ADVANCED AUTOMATION IN AIR TRAFFIC CONTROL:
A STUDY INVESTIGATING COGNITIVE ERROR, WORKLOAD AND CONTROLLER STRATEGIES IN THE CONTEXT OF UNCERTAINTY

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Abstract

The increase of air traffic worldwide is expected to increase the demands on current Air Traffic Management. In order to accommodate this growth, changes are required to increase the capacity of the airspace and safety of Air Traffic Control operations. Efforts to increase the capacity and safety of Air Traffic Control operations have expanded in two main directions.

First of all, safer and more efficient Air Traffic Control operations are envisioned by improving human performance through the implementation of advanced Controller Support Tools (CST) for air traffic controllers, including Conflict Detection Tools (CDT), Electronic coordination (E-coordination) and Monitoring Tools (MT). Secondly, much effort has been devoted to understand which task demands predict air traffic controller workload in order to increase the efficiency of Air Traffic Control. Knowledge of these factors support airspace design by optimizing airspace sectors and routings, as well as the development of workload prediction models. Workload prediction models enable the prediction of workload for air traffic controllers in advance, and are important instruments for strategic sector management, in order to keep workload within acceptable boundaries.

The development of advanced automation and the prediction of workload have a common challenge. Air Traffic Control is a highly dynamic operation, requiring controllers to make decisions under time pressure and under conditions of uncertainty (e.g. due to adverse weather). This generates questions as to how Controller Support Tools (CST) adequately support air traffic controllers in managing both routine as well as non-routine scenarios, and with varying levels of uncertainty. It also generates questions to what extent uncertainty influences workload for air traffic controllers. Currently, most workload prediction models do not take into account uncertainty, for example, generated by weather conditions. This generates questions related to the ability to accurately predict workload under the presence of uncertainty. In addition, uncertainty requires an understanding of how controllers cope with various sources of uncertainty in order to identify the system design requirements that support controllers in effectively managing these sources of uncertainty.

This study aims to contribute to these efforts making a contribution to the following challenges: 1) Designing controller support tools to optimally support human performance in context of dynamic task demands and uncertainty; 2) Understanding the workload factors that determine the capacity of Enroute Air Traffic Control; 3) Understanding the strategies that controllers adopt to cope with uncertainty in order to identify the system design requirements that support air traffic controllers with managing uncertainty.
The first study has focused on the following research question: To what extent do these technologies support human performance, specifically, under both routine as well as non-routine conditions and conditions with higher levels of uncertainty? The second study aimed to identify the answer to “What is the role of uncertainty on controller workload?”, whereas the third study aimed to find answers to: “What are the strategies that controllers adopt to cope with uncertainty and what are the system design requirements that support controllers with the execution of these strategies?”.

The data for the first and third paper was collected during four independent field studies in the two Enroute Area Control Centers (ACC’s) of skyguide, Air Navigation Service Provider, Switzerland. The ACC’s are located in Dübendorf (ZRH ACC) and Geneva (GVA ACC), Switzerland. The data collected for paper one and three relied on qualitative data, using “over the shoulder” observations, discussion sessions with controllers and engineers and a document study, including the analysis of operational procedures and simulation reports. Field notes, written by me and controllers (in the role of observers) during and after the “over the shoulder” observations, formed the most important source of data for paper one and three. The second paper relied on quantitative data, which were collected at the GVA ACC during the last of the four field visits, in parallel to the “over the shoulder” observations. The collected data included uncertainty ratings, performance ratings and continuous workload ratings by controllers in the role of observers as well as system data, including traffic density and traffic conflicts.

The first paper describes the results of a qualitative analysis, conducted in the two Area Control Centers (ACC’s). The study compares ZRH ACC, equipped with a classic ‘paper flight strip’ environment, with GVA ACC, equipped with ‘stripless’, where flight process strip information is integrated in the radar display and controllers are supported with Controller Support Tools, in terms of the possible cognitive errors which can occur in these environments. The results show that the number of potential cognitive (human) errors, overall, are reduced for ‘stripless’ operations. The results also show that the Controller Support Tools support controllers in both routine as well as non-routine situations in particular under conditions of uncertainty. However, further research needs, related to peripheral awareness, vigilance and controller trust in automation are discussed.

The second paper addresses the role of uncertainty on the prediction of workload. Firstly, the results showed that uncertainty interacts with traffic conflicts to predict workload such that the relationship between traffic conflicts and workload is stronger in the presence of uncertainty. Secondly, the results show that uncertainty moderates the indirect effect of traffic density on workload via traffic conflict, such that the indirect effect of traffic conflict only exists under conditions of uncertainty. These findings can be explained by the additional cognitive demands and strategies associated with managing traffic conflicts.
under conditions of uncertainty: controllers need to search for additional information, generate traffic solutions using mental simulation, develop back-up plans and engage in additional coordination when managing traffic conflicts under conditions of uncertainty. The results indicate that uncertainty should be considered in workload prediction models for Enroute Air Traffic Control, in particularly by including its interaction effect with dynamic complexity factors such as traffic conflicts, as it will improve the predictive power of these workload models.

The third paper continues with understanding the role of uncertainty in Air Traffic Control, by further exploring the sources of uncertainty in Enroute Air Traffic Control operations and the issues they generate for air traffic controllers. Subsequently, the study provides insight into the cognitive and collaborative strategies that controllers adopt to cope with uncertainty, and provides useful system design recommendations which support controllers in effectively managing uncertainty.

Finally, the results of paper two and paper three are discussed in the light of future changes, envisioned within SESAR and Next Gen, which aims to increase the efficiency and safety by optimizing the airspace and the implementation of 4D trajectory management.

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Zusammenfassung

Die stetige Zunahme des weltweiten Luftverkehrs stellt immer größere Anforderungen an das Luftverkehrsmanagement. Um diesem Wachstum gerecht zu werden, braucht es Veränderungen, die das Potenzial des Luftraums und die Sicherheit der Arbeitsabläufe der Flugsicherung weiter ausbauen. Die Anstrengungen, die Leistungsfähigkeit und Sicherheit der Arbeitsabläufe der Flugsicherung zu erhöhen, haben sich hauptsächlich in zwei Richtungen entwickelt.

Erstens werden sicherere und effizientere Arbeitsabläufe der Flugsicherung angestrebt, indem die Leistung der Fluglotsen mittels Implementation fortgeschrittener Controller Support Tools (CST) verbessert wird, z.B. Conflict Detection Tools (CDT), elektronische Koordination (E-coordination) und Monitoring Tools (MT). Zweitens ist man bemüht zu verstehen, welche Aufgabenanforderungen die Arbeitsbelastung von Fluglotsen vorhersagen, um so die Effizienz der Flugsicherung steigern zu können. Erkenntnisse bezüglich dieser Faktoren unterstützen einerseits die Planung des Luftraums, indem Luftraumsektoren und Routenplanungen optimiert werden können und ermöglichen andererseits, Modelle zur Vorhersage von Arbeitsbelastung zu entwickeln. Solche Modelle erlauben es, die Arbeitsbelastung von Fluglotsen im Voraus abzuschätzen und sind wichtige Instrumente für das strategische Management der Sektoren, um die Arbeitsbelastung in angemessenen Grenzen zu halten.


Im Rahmen dieser Bestrebungen besteht das Ziel der Studie darin, einen Beitrag zu den folgenden Herausforderungen zu leisten: 1) Entwerfen von Support Tools für Fluglotsen für eine optimale
Unterstützung der menschlichen Leistung im Kontext von dynamischen Aufgabenanforderungen und Unsicherheit; 2) Verstehen der Arbeitsbelastungsfaktoren, die die Leistungsfähigkeit der Flugsicherung bestimmen; 3) Verstehen der Strategien, die die Fluglotsen verfolgen, um mit Unsicherheit umzugehen, um dadurch die Anforderungen an Systeme zu identifizieren, die die Fluglotsen im Umgang mit Unsicherheit unterstützen.

Die erste Studie fokussierte auf die folgende Forschungsfrage: In welchem Ausmass unterstützen diese Technologien die menschliche Leistung, insbesondere unter Routine- sowie Nicht-Routine-Bedingungen und Bedingungen mit hoher Unsicherheit? Die zweite Studie zielte darauf ab, eine Antwort auf die Frage finden: Welchen Einfluss hat Unsicherheit auf die Arbeitsbelastung von Fluglotsen? Die dritte Studie versuchte die folgende Frage zu beantworten: Welche Strategien wenden die Fluglotsen an, um mit Unsicherheit umzugehen und welche Anforderungen an die Gestaltung von Systemen, die die Fluglotsen bei der Ausführung dieser Strategien unterstützen, sind damit verbunden?


unterstützen, insbesondere unter unsicheren Bedingungen. Es wird jedoch der weitere Forschungsbedarf zu „peripheral awareness“, Vigilanz und zum Vertrauens der Fluglotsen in die Automatisierung diskutiert.


Im dritten Artikel wird die Rolle der Unsicherheit in der Flugsicherung weiteruntersucht, indem die Quellen von Unsicherheit in der täglichen Flugsicherung und deren Auswirkungen auf die Fluglotsen exploriert werden. Weiter gibt die Studie einen Einblick in die kognitiven und kooperativen Strategien, die die Fluglotsen verfolgen, um mit Unsicherheit zurechtzukommen. Sie liefert nützliche Empfehlungen für die Gestaltung von Systemen, welche die Fluglotsen im erfolgreichen Umgang mit Unsicherheit unterstützen.

Schliesslich werden die Ergebnisse der Artikel zwei und drei im Hinblick auf zukünftige Veränderungen, die von SESAR und Next Gen vorgesehen sind, diskutiert. Diese Veränderungen zielen darauf ab, durch die Optimierung des Lufttraums und der Einführung des „4D trajectory management“ die Effizienz und Sicherheit zu erhöhen.

# Table of Contents

## Part 1

1. Introduction .......................................................................................................................... 1
   1.1. Challenge 1 and research aims ......................................................................................... 3
   1.2. Challenge 2 and research aims ......................................................................................... 5
   1.3. Challenge 3 and research aims ......................................................................................... 6
2. Background and research questions ...................................................................................... 8
   2.1. Enroute Air Traffic Control ............................................................................................... 8
   2.2. Human-centered automation ............................................................................................. 9
   2.3. Stripless operations ............................................................................................................. 10
   2.4. Research questions ............................................................................................................ 11
3. Methodological approach ....................................................................................................... 13
   3.1. Data collection activities .................................................................................................. 13
   3.2. Paper 1 and 3 ................................................................................................................... 14
   3.3. Paper 2 ............................................................................................................................. 16
   3.4. Ethical considerations and safety .................................................................................... 17
   3.5. Research agreement between skyguide and ETH ............................................................... 18
   3.6. Funding ........................................................................................................................... 19
   3.7. Doctoral candidate’s contribution to the papers ............................................................... 19
4. Summaries of scientific papers ............................................................................................... 20
   4.1. Paper 1 ............................................................................................................................ 20
   4.2. Paper 2 ............................................................................................................................ 21
   4.3. Paper 3 ............................................................................................................................ 22
5. Overall discussion: contribution and implications ................................................................. 24
   5.1. Cognitive performance and workload distribution in “stripless” operations ..................... 24
5.2. Implications for workload prediction models .......................................................... 25
5.3. Design recommendations to support uncertainty management ........................................... 26
5.4. Implications for future operations (SESAR and NextGen) .................................................. 27
6. Thesis references .................................................................................................................. 28

Part II

Paper 1 ..................................................................................................................................... 36
Paper 2 ..................................................................................................................................... 75
Paper 3 ..................................................................................................................................... 102

