS LA p=0.06 High MWL LS LA vs. High MWL LS HA p=0.08	High MWL LS LA vs. High MWL LS HA p<0.08	Low MWL LS LA vs. Low MWL LS HA p=0.01
Workload, stress, SA	Low MWL, LS SR vs. High MWL LS FR p=0.09	NS	NS	NS	NS
Workload, arousal, SA	High MWL LA FR vs. High MWL LA SR p=0.06 Low MWL LA SR vs. High MWL LA FR p<0.08	Low MWL HA FR vs. High MWL HA FR p=0.05 High MWL LA SR vs. High MWL HA FR p=0.09	NS	High MWL LA SR vs. High MWL HA SR p=0.01 Low MWL HA SR vs. High MWL HA SR p=0.05 Low MWL LA FR vs. High MWL HA SR p=0.05 High MWL LA FR vs. High MWL LA SR p=0.06 Low MWL LA SR vs. High MWL HA SR p=0.07 Low MWL HA FR vs. High MWL LA SR p=0.1	Low MWL LA SR vs., Low MWL HA FR p=0.08 Low MWL LA SR vs. Low MWL HA SR p=0.08
Fatigue, stress, arousal	LF LS HA vs. LF HS LA p=0.08 LF HS LA vs. HF HS HA p=0.08	LF HS LA vs. LF HS HA p=0.06 LF HS LA vs. HF LS LA p=0.06	LF HS LA vs. HF HS LA p=0.05 HF LS LA vs. HF HS LA p=0.05	LF LS HA vs. HF LS LA p=0.04 HF LS LA vs. HF HS LA p=0.05 HF LS LA vs. HF LS HA p=0.06 LF HS HA vs. HF LS LA p=0.08	LF LS LA vs. HF LS HA p=0.06 LF LS LA vs. LF LS HA p=0.01 LF LS LA vs. LF HS HA p<0.08
Fatigue, stress, SA	NS	HF HS FR vs. HF HS SR p=0.03 HF LS SR vs. HF HS FR p=0.03 LF HS FR vs. HF HS SR p=0.05 HF LS FR vs. HF HS SR p=0.05 LF LS FR vs. HF HS SR p=0.05	LF HS SR vs. HF HS SR p=0.08	NS	NS

		LF HS SR vs. HF HS SR p=0.08			
Fatigue, arousal, SA	LF LA SR vs. HF LA FR p=0.05	NS	HF LA FR vs. HF HA FR p=0.03	HF LA SR vs. HF HA SR p=0.06	LF LA SR vs. LF HA SR p=0.03
	LF LA SR vs. LF HA FR p=0.07		HF HA FR vs. HF HS SR p=0.08	LF HA SR vs. HF LA SR p=0.07	LF LA SR vs. HF HA SR p=0.08
			LF LA FR vs. HF HA SR p=0.08		LF LA SR vs. LF HA FR p=0.08
Stress, arousal, SA	LS HA SR vs. HS HA SR p=0.05	LS LA FR vs. HS LA SR p=0.03	NS	NS	LS LA SR vs. LS HA FR p=0.06
	LS LA SR vs. HS HA SR p=0.05	HS LA SR vs. HS HA FR p=0.03			LS LA FR vs. LS HA FR p=0.06
	HS LA FR vs. HSLA SR p=0.05	HS LA FR vs. HS LA SR p=0.03			
	HS LA SR vs. HS HA FR =0.08	LS LA SR vs. HS LA SR p=0.03			
	HS LA SR vs. HS HA SR p=0.07	LS HA FR vs. HS HA FR p=0.05			
	LS HA FR vs. HA LS SR p=0.08	LS HA SR vs. HS LA SR p=0.05			
		LS HA SR vs. HS LA SR p=0.05			