Appendix

Appendix A ............................................................................................................................... 146
Appendix B ............................................................................................................................... 147
Appendix C ............................................................................................................................... 149
Appendix D ............................................................................................................................... 150
Appendix E ............................................................................................................................... 153
List of Tables and Figures

Tables

Dissertation

Table 1: Levels of automation in Air Traffic Control (RHEA Project, Nijhuis, 2000) .......... 8
Table 2: Contributions of the authors to the three papers .................................................. 19

Paper 1

Table 1: Overview of ‘stripless’ functionalities and support tools ........................................ 60
Table 2: Internal error modes by TRACER ................................................................. 62
Table 3: Task descriptions of Generic Tasks ............................................................... 63

Paper 2

Table 1: Means, Standard Deviations, and Correlations Between Study Variables ............... 83
Table 2: Hierarchical Log-Linear Mediation analysis for traffic density on controller workload via traffic conflicts and single level bootstrap re-sampling results (PROCESS) .................... 87
Table 3a: Multilevel Moderated Mediation Analysis ....................................................... 89
Table 3b: Conditional indirect effect of traffic conflicts on controller workload at both values of the moderator .............................................................. 91

Paper 3

Table 1: Overview of controller support tools (adapted from Corver & Aneziris, 2014) ........ 133
Table 2: Sources of uncertainty in Enroute Air Traffic Control ......................................... 134
Table 3: Uncertainty coping strategies: reducing uncertainty .............................................. 136
Table 4: Uncertainty coping strategies: acknowledging uncertainty .................................... 137
Table 5: Uncertainty coping strategies: increasing uncertainty ........................................... 138
Table 6: Complexity and uncertainty management strategies ............................................. 139
Table 7: Automation requirements supporting cognitive and collaborative tactics ............. 140
Figures

Dissertation
Figure 1: Research model with references to research questions......................................................13
Figure 2: Data collection phases for paper 1, 2 and 3 .................................................................14

Paper 1
Figure 1a: ‘Strip’ operations ..............................................................................................................65
Figure 1b: ‘Stripless’ operations .....................................................................................................66
Figure 2: Electronic coordination window .........................................................................................67
Figure 3: Horizontal Scanning Tool alert ........................................................................................67
Figure 4: Exit conditions assistance tool (ECAT) ...........................................................................68
Figure 5: Dynamic Scanning Tool alert ..........................................................................................68
Figure 6a: Number of potential errors for ‘strip’ environment (possible errors) and ‘stripless’ environment (reduced and possible errors) for all perception tasks (Task 1-12) identified in the Cognitive Task Analysis ........................................................................................................69
Figure 6b. Number of potential errors for all memory tasks (Task 1-12) identified in the Cognitive Task Analysis ........................................................................................................69
Figure 6c. Number of potential errors for all judgment and decision-making tasks (Task 1-12) identified in the Cognitive Task Analysis ........................................................................................................70
Figure 6d. Number of potential errors for all action execution tasks (Task 1-12) identified in the Cognitive Task Analysis ........................................................................................................70
Figure 7. Frequencies of tasks for which the mental workload has been reduced, specified for each Generic Task (Task 1-12) as identified using the Cognitive Task Analysis ......................................71

Paper 2
Figure 1: The hypothesized model ..................................................................................................78
Figure 2: Interaction effect between traffic complexity and uncertainty on controller workload. ....91

Paper 3
Figure 1: Air Traffic Controller complexity and uncertainty management model..............................124
Preface

Air Traffic Control is a highly dynamic operation, requiring air traffic controllers to manage high levels of complexity under time pressure and under varying conditions of uncertainty. This thesis has aimed to answer various questions. Firstly, this thesis aims to understand how human-centered automation, currently implemented in Enroute Air Traffic Control supports air traffic controllers in managing both routine as well as non-routine scenarios, and with varying levels of uncertainty. Secondly, this thesis aims to understand how uncertainty influences controller workload. Thirdly, we aimed to generate a deeper understanding of the role of uncertainty in Enroute Air Traffic Control, by identifying, 1) the sources of uncertainty that impact operations in Enroute Air Traffic Control, 2) the strategies that air traffic controllers adopt to cope with these uncertainties, and finally, 3) the system design requirements that support controllers in effectively managing these sources of uncertainty. The thesis concludes by exploring the relevance of the findings for future ATM projects, including SESAR and NextGen.

Part I of this Thesis describes the background and research questions underlying the three papers. First, in Chapter 1, I provide a general introduction on current Enroute Air Traffic Control operations, with a deeper discussion into the three challenges that shape the research questions of the three papers. In Chapter 2, I present a background on Air Traffic Control and human-centered automation, as well as the operational environment (the upper sectors of the Enroute Area Control Centers in Geneva and Zürich) where the data for this thesis was collected. Chapter 3 describes the methods used to collect the data for the three papers. Chapter 4 provides the summaries of the three papers, after which I discuss the overall conclusions and practical implications in Chapter 5. The cumulative thesis consists of three scientific papers, presented in part II of this thesis.
PART I
1. Introduction

Air traffic management is a complex safety critical industry, characterized by standardized operational procedures (e.g. communication phraseology, routings) and coordination agreements between Air Navigation Service Providers (ANSP’s), aimed at improving the predictability of the system and minimizing uncertainty (Grote, 2004; Grote 2009). Although the flight plan of an aircraft and its planned route through the airspace sector are known well in advance, the actual transition of the aircraft through the sector is dependent on the control actions by air traffic controllers. Routing changes or changes in entry or exit conditions, in order to resolve traffic conflicts and/or to optimize the trajectory of an aircraft, may change the actual trajectory of an aircraft through the sector. In addition, air traffic controllers may resolve traffic conflicts by giving flight level instructions (thus managing the vertical evolution of an aircraft through the sector) as well as by heading or speed instructions.

The resolution of traffic conflicts and the optimization of traffic flows is particularly challenging due to uncertainty impacting operations, which may generate various issues for controllers. Stressing the subjective nature, uncertainty can be defined as the “sense of doubt that blocks or delays action” (Lipshitz & Strauss, 1997, p. 150). Uncertainty may originate from incomplete, unreliable or missing information, inadequate understanding or undifferentiated alternatives (e.g. traffic solutions which are equally (un)preferable. In Enroute Air Traffic Control, various sources of uncertainty may impact operations. For example, aircraft performance may be variable, for example due to winds or because underlying data to accurately predict aircraft performance (e.g. engine parameter settings by pilots) may be missing (Averty, Guittet, & Lezaud, 2008). Winds and unknown engine parameters may, in turn, impact the reliability of traffic predictions (Averty et al., 2008; Cummings & Tsonis, 2006). In addition, winds, thunderstorms or turbulence may cause (unexpected) deviations of aircraft, meaning that the most optimal traffic solution may be difficult to predict. This means that controllers need to optimize traffic flows and resolve conflicts in highly dynamic situations and under time pressure, with various sources of uncertainty influencing their decisions. In summary, although the performance of air traffic controllers can therefore be regarded as rule based performance (Rasmussen, 1983), the strategies and tactics that controllers need to adopt reach far beyond adhering to procedures.

In order to accommodate the increasing demands on the Air Traffic Management network, efforts have been directed at increasing the efficiency and safety of today’s Air Traffic Control operations. On the one hand, efforts have been directed at introducing human-centered automation (c.f. Billings, 1991), in order to support the human controller (Brooker, 2003; Kirwan, 2001). Another line of research has focused on aiming to understand the task demands that create workload for air traffic controllers. Understanding the
task demands that generate workload in air traffic control serves two main purposes. Firstly, it may support the optimization of airspace design, such as routings and sector boundaries (e.g. Majumdar & Ochieng, 2007; Loft, Bolland, Humphreys, & Neal, 2007), which, in turn, may increase the capacity of the sectors. Secondly, it supports the development of improved workload prediction models, which can be used for strategic sector management, in order to ensure that workload stays within acceptable boundaries (e.g. Neal et al., 2014).

Current initiatives to increase the capacity of European airspace sectors and safety of Air Traffic Control worldwide, by support controller performance, are focused on:

a) Developing and implementing human-centered automation (Billings, 1997) for human controllers to support controllers with conflict detection and resolution, monitoring and coordination between airspace sectors (e.g. Brooker, 2003; Kirwan, 2001; Kirwan & Flynn, 2002b).

b) Implementing automation to support controller-pilot communications, including Controller-Pilot Data Link Communications (CPDLC, Eurocontrol, 2009) and downlink of aircraft information to the controller workstation, Mode S EnHanced Surveillance (EHS, Eurocontrol, 2005);

c) Creating better understanding about the task demands, in particular static and dynamic complexity factors that generate workload for air traffic controllers (e.g. Brooker, 2003; Loft et al., 2007; Majumdar & Ochieng, 2007; Neal et al., 2014);

d) Developing accurate workload prediction models based on the understanding of these static and dynamic complexity factors (e.g. Neal et al., 2014);

There are a number of challenges with respect to these current efforts to increase the capacity and safety by supporting controller performance in Air Traffic Control operations. This thesis focusses on three of those challenges:

Challenge 1: Designing Human-centered automation for Enroute Air Traffic Control

Challenge 2: Understanding the task demands that determine workload in Enroute Air Traffic Control

Challenge 3: Understanding how controllers cope with uncertainty and understanding the requirements for automation that supports controllers with coping with uncertainty.

Paper 1 focusses on the first challenge, by addressing the following research question: To what extent does Human-centered automation support controller’s cognitive performance under both routine as well as non-routine conditions? Paper 2 addresses the second challenge, by addressing the following research question: “What is the role of uncertainty on controller workload?”. Paper 3 aims to create a better understanding about the strategies controllers use to manage uncertainty, and the automation requirements
that support controllers in following these strategies. Paper number 3 therefore focusses on the following research question: “What are the strategies that controllers adopt to cope with uncertainty and what are the system design requirements that support controllers with the execution of these strategies?”.

Two major ATM projects have been initiated in Europe, Single Sky Europe, supported by the SESAR Joint Undertaking (SESAR JU, 2012) and in the USA, NextGen (FAA, 2014). Although differences between SESAR and Next Gen exists, these projects both focus on the (re)design of airspace into functional airspace blocks, the implementation of 4D Business trajectories, a changed allocation of functions between pilots and controllers (e.g. Brooker, 2008; FAA, 2014; SESAR JU, 2012) and a change from space-based to time-based separation (Brooker, 2010). Authority concerning the flight path through the sector will be transferred to the flight deck, meaning that pilots will be able to deviate from trajectory within the agreed boundaries of the 4D trajectory without approval of air traffic controllers. The main task of air traffic controllers within SESAR and NextGen will involve monitoring of the performance of the aircrafts within these 4D trajectories, and to intervene when the 4D Business trajectory cannot be met. In such cases, air traffic controllers will engage in cooperative decision-making and negotiation with pilots.

Considering the importance of these ATM projects for the near future, this thesis will aim to identify the implications the findings for future operations within SESAR and NextGen. The results of paper two and paper three are therefore discussed in the light of these future changes, as envisioned within SESAR and NextGen. The discussion section of this thesis will summarize these conclusions.

1.1. Challenge 1: Designing Human-centered automation for Enroute Air Traffic Control Operations

Air Traffic Management is under increased pressure due to the increasing levels of air traffic. These pressures impact air traffic controllers, for example, through performance shaping factors, causing cognitive errors (Isaac, Shorrock, & Kirwan, 2002), which may ultimately lead to loss of separation. Losses of separation may range from a slight loss of separation between two aircraft, with no danger of collision, to losses of separations where the loss of separation was significant, with risk of collision, also known as an airprox (Majumdar & Ochieng, 2003). A study by Majumdar & Ochieng (2003), which investigated all airprox incidents in UK airspace from 1998-2000, showed that more than half of these airprox incidents were related to cognitive errors.

To reduce the risk of cognitive errors as a consequence of these increasing demands, human-centered automation (Billings, 1997) has been implemented in Enroute Air Traffic Control operations (Kirwan,
2001), also known as Controller Support Tools (CST). Examples of these tools include Medium Term Conflict Detection Tools (MTCD Tools), Monitoring Tools, and Electronic coordination (also known as SYstem Supported Coordination, SYSCO), for example as developed within FASTI (FASTI, 2006; 2008; 2009). These tools aim to increase controller’s cognitive performance by supporting controllers with cognitive tasks (e.g. scanning, monitoring, detection, memory, decision-making and planning), and the execution of collaborative tasks (e.g. coordination), while reducing the workload for these tasks (e.g. Kirwan, 2001). Similar automation, known as “stripless”, is currently implemented in the operational system of the upper Enroute airspace sectors of the Geneva Area Control Center (GVA ACC), by skyguide, Air Navigation Service Provider, Switzerland.

In the near future, Controller Support Tools may also support controllers with more advanced conflict resolution (e.g. Kirwan, 2001; Nijhuis, 2000; Kirwan & Flynn, 2002b), also known as Machine Proposal automation (Kirwan, 2001; Nijhuis, 2001). The development of such automation requires a lot of understanding about controller’s naturalistic decision-making models, for example controller strategies, preferences, trade-offs, and subjective evaluation of possible outcomes (Cummings & Tsonis, 2006; Kirwan & Flynn, 2002a) which remains particularly challenging to integrate with automation (Averty et al., 2008). Conflict resolution by automation remains therefore challenging (Cummings & Tsonis, 2006).

The aim of the first paper was to investigate how such human-centered automation, referred to as “stripless”, implemented in the upper sectors of the Enroute ACC in Geneva, improves the cognitive performance of air traffic controllers. In particular, we were interested how these controller support tools support controllers in managing both routine as well as non-routine situations, for example involving higher levels of uncertainty. Secondly, we analyzed to what extent, and for what tasks, these support tools reduce workload for controllers.

In order to investigate this, we compared the upper Enroute sectors of the Zürich ACC (a “classical” operational environment with paper flight strips) with the upper Enroute sectors of the Geneva ACC (equipped with a “stripless” work environment) regarding the types of cognitive error that may occur using the TRACeR method (Shorrock & Kirwan, 2002), with respect to the following cognitive domains perception and vigilance, working memory, long-term memory, judgment, planning and decision-making and response execution (Isaac et al., 2002).

The results discuss which cognitive errors have decreased in “stripless” operations, as well the cognitive errors which may have been newly introduced due to the introduction of new tasks in “stripless” operations. In addition, impact of “stripless” automation on controller workload is discussed. The paper
further elaborates on the role of trust and vigilance, in context of the reliability of the Conflict Detection Tools and the Electronic coordination tools. Finally, the paper discusses peripheral awareness in the control room as well as the need to further understand the implications of “stripless” automation on teamwork, in particular dynamic task distribution.

1.2. Challenge 2: Understanding the task demands that determine workload in Enroute Air Traffic Control

Controller workload, defined as the difference between the required capacity to manage tasks demands compared to the actual capacity to execute these task demands (Moray, 1979; Gopher & Donchin, 1986) is considered the main limiting factor of today’s Enroute Air Traffic Control operations (e.g. Brooker 2003; Majumdar & Ochieng, 2007). Therefore, much research has been conducted in the last few decades to identify the static as well as dynamic complexity factors that predict the workload of air traffic controllers (Hilburn, 2004; Loft et al., 2007; Majumdar & Ochieng, 2007; Mogford, Guttman, Morrow, & Kopardekar, 1995). A better understanding of the factors that determine workload may support Air Traffic Control operations in two ways. First of all, a better understanding of, in particular, static complexity factors may support sector design (e.g. Brooker 2003; Majumdar & Ochieng, 2007). Secondly, understanding the static and dynamic task demands that predict controller workload may support the development of workload prediction models for Enroute Air Traffic Control Sectors (e.g. Neal et al., 2014).

Although uncertainty has been acknowledged as an integral aspect of Air Traffic Control (Averty, 2008; Cummings & Tsonis, 2006; Kontogiannis & Malakis, 2013), up to now, no studies have investigated how uncertainty influences controller workload. Most workload prediction models are based on static and dynamic traffic complexity factors and do not acknowledge the role of uncertainty, for example, generated by adverse weather. However, recent work by Neal et al. (2014), showed that non-routine events, which included weather scenarios, caused actual workload to deviate from predicted workload, based on various (dynamic) complexity factors, suggesting that additional variance was explained by these weather scenarios.

This study aims to shed more light on uncertainty as a predictor of workload. More specifically, we aim to understand the interplay of uncertainty (recognizing weather as an important source) and traffic conflict (as an aspect of dynamic complexity) on controller workload in Enroute Air Traffic Control. This study will address the concern put forward by (Hillburn, 2004), that particular task demands, such as uncertainty, in combination with traffic complexity factors, can form “critical complexity combinations”,
and that dynamic complexity factors may interact to predict controller workload (Majumdar & Ochieng, 2007).

The aim of the second paper is to investigate if:

1) Uncertainty moderates the relationship between traffic conflict and workload;
2) Uncertainty moderates the mediation effect of traffic density on workload through traffic conflict.

The results discuss the findings and discuss the implications for operations as well as the implications for the development of controller workload models. The paper concludes with discussing the implications for future operations as envisioned by SESAR.

1.3. Challenge 3: Designing flexibility into the system that supports controllers with managing uncertainty

In the past decades, much research has been devoted to understand how controllers detect traffic conflicts (e.g. Boag 2006; Loft, Bolland, Humphreys, & Neal, 2009; Rantanen & Nunes, 2005), how controllers judge risks (e.g. Averty et al., 2008; Stankovic, Raufaste, & Averty, 2008) and the strategies controllers prefer to solve them (e.g. Kirwan & Flynn, 2002a). How controllers manage uncertainty, either separately or in context of traffic complexity, has, surprisingly enough, received much less attention. The management of uncertainty, however, is a critical aspect of Air Traffic Control and, similar to the management of complexity, a core aspect of controllers’ task work strategies (Malakis, Kontogiannis & Kirwan, 2010).

More recently, the importance of naturalistic decision-making theories (c.f. Lipshitz, Klein, Orasanu, & Salas, 2001) has been recognized as a useful approach how air traffic controllers manage uncertainty. For example, two recent studies have investigated how Air Traffic Controllers reduce uncertainty using the data/frame theory (Klein et al., 2006b) based on sensemaking theory (Malakis & Kontogiannis, 2013; Malakis & Kontogiannis, 2014). In addition, in an earlier paper (Malakis et al., 2010), identified strategies based the Recognition/Meta-recognition (R/M) framework (Cohen et al., 1996), suggesting that air traffic controllers critique their mental model of the situation, goals and responses, when managing traffic situations which are influenced by high levels of uncertainty. A limitation of these meta-cognitive models of decision-making is that they mainly discuss how decision-makers reduce uncertainty, rather than explaining the various strategies that aim to acknowledge uncertainty, for example, by comparing options or by creating backup plans.
The aim of this study was to investigate how controllers manage uncertainty through the adoption of three uncertainty coping strategies: reducing uncertainty, acknowledging uncertainty and increasing uncertainty. The paper used the RAWFS heuristic (Lipshitz & Strauss, 1997) and anticipatory thinking (Klein, Pin, & Snowdon, 2007) in order to identify reduction and acknowledgement strategies. In addition, recent suggestions by Grote (2015) were used to identify if controllers also preferred to increase uncertainty, and explore under what conditions and for what reasons they prefer to do so.

The data was collected using a field study in two Enroute Air Traffic Control Centers, involving “over the shoulder” observation sessions, discussions with air traffic controllers and document analysis.

The results show that controllers use a variety of strategies that aim to reduce, acknowledge and also increase uncertainty but that the adoption of these strategies is dependent on several contingency factors and trade-offs. In addition, the paper discusses system design recommendations that support controllers in following these coping strategies. These system design recommendations are discussed in context of existing design recommendations, including 1) the design of alerts and forcing functions; 2) transparency of prediction tools, and 3) system flexibility. The paper concludes with discussing the implications for future operations as envisioned by SESAR.
2. Background

2.1. Enroute Air Traffic Control

In most European Enroute Air Traffic Control sectors, as at the ZRH and GVA ACC, upper and lower Enroute airspace sectors are managed by a team of two air traffic controllers: a radar planner and a radar executive. The main goal of the air traffic control team is to provide safe, efficient and service oriented traffic flows. Air traffic controllers most important task demand is to provide separation between aircraft by adhering to minimum separation between aircraft according to ICAO regulations, 2000ft vertically and 5 nautical miles horizontally unless reduced separation minima apply.

The primary control tasks for the radar executive and the radar planner are presented in Appendix B.

Air traffic controllers may be supported by different levels of automation. The level of automation, that is currently implemented in the various Enroute ACCs in Europe, differs across ACCs. The levels of automation, for current operations as well as the levels of automation as foreseen for future operations, have been defined in the RHEA (the Role of the Human in the Evolution of ATM) Project (Nijhuis, 2000). The framework of levels of automation is presented in Table 1.

The levels of automation for Zurich and Geneva ACC will be discussed in paragraph 2.3.

Table 1 Levels of automation in Air Traffic Control (RHEA Project, Nijhuis, 2000).

<table>
<thead>
<tr>
<th>Level of automation (Kirwan, 2001)</th>
<th>Definition by RHEA Project (Nijhuis, 2000)</th>
<th>Implementation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Full Automation</td>
<td>Machine acts without informing or interacting with the operator.</td>
<td>Not part of current operations.</td>
</tr>
<tr>
<td>2 Controllers as Supervisor (CS)</td>
<td>The controller monitors the system and intervenes in system dynamics only in exceptional circumstances.</td>
<td>Not part of current operations.</td>
</tr>
<tr>
<td>3 Machine Proposals Strategy (MP)</td>
<td>The system offers options so as to meet high-level system goals (i.e. solutions), which human is free to evaluate. Sometimes the term advisor is used to describe the role of a machine providing recommendations (e.g. advising), or suggesting a selection.</td>
<td>Available in current operations, but to a limited extent.</td>
</tr>
<tr>
<td>4 Machine Aided Evaluation (MA)</td>
<td>Solutions are suggested by controller and assessed using computer aids, usually graphical aids (e.g. “What-if” tools).</td>
<td>Available in current operations, but to a limited extent.</td>
</tr>
<tr>
<td></td>
<td>Dynamic allocation with human delegation (FDH)</td>
<td>The same tasks may be done, at different times, either by human or by machine. Controller decides when and what task will be done by human or machine.</td>
</tr>
<tr>
<td>---</td>
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</tr>
<tr>
<td></td>
<td>Dynamic allocation with machine delegation (FDM)</td>
<td>Machine decides when and what task will be done by one or another. The decision could be based on measurements of human workload or stress, traffic loading, or time.</td>
</tr>
<tr>
<td></td>
<td>Aircraft delegation (AD)</td>
<td>Tactical conflict resolution, for example, is delegated from the groundside to the airborne side.</td>
</tr>
<tr>
<td></td>
<td>Cognitive Tools (CT)</td>
<td>The system allows the controller to carry out the high level system functions, such as conflict detection and resolution, but the tasks are supported by the system through the design of cognitive tools.</td>
</tr>
<tr>
<td></td>
<td>HMI Enhancements</td>
<td>Improvement of the Controller Working Position mainly consists of enhancing HMI without adding intelligent functions.</td>
</tr>
</tbody>
</table>

### 2.2. Human-centered automation

Designing human-centered automation, as outlined in the previous paragraph, is challenging. An important challenge is how to create cooperative human-machine systems while keeping the human-controller in the loop (e.g. Parasuraman, Sheridan, & Wickens, 2000; Kirwan, 2001) when critical functions (e.g. detection and monitoring) are delegated to automation. An overview of some of these challenges, which have been elaborately discussed in the literature, are:

- New tasks means new possible risks for cognitive error, e.g. due to the introduction of new tasks (e.g. Isaac et al., 2002; Kirwan, 2001);
- Poorly designed automation notifications and alerts (e.g. Imbert et al., 2014);
- Poor design of system feedback (e.g. Leveson, 2004);
- Automation may reduce flexibility (Grote 2004; Grote, 2009; Kirwan, 2001);
- Uncertainty may decrease the reliability of traffic prediction tools (e.g. Averty et al., 2008). Too low reliability may lead to lack of trust, whereas too high reliability may lead to too much trust (overreliance) or reduced vigilance, which is also referred to as complacency (Parasuraman & Manzey, 2010; Parasuraman & Wickens, 2008);
• Automating functions may lead to increased risk of fixation errors (De Keyser & Woods, 1990);
• Limitations of automation to integrate human trade-offs and preferences, particularly for Conflict Detection & Resolution support tools (Cummings & Tsonis, 2006; Kirwan & Flynn, 2002a; Kirwan & Flynn, 2002b).