Significant results for dyad factor combinations, high taskload 2

Factor combination	Marker: STCAs	Reaction time to assume aircraft	Reaction time offered aircraft	Route directs for aircraft	Posture
Workload & fatigue	NS	NS	NS	Low MWL LF vs. High MWL HF p=0.08	NS
Workload & stress	NS	NS	NS	NS	NS
Workload & Arousal	NS	Low MWL LA vs. Low MWL HA p=0.06	NS	NS	NS
Workload & SA	NS	NS	NS	Low MWL good SA vs. Low MWL poor SA p=0.01	NS
				Low MWL good SA vs. High MWL good SA p=0.03	
Fatigue & Stress	NS	LF LS vs. HF LS p=0.09	NS	NS	NS
Fatigue & Arousal	NS	LF LA vs. LF HA p=0.09	NS	LF LA vs. LF HA p=0.06	NS
				LF LA vs. HF HA p=0.08	
Fatigue & SA	NS	LF poor SA vs. HF poor SA p=0.1	NS	LF good SA vs. HF poor SA p=0.01	NS
Stress & Arousal	NS	NS	NS	NS	NS
Stress & SA	NS	NS	NS	NS	NS
Arousal & SA	NS	NS	NS	NS	Interaction (parametric) p<0.005

Significant results for triad factor combinations, high taskload 2

Factor combination	Marker: STCAs	Reaction time to assume aircraft	Reaction time offered aircraft	Route directs for aircraft	Posture
Workload, fatigue, stress	NS	NS	High MWL HF LS vs. High MWL HF HS p=0.08 Low MWL LF HS vs. Low MWL HF HS p=0.08	NS	NS
Workload, fatigue, arousal	NS	Low MWL LFL A vs. Low MWL LF HA p=0.02 Low MWL LF HA vs. Low MWL HF HA p=0.04 Low MWL LF HA vs. Low MWL HF LA p=0.07	NS	NS	NP – Low MWL LF LA vs. High MWL HF HA =p=0.06 p<0.05 3 way interaction. MW=p=0.06 WL main effect p< 0.05
Workload, fatigue, SA	NS	Low MWL LF SR vs. High MWL HF SR p=0.06 Low MWL LF SR vs. Low MWL HF SR p=0.07	NS	Low MWL LF FR vs. Low MWL HF SR p=0.02 Low MWL HF FR vs. Low MWL HF SR p=0.08 Low MWL HS SR vs. High MWL LS SR p=0.09	NP: Low MWL HF FR vs. Low MWL HF SR p=0.08
Workload, stress, arousal	NS	Low MWL LS LA vs. Low MWL HS HA p=0.06	High MWL LS LA vs. High MWL HS LA p=0.03 Low MWL HS HA vs. High MWL LS LA p=0.08	Low MWL HS HA vs. High MWL HS HA p=0.06 Low MWL LS HA vs. Low MWL HS HA p=0.06	p<0.05 3 way int. NP: High MWL LS LA vs. High MWL LS HA p=0.08 Low MWL LS LA vs. High MWL LS LA p=0.08 Low MWL HS HA vs. High MWL LS LA p=0.08
Workload, stress, SA	Low MWL HS FR vs. High MWL LA SR p=0.06	High MWL HS FR vs. High MWL HS SR p=0.08 Low MWL HS FR vs. High MWL HS SR p<0.07	NS	Low MWL LS SR vs. Low MWL HS FR p=0.05 Low MWL LS FR vs. Low MWL LS SR p=0.02 Low MWL LS FR vs. High MWL HS SR p<0.07	
Workload, arousal, SA	Low MWL HA FR vs. High MWL HA SR p=0.08	NS	NS	Low MWL LA FR vs. Low MWL LA SR p=0.03 Low MWL LA SR vs. Low MWL HA SR p=0.03	Low MWL LA FR vs. High MWL LA SR p=0.03 Low MWL LA FR vs. High MWL HA FR p=0.06 High MWL LA SR vs. High MWL HA SR