2.3. Stripless operations

In 2005, Skyguide introduced a new operational concept for enroute Air Traffic Control in the upper sectors of Skyguide’s Area Control Centre in Geneva (GVA ACC). The main objective was to reduce the time controllers spent on each aircraft for routine tasks as well as to enhance their situational awareness. The operational concept involved a change from paper Flight Progress Strips (FPS) to a “stripless” work environment, where FPS information is integrated in the radar display. Thus, the concept of using rigidly grouped flight data in a fixed arrangement, either on a paper or an electronic FPS, was abandoned. Under the new concept, flight data is integrated in the radar display, the controller’s main work environment.

Furthermore, the system allows controllers to enter all clearances and instructions issued to aircraft directly into the system, making real-time coordinated data available. This information can then be used by the system itself, but can also be shared with other sectors. As a result, system functions and controllers in adjacent sectors can now be continuously aware of the actual clearances to which a given aircraft should be responding. This, in turn, has enabled new functionality, like electronic coordination between Swiss upper airspace sectors or advanced Conflict Detection Tools (CDT) for controllers.

The plan is to implement “stripless” also in Skyguide’s Area Control Center in Zürich (ZRH ACC). Currently, the Zürich ACC is still equipped with the classical environment, including paper Flight Process Strips. Both “strip” operations (ZRH ACC) as well as “stripless” operations (GVA ACC) are equipped with planning and measuring tools, which support controllers with developing traffic plans, trajectory tracking and conflict analysis:

• **Planning tools** include speed vectors (vector in the aircraft label giving controllers visual information about heading and speed), extrapolated speed vectors and a planning tool. The planning tool allows controllers to extrapolate a trajectory to a certain point, which then provides controllers with estimates of the extrapolated trajectory.
• **Measuring tool** supports controllers in measuring distances between aircraft, between trajectories, or other critical points)
In addition, the “stripless” work environment at the Geneva ACC, included:

- *Electronic coordination tools (E-coordination)*, which support the exchange of coordination proposals between the upper sectors of GVA ACC;
- *Medium Term Conflict Detection tools (MTCD)*, which support controllers with the detection and analysis of exit conflicts (ECAT window), horizontal crossings (Horizontal Scanning Tool, HST). In addition, “stripless” provides a Dynamic Scanning Tool (DST), which displays a prompt window when a controller enters a solution which, according to the system, is unsafe;
- *Analysis support tools*, which support controllers with the analysis of a crossing of two aircraft on the same flight level (Crossing Tool);
- *Monitoring tools*, which support controllers in detecting aircraft deviations, including a lateral deviation (Route Adherence Monitoring function), or a vertical deviation (CLAM).

For a full overview of all the tools, see Appendix C. Based on the levels of automation support, presented in Table 1, “stripless” automation can be classified into three different categories:

- **HMI Enhancements**
  - Various radar display functionalities
- **Cognitive Tools (CT):**
  - Medium Term Conflict Detection tools (HST, ECAT, DST)
  - Monitoring Tools
  - Analysis support tools (Crossing Tool)
  - Planning and measuring tools
- **Machine Proposal Strategy (MP):**
  - ECAT (provides a proposal for new Exit Flight Level)

### 2.4. Research questions

The research questions of this thesis for Paper 1, 2 and 3 are presented below.

*Research questions addressed in Paper 1*

1.1. **How does the work environment of “stripless” operations support controllers in managing task demands by optimizing cognitive performance?**

- What potential cognitive errors are likely to be reduced and what new errors are introduced in the new operational system?
To what extent does the work environment of “stripless” operations support controllers by optimizing their cognitive performance during both routine- as well as non-routine conditions?

1.2. How does the work environment of “stripless” operations support controllers in managing task demands by decreasing their workload?

- Which tasks in ‘stripless’ operations support controllers, by reducing the mental workload required for the execution of these tasks?

Research questions addressed in Paper 2

2.1. What are the sources of uncertainty in Enroute air traffic control operations?

- What sources uncertainty impact the work of controllers?
- What issues (action requirements) generate these sources of uncertainty for controllers?

2.2. What task demands predict workload?

- Does traffic conflict mediate the relationship between traffic density and workload?
- Does uncertainty moderate the relationship between traffic conflict and workload?
- Does uncertainty moderate the mediation effect of traffic density on workload via traffic conflict?

Research questions addressed in Paper 3

3.1. What are the sources of uncertainty in Enroute air traffic control operations?

- What sources uncertainty impact the work of controllers?
- What issues (action requirements) generate these sources of uncertainty for controllers?

3.2. How does uncertainty influence controllers choice of working method?

- What are the tactics and underlying strategies used by air traffic controllers when deciding to reduce, acknowledge or increase uncertainty?

3.3. What factors influence the adoption of these strategies?

- What trade-offs (operational goals) influence the adoption of these strategies?
- What contingency factors influence the choice of controller adaptive strategies?
3.4. How does system design support controllers with adaptive strategies to meet their operational goals?

- What are the requirements for system design to support controllers in following different strategies for uncertainty management?

The research questions presented above are modelled in Figure 1.

Figure 1. Research model with references to research questions.

3. Methodology

3.1. Data collection activities

The data for this study was collected in four data collection phases. The data collection took place between 2009 and 2013. The activities are presented in Figure 2.
As depicted in Figure 2, the data collection was conducted in four subsequent phases. The first and second phase concerned exploratory visits at ZRH and GVA ACC, whereas the third and fourth phase concerned the field observations including qualitative and quantitative data collection activities at ZRH ACC and GVA ACC. The quantitative and qualitative data of the third and fourth phase were collected in parallel, as the data originated from the same observation sessions, using different methods.

The white blocks in Figure 2 indicate the qualitative data collection activities used for paper 1 and paper 3, whereas the grey colored boxes indicate the quantitative data collection activities for paper 2. The quantitative data collected at ZRH ACC are not part of this thesis, however, they supported paper 2 as a pilot study for the quantitative data collected at GVA ACC. These pilot activities included:

- the development of performance rating scales for radar planner and radar executive;
- the development of the uncertainty rating scale;
- pilot test for workload ratings.

Figure 2. Data collection phases for paper 1, 2 and 3.

### 3.2. Paper 1 and 3

**Field study**

An ethnographic approach was chosen by conducting a field study for paper 1 and paper 3. Field studies in naturalistic settings are the recommended approach to study macro cognition, such as decision-making, planning and uncertainty management (Klein, Ross, & Moon, 2003; Hutchins, 1995; Xiao, 2005).
The field study activities, which generated the data for paper 1 and 3, included:

**Exploratory visit ZRH:**
- “Over the shoulder” observations at ZRH ACC (approximately 60 hours), supported by field notes;
- In-depth discussions with air traffic controllers during and after breaks;
- Analysis of procedure manuals of ZRH and GVA operations.

**Exploratory visit GVA:**
- “Over the shoulder” observations at GVA ACC (approximately 30 hours), supported by field notes;
- In-depth discussions with air traffic controllers during and after breaks;
- In-depth discussions with system engineers during various meetings.

**Field observation (quantitative and qualitative data collection) ZRH:**
- “Over the shoulder” observations at ZRH ACC (approximately 20 hours) environment in parallel with quantitative data collection, supported by field notes;
- In-depth discussions with air traffic controllers during and after breaks.

**Field observation (quantitative and qualitative data collection) GVA:**
- “Over the shoulder” observations in a ‘stripless’ environment (approximately 20 hours), in parallel with quantitative data collection, supported by field notes;
- In-depth discussions with air traffic controllers during and after breaks;
- In-depth discussions with system engineers during various meetings.

**Literature and document study**
- Real Time Simulation reports of earlier versions of ‘stripless’ and operational trial reports (e.g. FASTI, 2008, 2009; Skyguide, 2010).

In addition, Paper 1 required the following analysis techniques:
- Cognitive Task Analysis (Militello & Hutton, 1998)
- TRACEr (Shorrock & Kirwan, 2002) as a predictive analysis, involving the following steps:
  - Step P1: Identification of performance shaping factors (PSF);
  - Step P2: Identification of all external errors modes (EEM);
Step P3: Identification of internal error modes (IEM);
Step P4: Identification of error recovery modes (ERM).

3.3. Paper 2

The data for paper 2 was based on the “Quantitative data collection” in the GVA ACC

Design

The study took place at the GVA ACC in the upper airspace sectors L1-L6, covering altitudes between 25,000-66,000 feet (FL 250-660). The radar executive and radar planner, working in these sectors, were observed by two observers for a duration of 15-20 minutes. The observers rated workload for both positions at five minute intervals. The workload ratings were entered electronically on a small laptop or paper sheets. The observers would change position randomly, so that the observers rated workload for the two positions in a random manner. The observers were licensed controllers at the GVA ACC.

A third observer (either a system engineer or me) recorded traffic density and traffic conflict continuously on a tablet based on information provided by the Horizontal Scanning Tool (HST) and Exit Conditions Assistance Tool (ECAT window).

Sample description

In total, 61 sessions of 15-20 minutes were observed. Due to technical limitations, a total of 54 out of the 61 sessions could be used for the analysis. Workload ratings subdivided each session into two to four sub-sessions, resulting in a total of 176 sub-sessions for which an average traffic density and traffic conflict was calculated. For each sub-session, workload ratings were provided for both positions, generating N = 334 workload ratings.

Measures

Traffic density and traffic conflict were measured based on recorded sector data. Traffic density was defined as the number of aircraft divided by sector volume (Kopardekar and Magyarits, 2003). Traffic conflict was measured as a composite scale of two types of traffic conflict: horizontal crossings and exit conflicts, and was calculated as the average number of active horizontal crossings and exit conflicts per minute. Workload was rated on a 3-point scale of “low”, “medium” to “high”. In addition, several control variables were included in the study, including: military sector activity, sub-session duration, actor and partner (radar planner and radar executive) performance, controller position, controller observer, sector volume and sector average flight level.

Methods
*Hierarchical Log-Linear Models*

Hierarchical Log-Linear Models with cross-level interaction effects were used to accommodate the non-independent (repeated) observations as well as the nested structure of the data. Workload, traffic density and traffic complexity (repeated observations, level 1) were nested in controller performance and observer (level 2), which were nested in session effects which includes sector characteristics and uncertainty (level 3). The data were analyzed using HLM v7.0 (Raudenbush, Bryk & Congdon, 2004). In addition, the moderated mediation model was tested using the SPSS macro PROCESS, based on single level bootstrapping (Preacher, Rucker, & Hayes, 2007).

*Actor Partner Interdependence Model*

As the workload of the radar planner is dependent on the performance of the radar executive, and the workload of the radar executive dependent on the performance of the radar planner, we adopted the Actor Partner Interdependence Model (Kenny, Kashy, & Cook, 2006) to take this interdependency into account. The Actor Partner Interdependence Model allows to differentiate between actor and partner effects and to analyze the separate effects. Cook and Kenny (2005, p. 102) refer to an actor effect as to “how much a person’s current behavior is predicted by his or her own past behavior”, whereas partner effects are defined as “how much one person is influenced by a partner”. In order to analyze actor and partner effects, we therefore included separate actor and partner effects (individual performance) for the radar executive as well as the radar planner. The actor effect for the radar executive was the individual performance of the radar executive, and the partner effect the performance of the radar planner. For the radar planner, the actor effect was the individual performance of the radar executive, and the partner effect the individual performance of the radar planner.

### 3.4. Ethical considerations and safety

The data collection followed ethical standards as outlined by the “Ethical Principles in the Conduct of Research with Human Participants” (American Psychology Association, 2002). For the explorative field studies, permission was obtained from the controllers who volunteered to be followed for the explorative field study. The controllers informed the daily operational manager in advance to inform him/her about my presence in the ACC. As controllers work in pairs of two controllers, the controller would also ask explicit permission to his/her colleague for our “over the shoulder” observation. The other controllers working at the ACC were not formally notified, but informally introduced at the sector work stations.
For the quantitative data collection, explicit permission was obtained from operational management at both ACCs. Daily operational managers (supervisors, in charge with tactical sector planning for the lower and upper sectors) and air traffic controllers, on duty of the days of the data collection, were informed of our data collection by email one or two days in advance. The email included a short introduction about the research and included an informed consent form (Appendix D) as attachment. This informed consent was based on an FAA template, see Friedman-Berg, Allendoerfer and Deshmukh (2010) for an example.

The participation with this study was voluntary. Controllers who wanted to participate with the study signed the informed consent form, either at the supervisors desk prior to starting their shift, or at the beginning of the observation. Almost all controllers in ZRH and GVA volunteered, allowing us to observe almost all controller sector teams.

Safety was guaranteed by:

1) Presenting the controllers, who were being observed, the option to stop the observation at any time, as outlined in the Informed Consent Form.

2) Ensuring that the controllers who were being observed did not have any other duties other than their normal work.

3) Increased sensitivity of the observer to the comfort levels of the controllers observed, and presenting them the option to stop observation if they felt it was necessary.

3.5. Research agreement between skyguide and ETH

A research agreement was signed by Skyguide Swiss Air Navigation Services Ltd and ETH in order to ensure a cooperative relationship, allowing dissemination of the research through scientific channels as well as adhering to non-disclosure agreements at the same time.
3.6. Funding

This research was funded by the resources of Gudela Grote’s chair at the Department of Management, Technology, and Economics. In addition, this project was financially supported by the ‘ETHIIRA Research Grant’, project ETH-19-10-3. The project was in collaboration with skyguide, Air Navigation Service Provider Switzerland. I am grateful to skyguide, for providing all the resources and operational support for this thesis.

3.7. Doctoral candidate’s contribution to the papers.

The contribution of the doctoral candidate’s contribution for each of the paper is outlined in Table 2. In all the three papers, I had the main lead.

I am grateful for the support of Joost Hamers (skyguide), for co-writing section 2.3. of this thesis. Furthermore I am grateful for Manuel Stühlinger (ETH) and Michaela Kolbe (ETH) for translating the abstract of this thesis.

Table 2. Contributions of the authors to the three papers.

<table>
<thead>
<tr>
<th></th>
<th>Paper 1</th>
<th>Paper 2</th>
<th>Paper 3</th>
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<tbody>
<tr>
<td>Authors</td>
<td>SC, OA</td>
<td>SC, DU, GG</td>
<td>SC, GG</td>
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<tr>
<td>Literature research</td>
<td>SC</td>
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<td>SC, DU</td>
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<td>SC, DU</td>
<td>SC, GG</td>
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<tr>
<td>Commenting</td>
<td>JH, MM, YLR, SD, BK</td>
<td>DU, GG, JH</td>
<td>GG</td>
</tr>
</tbody>
</table>

Note: OA = Olga Aneziris; SC = Sifra Corver; SD = Samuel Dépraz; GG = Gudela Grote; JH = Joost Hamers; BK = Barry Kirwan; MM = Montserrat Mendoza; YLR = Yves Le Roux; DU = Dana Unger.

At the moment of writing this dissertation, skyguide has approved paper 1 and 2 in this dissertation as released for review and publication. The release of paper 3 for review and publication is pending.
4. Summary of scientific papers

This chapter gives a short summary for all three scientific papers.

4.1. Paper 1


Air traffic is increasing worldwide. In order to accommodate the anticipated rapid growth in air traffic in the future, human-centered automation is being implemented to support controller performance and to increase safety and efficiency of operations. Examples of human-centered automation include Conflict Detection Tools, Monitoring Tools and Electronic coordination tools, together also known as Controller Support Tools, or Cognitive Tools (Kirwan, 2001; Nijhuis, 2000). These tools aim to support controller’s cognitive performance by supporting various cognitive tasks, such as scanning, detection, monitoring, decision-making and analysis (Kirwan, 2001). At the same, these tools also aim to alleviate workload by reducing workload of (routine) tasks.

The aim of this paper is to compare the ‘classical’ operational environment with paper flight strips (“strip” environment) with a ‘stripless’ work environment, supported with Controller Support Tools, in order to understand how “stripless” supports controller’s cognitive performance.

The research questions are:

1) What potential human errors are likely to be reduced and what new errors are introduced in the new operational system? To what extent does the new operational system support controllers in routine and non-routine conditions?

2) Which tasks in ‘stripless’ operations support controllers, by reducing the mental workload required for the execution of these tasks?

Methods

A TRACEr analysis, applied as a predictive analysis as proposed by Shorrock and Kirwan (2002), was conducted. The tasks in “strip” operations and “stripless” operations were identified by two CTA’s, developed for “strip” and “stripless” operations. The two CTA’s were based on two existing CTA’s, developed for the FASTI project (Dehn, Lowe, & Hill, 2007) and the Episode 3 project (Gordon and Fitzpatrick, 2007).
Results

The results of the TRACEr analysis showed that the possibilities for cognitive errors related to detection, memory, decision-making and action execution tasks in “stripless” operations have decreased, due to (1) the decreased possibility for cognitive error overall, and (2) the increased error recovery opportunities provided by the system. However, the new tasks in “stripless” may also introduce new errors such as those related to timely detection of information (e.g. coordination messages). Furthermore, the results show that there is a shift in type of errors which may occur during the execution of tasks. The study concludes that overall safety has improved due to the reduction of cognitive error as well as through the reduction of mental workload related to the execution of routine tasks.

4.2. Paper 2

Corver, S.C., Unger, D., & Grote, G. “Predicting air traffic controller workload: Uncertainty as the moderator of the indirect effect of traffic density on controller workload through traffic conflicts”. Manuscript submitted to Human Factors.

Air traffic controller workload originates from various expected and unexpected task demands. The complexity of the traffic, originating from static and dynamic traffic complexity factors, have frequently been identified as the most important factors that predict air traffic controller workload (Chatterji & Sridhar, 2001; Djokic et al., 2010; Kopardekar & Magyarits, 2003; Majumbar & Ochieng, 2007; Neal et al., 2014). An important factor which may explain additional variance of controller workload is uncertainty. Uncertainty, defined as the “sense of doubt that blocks or delays action” (Lipshitz & Strauss, 1997, p. 150), is considered a fundamental aspect of air traffic control (Averty et al., 2008; Kontogiannis & Malakis, 2013).

Uncertainty may originate from various sources. For example, weather conditions may influence the validity of traffic predictions (e.g. Averty, 2008). Uncertainty may also originate from missing or conflicting system data, or from ambiguity concerning intentions or actions of other actors in the system such as pilots and neighboring sectors. In line with Bedwell and colleagues (2014) and Kontogiannis & Malakis (2013), we view uncertainty as an independent task demand, which generates additional task complexity (e.g. Averty et al., 2008; Cummings & Tsonis, 2006; Kontogiannis & Malakis, 2013). Finally, we consider uncertainty as a dynamic complexity factor, which may interact with other dynamic complexity factors.

This paper aims to understand the role of uncertainty on air traffic controller workload in Enroute Air Traffic Control. We tested the following hypotheses:
Hypothesis 1: The relationship between traffic density and controller workload is partially mediated by traffic conflicts in the sector.

Hypothesis 2: Uncertainty moderates the relationship between traffic conflicts and controller workload such that the relationship between traffic conflicts and workload is stronger when uncertainty is present.

Hypothesis 3: Uncertainty moderates the mediating effect of traffic density and workload via traffic conflict, in such a way that the mediation effect is strongest when uncertainty is present.

Our data confirmed our hypotheses. The results showed that the relationship between traffic density and controller workload was mediated by traffic conflicts. Furthermore, the result shows that uncertainty interacts with traffic conflict in such a way that the relationship between traffic conflict and workload is strongest in the presence of uncertainty. Finally, we also found partial support for hypothesis 3. Uncertainty moderates the indirect effect of traffic density on workload via traffic conflict, however, in such a way that there is only an indirect effect of traffic density on workload via traffic conflicts when uncertainty is present. The findings confirm that the relative contribution of traffic conflicts on workload cannot be seen as static. The effect of traffic conflict generated by traffic density is *conditional* on the amount of uncertainty influencing operations.

Our findings support earlier arguments by Hilburn (2004), stating that adverse weather may interact with other traffic (dynamic) complexity metrics as predictors of workload. In addition, the study confirmed earlier arguments by Majumdar & Ochieng (2007), who stated that dynamic complexity factors may interact to predict workload. The implications

4.3. Paper 3


Air Traffic Controllers are able to provide safe and efficient traffic solutions while working under highly complex, dynamic and often unpredictable circumstances with higher levels of uncertainty. Uncertainty may be considered as a mental state, defined as a “sense of doubt that blocks or delays action” (Lipshitz & Strauss, 1997, p. 150), generated by conditions in the environment. In air traffic control, uncertainty may originate from data variability, conflicting or missing data, or ambiguity concerning the actions or preferences of pilots as well as other sources which may increase the difficulty of predicting the future
traffic situation and required actions. Currently, uncertainty is still an ill-defined concept in Air Traffic Control operations.

This study aims so investigate: 1) The sources of uncertainty in Enroute Air Traffic Control, 2) the strategies that Air Traffic Controllers adopt to cope with uncertainty, and 3) the requirements for system design which support controllers in following these strategies. This study identifies three types of uncertainty coping strategies. Recent suggestions by Grote (2015) were used to further explore to identify if and how controllers increase uncertainty, and under what conditions.

**Research questions**

The research questions for this study are:

1) What are the sources of uncertainties in air traffic control, and what are the issues they generate for air traffic controllers?
2) What are the tactics and underlying strategies used by air traffic controllers when deciding to reduce, acknowledge or increase uncertainty?
3) What contingency factors and trade-offs influence the adoption of these strategies?
4) What are the requirements for system design to support controllers in following different strategies for uncertainty management?