					p=0.08
				Low MWL LA FR vs. High MWL HA FR p=0.06	Para: A and SA int p<0.005
					Para: WL p=0.06
Fatigue, stress, arousal	NS	LF LS HA vs. HF LS HA p=0.04	NS	LF LS LA vs. LF LS HA p=0.07	NS
		LF LS HA vs. .HF LS LA p=0.09			
Fatigue, stress, SA	parametric= p=0.06 SA, p<0.05 3 way interaction	NS	NS	LF LS FR vs. HF HS SR p=0.02	NS
Fatigue, arousal, SA	NS	LF HA FR vs. HF LA SR p=0.08	NS	LF LA FR vs. HF LA SR p=0.03	LF LA FR vs. HF LA SR p=0.08
				LF LA SR vs. HF HA FR p=0.05	Parametric – A & SA interaction p=0.07
Stress, arousal, SA	NS	HS LA FR vs. HS LA SR p=0.05	NS	LS LA FR vs. LS HA SR p=0.1	HS LA5 FR vs. HS LA SR p=0.05
		LS LA FR vs. LS HA SR p=0.09			Parametric: A & SA p=0.01
		LS HA SR vs. HS LA SR p=0.1			

Appendix 15. Initial 137 behavioural markers

Behavioural markers
Mouthing' instructions or flight levels etc under breath
'oh well'
Angry
Arms folded
Bang mouse on table?
Bite finger
Blink more- keeping awake?
Blinking hard
Blinking slower
Blow cheeks out
Bottom lip out
Burst of sudden activity (usually after a 1 min 'rest' from completing SACL)
Cheek twitch
Chew bottom lip
Chew inside cheek
Clench fist
Clicking inaccuracy/errors
Clicking with no need
Come on
Cradle face
Defensive controlling - reactive
Drink
Drowsy (narrowing eyelids etc.)
Eyebrows pulled together-frown
Eyebrows raised
Eyebrows together and up – puzzled?
Eyes wide
Face red
Face relaxed
Face scrunched 'what?'
Faster and more clicking
Fidgeting with arm
forgetting
Glance away from screen
Grouped controlling
Hand in fist
Hand in lap
Hand off mouse
Hand to face
Hand to face - fidgeting
Hand to mouth – not sighing
Harder clicking
Head down (chin towards chest)
Head forward
Head supported by hands
Head to side- considering?
Head up (straightened to be level with screen)
Hmm'
Hold arm
Hold breath
Hunched/body close together
Itch face
Itch head
Itch leg
Itch neck
Jerky and sudden movements
Jerky head movements
Laugh
Leaning on desk
Less eye movement
Lick lips
Little movement/still
Look at watch
More decisive actions
More eye movement, faster
More focused on centre
More moving
Mouth open
Move head around the screen instead of just eyes
Move jaw
Moving leg up and down
Moving side to side
Moving whole body up and down
Negative verbal - bored
Negative verbal expressions
Negative verbal sounds
Negative verbal words
Nod
Not blinking
oo' shape with lips
Open and close mouth
Open hand (that's not on mouse) and turn palm up – sometime accompanied with
Play with mouth
Play with pen
Playing' with face? i.e. scrunch up (move face?) or pull skin/lip etc. {(need to be specific?)
Pout
Press lips together
Pull mouth (like small smile/considering)
relaxed
Release/forceful blow of air
Rigid position
Rub eyes
Rub face/neck
Rub self
Sat back
Sat forward towards screen
Scan screen more
Scowl
Scratch head
Scrunch lips to side of face
Shake head
Shift position/move in chair
Shrug
Sigh
Sit up straighter
Slow, considered actions
Slump down in seat
Smile
Speaking louder in answer to questions
Squinting
Staring/fixed
Stretch
Stretches neck/head up
Suck bottom lip
Suck in breath
Suck lips
Swallowing hard
Swearing
Swing side to side on chair
Talk to self
Tapping fingers
Teeth on lips
Teeth/jaw clenched
Tongue out
Touch face
Touch hair
Tut
Unnecessary actions (commissions?)
Verbal expressions of panic/no idea
Verbal relaxed
Verbal relief i.e. ok, cool, good
Verbal tired
What?'
Worried – face tense
Wrinkle nose
Yawn