**Methods**

The data was collected following an ethnographic approach, using a field study in two Enroute Air Traffic Control Centers, including “over the shoulder” observations, supported by field notes and discussions with controllers and system engineers.

**Results**

The results show that controllers, in addition to *reduction* and *acknowledgement* of uncertainty, may deliberately *increase* uncertainty in order to increase flexibility for other actors to meet their operational goals. The results discusses system design recommendations which allow controllers to follow their preferred coping strategies. These system design recommendations were discussed in context of existing design proposal, which included: 1) the design of alerts and forcing functions; 2) transparency of prediction tools, and 3) system flexibility as requirements for acknowledging and increasing uncertainty.
5. Overall discussion: contributions and practical implications

5.1. Cognitive performance and workload distribution in “stripless” operations

The main goal of Paper 1 was to understand how “stripless” improved controller cognitive performance (Kirwan, 2001), by investigating the possibility for cognitive errors in “stripless” operations compared to “strip” operations. Building on the results from the FASTI project (Dehn et al., 2007), the aim of this paper was not only to identify new sources of potential cognitive error, but also to identify which type of errors are potentially reduced in ‘stripless’ operations. The overall result of the TRACER cognitive error analysis (Shorrock & Kirwan, 2002), showed that the possibilities for cognitive error in “stripless” operations have decreased, due to:

1) Reduced possibilities for cognitive error, either because tasks have been removed or changed;
2) Increased possibilities for detecting errors due to increased error recovery opportunities;
3) The reduction of mental workload related to the execution of routine tasks.

The results also showed that “stripless” supports cognitive performance in both routine as well as non-routine situations. Examples of such non-routine situations with higher levels of uncertainty may concern adverse weather situations, such as winds or thunderstorms, where deviations of aircraft from the agreed trajectory, either laterally or vertically, may occur. In these situations, controllers are especially supported by Monitoring Tools, which provide increased error recovery opportunities.

The impact of “stripless” on peripheral awareness in the control room was discussed. The results indicated that voice coordination, due to the introduction of electronic coordination, did not disappear for two reasons. The first reason was that controllers still needed to request a coordination by phone, and because controllers still preferred to engage in shared planning through voice coordination. The noise reduction in “stripless” operations was significantly reduced due to the removal of the flight strip handling. This may have additional benefits of reducing further errors related to mishearing pilot communication.

However, although these findings may indicate increased safety levels, the results also showed that, similar to the results of the FASTI project (Dehn et al., 2007), also new errors were introduced, such as those related to timely detection of information. These findings suggest the importance of working methods, in particular when extending the concept between different Area Control Centers.

Future research is important to further understand how “stripless” supports the distribution of tasks within the team. In line with earlier conclusions by FASTI (2008), improved detection opportunities of conflicts in a strategic manner may increase workload for the radar planner, whereas it may reduce the workload for
the radar executive. This suggests that the actual workload distribution in the team may not be a direct translation of the workload reduction of the individual tasks, but rather a consequence of newly adopted dynamic task distribution between the radar planner and the radar executive. Within stripless operations, tasks may be more dynamically allocated, serving a more balanced workload, which may support the reduction of high workload peaks for both positions. More research should investigate the dynamic task distribution in “stripless” operations and its impact on shared cognition, adaptive coordination mechanisms and team situation awareness (Burke et al., 2006).

5.2. Implications for workload prediction models

The interaction effect of uncertainty with traffic complexity is in line with earlier suggestions by other authors, who claim that adverse weather may possibly interact with other traffic (dynamic) complexity metrics (Hilburn 2004; Majumdar & Ochieng, 2007) as predictors of workload. Up to now, uncertainty had not yet been identified as predictor of workload.

This finding has practical implications for the development of workload prediction models. Workload prediction models, which are based on dynamic density factors such as traffic conflicts, might underestimate actual workload when uncertainty is high. This could lead to possible overload situations, generating safety risks. Further research could explore how weather, as an important source of uncertainty, can be integrated in workload prediction models, in order to increase the predictive power of these models. Furthermore, future research could explore possible other interaction effects of dynamic complexity factors. Such interaction effect may likely exist and may explain additional variance of controller workload. Future research should also investigate if our findings are valid for both positions (the radar planner and the radar executive) as the controllers work with different look-ahead times and, in addition, may be effected differently by the same source of uncertainty, as was identified in paper 3.

These findings do not have direct implications for skyguide, as the “Crystal” complexity predictor currently does not include traffic conflicts as a workload predictor. However, future research could investigate if uncertainty, for example, generated by weather could be a useful predictor for controller workload in Enroute Air Traffic Control operations at GVA ACC and ZRH ACC.

An important limitation of the present study was that controller’s cognitive strategies to manage workload were not measured nor modelled in this study. This may be important, as many researchers have suggested that there is a feedback loop between controller cognitive strategies and workload: Controllers carefully manage their workload by regulating their resources and adopting strategies (e.g. Loft., 2007; Sperandio, 1971), suggesting that workload is a deliberate outcome, as a result of controller strategies. Controller workload is therefore the result (emergent state) of the dynamic interaction between the controller (choice
of work methods) and the task demands (Loft et al., 2007). This feedback loop was also discovered in paper 3. We therefore included controller performance (which included planning) as a covariate in our study, whilst acknowledging the limitations of (hierarchical) linear regression to take into account such feedback loops.

The results were also shortly discussed in context of future air traffic scenarios as envisioned in SESAR (SESAR JU, 2012) and NextGen (FAA, 2014). Although these programs aim to minimize uncertainty (Grote, 2009), uncertainty will remain an integral aspect or air traffic management. Uncertainty generated by adverse weather conditions or ambiguity concerning pilot intentions will likely become important sources of uncertainty for future operations. This means that workload prediction models for future operations should aim to identify the sources of uncertainty, in particular related to weather, in order to understand how uncertainty may influence workload. Weather conditions in particular may be an important predictor, as adverse weather may be one of the main reasons for replanning 4D trajectories. Uncertainty should therefore be considered as a predictor of controller workload in future trajectory-based operations, and possible interactive effects of uncertainty with other (dynamic) complexity factors, identified as critical for trajectory-based operations, should be identified.

5.3. Design recommendations to support uncertainty management

In the third paper, we identified that air traffic controllers rely on various strategies to manage uncertainty, including reduction, acknowledgement and increasing uncertainty. Up to now, only reduction and acknowledgement strategies had been identified. We found that controllers prefer to increase uncertainty, in particular to generate flexibility for other actors (pilots and neighboring sectors). In the second part of the analysis, we identified that current air traffic control system design supports controllers with following these strategies, through 1) controller support tools, 2 and human-machine interface enhancements as well as overall system design. We have discussed our findings in context of existing design proposals for automation, including the concept of transparency and appropriate reliance (Lee & See, 2004).

In line with Paper 1, we acknowledge that automation may increase the risk on fixation (De Keyser & Woods, 1990) and reduce vigilance, also referred to as complacency (Parasuraman & Manzey, 2010; Parasuraman & Wickens, 2008) due to passivity created by automation (Klein et al., 2007). However, we identified that automating the detection of uncertainty, for example, through forcing functions is preferred when 1) the data behind these functions are stable/reliable and, 2) failure to detect the uncertainty has a high impact on safety, and, 3) the timing and the sensitivity of these alerts is carefully acknowledged. However, such alerts should be carefully designed to take into account trade-offs between intrusiveness/cognitive costs of animated visual cues versus the detectability of non-intrusive cues such as
color changes (Imbert et al., 2014). In addition, we identified that transparency of automation is an important design requirement. We identified that the conflict prediction tools are based human algorithms, in favor of integrating more sophisticated weather models into these prediction tools, which may increase the reliability of the predictions under more adverse weather conditions. This has not only the advantage of increasing trust, but, at the same time, it may reduce fixating and increase vigilance, for example, by stimulating manual trajectory tracking through mental simulation and assumptions. These findings support the notion of transparency and the concept of appropriate reliance (Lee & Moray, 1994; Lee & See, 2004). Finally, we argued that system flexibility is an important requirement to support uncertainty management. This finding will be more elaborately discussed in the next section.

An overview of the automation issues addressed in paper 1 and paper 3 are provided in Appendix C.

5.4. Implications for future operations (SESAR and NextGen)

The role of uncertainty for future ATM scenarios within SESAR and NextGen is still poorly understood. Although SESAR and NextGen aim to minimize uncertainties by increasing the predictability of operations, uncertainty cannot be completely eliminated (Malakis & Kontogiannis, 2014; Nicholls, 2001). In particular during non-routine events (e.g. adverse weather or emergency situations), controllers need to decide if or when to intervene (Dekker & Woods, 1999), which may be more difficult due to the higher levels of ambiguity concerning the anticipated flight path by the pilot. This ambiguity may increase the need for assumptions for controllers, regarding the state and intentions of aircraft (Malakis & Kontogiannis, 2014). Although controller-pilot coordination is likely to be supported by increased levels of information sharing (aimed at reducing uncertainty), it is doubtful that this will sufficiently support controllers to adequately manage uncertainty (Malakis & Kontogiannis, 2014). Instead, we proposed that controllers should have sufficient degrees of freedom to adequately manage these uncertainties based on their preferred coping strategies. These degrees of freedom should be supported by system design, for example, by enabling delegation structures, whilst acknowledging a balance between authority and control (Boy & Grote, 2009; Boy & Grote, 2011; Straussberger et al., 2008) and by adopting flexible procedures (Grote, 2015).

SESAR and NextGen should acknowledge that doubt is good (Averty et al., 2008), as doubting is the cognitive driver of uncertainty coping strategies. The system design requirements that support controllers with managing uncertainty should therefore be identified in future operations, for example by beginning to understand the sources of uncertainty and the preferred corresponding strategies by controllers to manage these uncertainties.
6. Thesis references


PART II
Scientific paper 1

The impact of new controller support tools in Enroute Air Traffic Control on cognitive error modes: A comparative analysis in two operational environments

The impact of controller support tools in Enroute Air Traffic Control on cognitive error modes

A comparative analysis in two operational environments

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Abstract

Air traffic is increasing worldwide. In order to accommodate the anticipated rapid growth in air traffic in the future, changes are required to increase the capacity of the airspace. Although major structural changes in Air Traffic Management in Europe are still underway through the implementation of 4D trajectories, many changes happened and are happening now through the introduction of new automated features in the enroute air traffic control systems. Examples of such air traffic control features are electronic coordination and conflict detection tools designed for air traffic controllers. Although it is likely that these controller support tools may decrease the possibilities of cognitive error, the introduction of new tasks may also introduce new sources of cognitive error. This paper describes the results of a qualitative analysis conducted in two European Area Control Centers, and compares possible cognitive error modes using the TRACEr method. The results show that for an operational environment equipped with controller support tools, the cognitive errors that may occur, have changed. Errors related to detection, memory, decision-making and action execution may decrease. However, new tasks related to the controller support tools may also introduce new errors such as those related to timely detection of information. Furthermore, the results show that there is a shift in type of errors which may occur during the execution of tasks. System safety may be increased through eliminating or reducing possibilities for cognitive error, increasing error recovery opportunities and indirectly through reducing mental workload related to the execution of tasks.

Keywords: cognitive error analysis, air traffic control, controller support tools
1. Introduction

In Europe, air traffic transportation demands have increased significantly and were exceeding capacity limits of the European airspace network (Eurocontrol, 2008; International Civil Aviation Organization, 2007). In order to deal with these expected traffic demands in the future, a structural redesign of the European airspace is planned to increase the capacity of airspace sectors. Programs such as the Single European Sky ATM Research Program (SESAR) and USA’s Free Flight-based NextGen (Eurocontrol, 2008; Joint Planning and Development Office, 2007; SESAR Consortium 2008) aim to increase the capacity of airspace sectors through the introduction of 4D trajectories. The implementation of 4D trajectories incorporates significant changes, including a different organization and management of the airspace, higher levels of automation and modified distribution of tasks between pilots and air traffic controllers (Langan-Fox et al., 2009; Guibert et al., 2010; Rognin et al., 2001; Straussberger et al., 2008). Although these new operational scenarios have not yet been implemented in today’s operations, many technological tools are currently being implemented in enroute control sectors as first steps towards the implementation of the operational scenarios as outlined and envisioned in programs SESAR and NextGen. Examples of these tools are the introduction of electronic communication between pilots and air traffic controllers, referred to as Controller–Pilot Data Link Communications, which is part of the LINK 2000+ programme (EUROCONTROL, 2009), and the implementation of controller support tools such as electronic coordination between airspace sectors, (System Supported Coordination), conflict detection and traffic monitoring.

An example of such an initiative in Europe is Eurocontrol’s First Air Traffic Control Support Tools Implementation (FASTI) Program (FASTI, 2006; FASTI, 2008). The objective of this program was to increase the capacity of the airspace sectors by reducing the workload of controllers for routine tasks and to increase safety by supporting controllers with Medium Term Conflict Detection tools, Monitoring Aids and System Supported Coordination. Electronic coordination allows air traffic controllers to electronically request and propose changes to flight trajectories, instead of coordination by telephone, required for tactical air traffic management. Currently, a number of European Area Control Centers (ACC) are already equipped with these technologies (EUROCONTROL, 2011; Le Roux, 2007).
The main advantages of these automated support systems are two-fold. First of all, the new technologies may reduce potential sources of cognitive error. Controller support tools reduce or even completely eliminate the possibilities for certain cognitive errors. For example, the replacement of verbal or voice coordination with electronic coordination may create various advantages by eliminating cognitive errors resulting from mishearing or misunderstanding information exchanged over the phone or forgetting to record information (e.g. flight instructions on paper flight strips) for example during situations of high workload (Shorrock, 2005; Shorrock, 2007). Additionally, controller support tools may also provide opportunities to detect, diagnose and correct potential errors and thus reducing the operational impact of cognitive error through improved means for error detection, diagnosis and correction, also referred to as recovery opportunities (Shorrock, 2003).

Secondly, new technologies may also decrease task demands such as mental workload. For example, automated systems may support controllers directly at reducing the required mental workload related to required execution time for simple and routine tasks. Additionally, controller support tools may support controllers in reducing the required mental workload related to the detection and analysis of conflicts as well as the identification of conflict solutions (e.g. Kirwan and Flynn, 2002a). Mental workload is one of the most important factors driving human performance in air traffic control, also referred to as a performance shaping factor (Shorrock and Kirwan, 2002; Shorrock, 2003).

1.1 Challenges

Changing the operational work environment through the implementation of controller support tools in enroute control is a delicate process, since implementing new automation systems modifies the distribution of tasks between human and automated systems. For instance, conflict detection and analysis is now shared between automated systems and human agents which previously were solely allocated to the humans (air traffic controllers). This includes new tasks including monitoring conflict detection tools, interpreting the information and assessing the reliability of the conflict detection tools as well as identifying and analyzing possible discrepancies and making a final decision. Therefore, to what extent automation tools support controllers in making accurate and fast decisions, heavily depends on the reliability and the accuracy of the prediction tools, as well as the controller’s ability to assess the accuracy of these
predictions. The accuracy of the trajectory predictions may be impacted by winds, but also on the availability of airspace, phase of flight (e.g. holdings) as well as up-to-date information of aircraft performance. For example, in an experimental study conducted by Metzger and Parasuraman (2005), automation support tools increased controller’s performance and reduced controller’s mental workload, but only when the automation was reliable. Controller performance was better without support tools when the automation was inaccurate. Therefore, in order to make accurate statements about to what extent automation support tools may impact controller performance is highly dependent on the reliability and the accuracy of the support tools during all environmental conditions.

Various concerns have also been raised concerning the replacement of voice coordination with electronic coordination in air traffic control. As with datalink, electronic communication relies on the visual modality instead of auditory modality (Stedmond et al., 2007). Electronic communication messages may fail to be detected, and therefore may not be suitable for urgent situations which require immediate action (FASTI, 2009).

Cognitive error analysis is a useful approach to understand how these automated systems impact human performance at an individual level, and therefore safety and reliability of air traffic control (Kirwan, 2001). Although many studies have been conducted to evaluate the impact of new automated support tools using a cognitive error analysis (e.g. Kirwan, 2001; Shorrock, 2005; Shorrock, 2007), only few studies have conducted a complete systematic cognitive error analysis for an operational environment equipped with controller support tools. An example of such a systematic analysis was the human error analysis conducted in the FASTI project (Dehn et al., 2007).

1.2 Research aim

The aim of this paper is to compare the “classical” operational environment with paper flight strips with a ‘stripless’ work environment regarding the types of human error that may occur. The ‘stripless’ work environment includes dynamic and real-time integration of flight data onto the radar screen, electronic coordination, monitoring aids and provides controllers with Medium Term Conflict Detection tools.

The ‘stripless’ operational system may not only directly reduce the possibilities for cognitive errors by addressing the design of the operational system, but also through increasing the
opportunity for detecting errors and reducing workload (an important *performance shaping factor*), required for the execution of tasks (Shorrock, 2003). Controller support tools, in particular monitoring tools, may especially support controllers under non-routine conditions or situations characterized by high levels of uncertainty such as weather conditions, when aircraft behavior is more difficult to predict.

This paper therefore tries to identify:

1. What potential human errors are likely to be reduced and what new errors are introduced in the new operational system? To what extent does the new operational system support controllers in routine and non-routine conditions?
2. Which tasks in ‘stripless’ operations support controllers, by reducing the mental workload required for the execution of these tasks?

This paper builds on previous research conducted within the human factors study of the FASTI project (Dehn et al, 2007). The FASTI project developed a Cognitive Task Analysis and conducted a human error analysis for all changed tasks as well as new tasks. Building on the results from the FASTI project, the aim of this paper is not only to identify new sources of potential cognitive error, but also to identify which errors are potentially reduced in ‘stripless’ operations.

### 1.3 Background

The main task of air traffic controllers in enroute air traffic control sectors is to ensure efficient and safe air transportation of aircraft within their area of responsibility, maintaining the separation standards mandated by the International Civil Aviation Organization (ICAO) ensuring that aircraft are separated by at least 2,000 feet vertically above 29,000 feet (or 1,000ft when reduced vertical separation minima apply), and 5 nautical miles horizontally. In Europe, each enroute airspace sector is occupied by two air traffic controllers, forming a sector team, consisting of a radar planner (RP) and a radar executive (RE). The radar planner is mainly responsible for strategically managing the anticipated traffic by coordinating solutions with neighboring sectors in case of a potential conflict. Different geometry conflict scenarios are possible, for example head-on conflicts (aircraft pair on the same Flight Level in opposing direction), catch-up conflicts (aircraft pair in the same direction on the same Flight Level but with a faster aircraft catching up on a slower aircraft), climb- or descent-through conflict in the same
or opposite directions (conflict with one aircraft expected to either climb or descend through the Cleared Flight Level of another aircraft), climbing conflict (two aircraft both climbing and converging) or opposing traffic both in vertical movement (Kirwan and Flynn, 2002a).

Solutions to resolve these conflicts usually involve coordination proposals of Cleared Flight Levels, which gives an aircraft the lowest or highest usable flight level through which it may descent or ascent through the sector. Solutions may also involve requests for changes in Exit Flight conditions or trajectory changes, such as changes of Exit Points, Exit Flight Levels or direct routings. The radar executive is responsible for identifying the aircraft, monitoring its flight path through the sector and managing conformance in case it deviates from the agreed flight path. The radar executive is also responsible for resolving tactical conflicts. Tactical solutions may involve flight level clearances or heading and speed instructions. The radar executive may also need to deal with requests by aircraft, such as requests for direct routings or higher flight levels. In case this requires coordination with downstream sectors, the radar planner will need to coordinate. Whenever possible, the radar planner supports the radar executive with the execution of aircraft monitoring and conformance management.

1.4 Description of the operational systems

The two operational environments selected for our study were located in Switzerland. In Switzerland there are two Area Control Centers (ACCs), Zurich ACC and Geneva ACC. At the time of analysis, both ACCs operated with different operational systems. Zurich ACC was using the classic strip environment, whereas Geneva ACC was equipped with the new ‘stripless’ environment. This unique setting allowed the authors to compare the operational environments in the same timeframe.

1.4.1 ‘Strip’ operations

In the classic ‘strip’ operation environment in Zurich, air traffic controllers use individual planning boards with paper flight strips to manage and plan the traffic in their sector (Figure 1a). The radar executive and radar planner each need to update their own paper flight strips manually. This means that additional coordination within the team may be required to update the individual boards.
Within ‘strip’ operations in Zurich, flight data such as the Cleared Flight Level (CFL), speed and heading are manually recorded on the paper flight strips, but are not entered into the system except for the Cleared Flight Level. A Cleared Flight Level is the Flight Level to which an aircraft has been cleared to fly. In ‘strip’ operations, controllers use the paper strips and an air situation display (with basic measuring tools) for conflict detection and analysis. Coordination proposals and requests between sectors are conducted by voice coordination. Their support tools do not include electronic coordination or conflict detection tools, however, the Exit Conditions Assistance Tool has recently been implemented in Zürich. The Exit Conditions Assistance Tool has not been considered as part of ‘strip’ operations in this analysis to contrast classic ‘strip’ operations with ‘stripless’ operations.

1.4.2 ‘Stripless’ operations

In the ‘stripless’ work environment of Geneva, all Flight Process Strip information is integrated in the radar display (Figure 1b). Instead of planning flights by arranging paper flight strips on a strip board and manually updating paper flight strips, controllers monitor Entry and Exit windows on the radar screen and enter all clearances and instructions issued to aircraft directly into the system. For coordination between stripless sectors of Geneva, controllers simply interact via the radar interface, by electronically proposing and accepting changes. This information is then shared in real-time with other sectors of Geneva, allowing controllers in adjacent sectors to be continuously aware of the actual clearances to which a given aircraft should be responding.

The implementation of ‘stripless’ has significantly reduced “head-down time”, the time controllers are focusing their attention away from the radar screen, when updating and arranging flight strips. The implementation of electronic coordination has also completely changed the way controllers communicate and coordinate and the channels they use for communication and coordination. ‘Stripless’ operations are much more silent as most of the coordination between sectors within the Area Control Center is now performed electronically instead of over the phone. In ‘stripless’ operations, shared situational awareness (Endsley and Jones, 1997) is now primarily maintained through the human-machine interface, the radar screen, instead of the shared paper strip board. Every coordination with other sectors executed by a controller, must be manually accepted by the other controller in the team, by clicking the highlighted changes in the aircraft label, to acknowledge the change or, in other words, to “close the loop”.
At the time of conducting this research, in ‘stripless’ operations in Geneva, controllers were only able to electronically perform coordination proposals (e.g. allowing upstream sector of the center to clear an aircraft to a certain FL in your sector) to Geneva sectors. However, coordination with sectors of adjacent centers and coordination requests with other Geneva sectors (e.g. requesting a solution to another sector, including ‘stripless’ equipped sectors) still needed to be conducted by telephone. This implies that voice coordination between upper airspace sectors in Geneva was still part of normal operations, but to a reduced extent. The analysis presented here has used this ‘stripless’ environment as basis for analysis.

In ‘stripless’, the controllers are also supported by conflict detection and analysis tools: The Horizontal Scanning Tool and the Crossing Tool to detect and analyze conflicts between aircrafts currently at the same FL, such as head-on conflicts or catch-up conflicts or crossings at any angle at the same FL. These tools support the controllers with continuous conflict information and also visualize where in the trajectories separation is expected to be minimal. Additionally, the Exit Conditions Assistance Tool (ECAT) window supports controllers with the detection and analysis of exit conditions (aircraft with the same Exit Flight Level at the same Exit Point which have less separation in minutes than allowed) by marking these flights in the ECAT window and on the radar and suggesting a possible exit solution. This means that the detection and analysis of these conflicts is now shared between humans (controllers) and automation. ‘Stripless’ also provides controllers with monitoring tools (Monitoring Aids) that notify controllers when the aircraft laterally deviates from its trajectory (Route Adherence Monitoring function) as well as makes unauthorized vertical deviations from its trajectory (Cleared Level Adherence Monitoring function). Table 1 presents an overview of the main ‘stripless’ functionalities and tools.

2 Methods of analysis

2.1 Cognitive Task Analysis

In order to compare both operational environments on the types of cognitive errors that can occur, existing hierarchical Cognitive Task Analyses for enroute control were used to develop a Cognitive Task Analysis for the control tasks, specifically the operational systems in Zurich and
Geneva ACC. Two existing hierarchical Cognitive Task Analyses from the literature, developed for enroute control in European Airspace, were found to be useful.

The task analysis originally developed for FASTI (Dehn et al., 2007) was used as a main basis for the hierarchical task analysis as ‘stripless’ shares the same operational concepts as FASTI including electronic coordination (System Supported Coordination), Medium Term Conflict Detection tools and Monitoring Aids. The second task analysis, developed within the SESAR framework (SESAR Consortium, 2008) for the project Episode 3 (Gordon and Fitzpatrick, 2007), was chosen as a second task analysis. The task analysis describes all controller tasks in today’s operational context under nominal conditions. It was chosen because it supported the identification of the main generic tasks and because it is applicable to both operational systems under study, including classic ‘strip’ operations.

Based on these task analyses, a single Cognitive Task Analysis was developed. The Cognitive Task Analysis includes all traffic management related tasks for both radar executive and radar planner, except tasks related to sector management. The Cognitive Task Analysis includes generic tasks applicable to both environments as well as generic tasks which are unique to the operational environment. Generic tasks which are applicable in both ‘strip’ as well as ‘stripless’ environments may differ on how the tasks are executed and which support tools are used depending on the environment. In addition, generic tasks applicable in both environments may have unique subtasks specifically for either strip or ‘stripless’ environment (for example, paper Flight Process Strip handling in ‘strip’ environment or sending electronic coordination messages in ‘stripless’ environment).

2.2 Cognitive error analysis using TRACEr

A human error analysis was conducted with the Technique for the Retrospective and Predictive Analysis of Cognitive Errors (TRACEr) approach (Isaac et al, 2002; Shorrock and Kirwan, 2002; Shorrock, 2003). The TRACEr method is a human error identification technique, developed especially for an Air Traffic Control environment, and is based on a cognitive framework incorporating a set of classifications of human error with underlying taxonomies. The technique allows for a predictive as well as a retrospective analysis of cognitive errors. In this paper, the TRACEr method was applied as a predictive analysis, as proposed by Shorrock and Kirwan (2002). The TRACEr method incorporates four steps of analysis:
1) Step P1: Identification of performance shaping factors. Analysis of factors which may influence a controller performance, such as system design or tasks demands (high traffic loads or high uncertainty situations such as weather).

2) Step P2: Identification of all external errors (output related errors such as transferring unclear information) for each task.

3) Step P3: Identification of internal error modes. Internal error modes are classified in four cognitive domains, ‘perception’, ‘memory’, ‘decision-making’ or ‘action control’. They are linked to specific cognitive functions (e.g. detection, identification and timing execution) and describe how it has failed (e.g. forgetting temporary information) (Shorrock and Kirwan, 2002). Table 2 presents the internal error modes by TRACEr, adopting the definitions from Shorrock (2005; 2007). According to Shorrock (2007) ‘perception’ is different from ‘situational awareness’ as defined by Endsley (1995) as this definition includes comprehension and projection, which is related to memory. However, according to Shorrock (2007) ‘perception’ errors are similar to ‘level 1’ of situational awareness as defined by Endsley (1995).

4) Step P4: Identification of error recovery modes. Recovery opportunities can be defined as checks, executed by the controller, other controllers or the system which provide opportunities for error detection and correction (Shorrock, 2003). For example, the Dynamic Scanning Tool may not prevent controllers from making a cognitive error, but may support them in detecting their error in a timely manner and correct it in a timely manner to avoid task errors (or: external errors).

For the purpose of this paper, we report the possible internal error modes (P3) and recovery opportunities (P4) in context of performance shaping factors (P1) in both environments in section 3.2.

Following the approach as proposed for the TRACEr method, the Cognitive Task Analysis was used for the identification of cognitive errors. All the tasks as identified in the Cognitive Task Analysis were scanned and evaluated on the potential internal error modes. The identified errors have been classified into three major classes as follows:
- Possible error: Errors which are in theory possible, even though highly unlikely by experienced controllers in operations. Some may be very unlikely, some might be possible, but all have been assigned with the same weight, since they are possible.

- Reduced error: Errors of which the possibility of occurring are reduced in ‘stripless’ environment due to the changes in the operational design and working methods or when the effect on operational performance is reduced through recovery opportunities for error detection, diagnosis and correction (Shorrock and Kirwan, 2002).

- Possible new error: Errors which are possible in theory, and which is introduced in ‘stripless’ operations due to new tasks.

The motivation for assessing errors was based on:

- Information collected from semi-structured interviews (N = 10) with system engineers and air traffic controllers working in ‘strip’ as well as ‘stripless’ operations. The licensed air traffic controllers consulted in this study (through observation and interviews) had more than fifteen years of working experience in enroute air traffic control of which more than five years in ‘stripless’ operations;

- Over the shoulder observations in a ‘strip’ (80 hours) and ‘stripless’ operational environment (50 hours);

- Analysis of Real Time Simulation reports of earlier versions of ‘stripless’ and operational trial reports (e.g. FASTI, 2008; FASTI, 2009; Skyguide, 2010).

2.3 Mental workload assessment

The Cognitive Task Analysis for ‘strip’ and ‘stripless’ operations was used to identify potential reduction on cognitive workload for each task. Each task was assessed carefully on potential workload reduction, taking into account the subtasks in both environments, and the support tools used for the execution of the (sub)tasks. Cognitive workload was assessed to be reduced by either a) a reduced load on working memory, b) reduced required execution time, or c) by removing tasks.
3 Results

3.1 Cognitive Task Analysis for strip and ‘stripless’ operations

For ‘strip’ operations, in total 237 subtasks were identified. For ‘stripless’ operations, in total 284 subtasks were identified. Of the 284 stripless tasks, 54 tasks were identified as new tasks, 138 tasks concerned changed tasks, for example due to new operational tools used for executing these tasks and 92 tasks remained unchanged. The generic tasks are listed and described in Table 3.

3.2 Cognitive error analysis for strip and ‘stripless’ operations using TRACER

Using the Cognitive Task Analysis, potential cognitive errors were identified following the procedure described in 2.2. For each identified subtask, potential errors were identified, even if unlikely to happen in real operations by licensed controllers under nominal conditions as well as in situations with high task demands or factors considered as performance shaping factors. The results below discuss the main findings, focusing on the main changes with respect to potential cognitive errors, in particular those which may be reduced or introduced as new tasks within a ‘stripless’ environment.

3.2.1. Aircraft detection and flight plan assimilation

*RP detects incoming aircraft and assimilates flight plan (Task 1)*

*RE detects incoming aircraft, assimilates flight plan and assumes aircraft (Task 8)*

In the ‘strip’ environment, controllers use the aircraft information on the radar screen as well as the information on the paper flight strips to assimilate the flight plan. In ‘stripless’, all the required flight process information is located in one single place, the radar screen. Detection of flight information and assimilation of the flight plan now occurs mainly via the Entry window (particularly when the aircraft is not yet seen on the radar) and is therefore expected to be faster (reduced possibility of late identification of the flight trajectory) as the controller does not need to search for the corresponding flight strip to assimilate the flight plan. The relevant flight strip information (past and planned instructions) is integrated on the radar screen (in the aircraft label,
Entry and Exit windows). In the ‘strip’ environment, accurate scanning of the traffic situation is not only dependent on the accuracy of the system data, but also on up-to-date paper flight strip information. However, manually updating flight strips is a task likely to be forgotten, especially during heavy traffic load, which may cause inaccurate scanning due to missing (or no visual detection of) up-to-date flight progress information. The possibility of inaccurate scanning is therefore expected to be reduced in ‘stripless’ operations. However, particularly in a ‘stripless’ environment, the controller is dependent on accurate and timely system input of already implemented instructions (e.g. CFL, heading or speed) as well as planned instructions (e.g. E-coordination proposed for the flight) to ensure accurate scanning, which heavily relies on the use of appropriate controller working methods when updating the system.

3.2.2. Conflict detection and analysis

RP detects potential conflict or service improvement (Task 2)
RP analyzes potential conflict and identifies solution or service improvement (Task 3)
RE detects potential conflict (Task 9)
RE analyzes potential conflict and identifies solution in tactical timeframe (Task 10)

The Horizontal Scanning Tool and the ECAT window support controllers in detecting and analyzing horizontal crossings and exit conditions early, thus decreasing the possibility of late detection of these conflicts. The conflict detection tools also support controllers by identifying more efficient solutions due to earlier detection of conflicts (reducing the possibility of late and poor decisions). It must be noted, that not all types of conflicts are detected by these support tools. Conflicts involving vertical movement (descending or ascending aircraft) within the sector are not yet recognized by these support tools and therefore still fully rely on manual detection by controllers (with warning support of the Dynamic Scanning Tool).

These support tools may also reduce the risk of forgetting to monitor a particular traffic situation, in particular under conditions such as high workload conditions or high traffic complexity. In ‘strip’ operations, controllers memorize planned actions or future conflicts by holding the flight strips. Paper flight strips also support controller’s memory by writing reminders or highlighting elements on the strip. However, in particular during high workload situations, mental reminders or writing mental reminders on paper flight strips may be forgotten. In ‘stripless’ operations,
memory is supported by the Horizontal Scanning Tool, Crossing Tool and ECAT window as they will continuously highlight potential conflicts and therefore support the controller in memorizing a traffic situation. In addition, ‘stripless’ also allows highlighting particular flights or de-collapsing the flight labels by clicking the label, which may have a similar function as holding flight strips to memorize an aircraft or planned actions. In both environments, controllers may also leave measuring tools active in the display as well as forcing the display of speed vectors for particular aircraft as a reminder to monitor a conflict situation. It is expected that the ‘stripless’ system may decrease errors related to memory as controllers are reminded of conflicts due to continuous information about potential conflicts in their sector.

However, the current conflict detection tools may not always be reliable, e.g. in case of strong winds, or if aircraft do not follow their flight plan speed. In such conditions, errors related to misprojection and decision-making are likely. Controllers therefore need to have a good understanding of situations which may compromise the reliability of the predictions of the conflict detection tools and take into account uncertainty to account for possible inaccuracies of the predictions, similarly when using mental predictions without controller support tools.

### 3.2.3. Coordination between stripless sectors and updating the system

*RP initiates coordination (Task 4)*

*RP updates system and notified RE (Task 5)*

*RP and RE respond to Dynamic Scanning Tool alert (Task 6)*

*RP receives a coordination (Task 7)*

The implementation of electronic coordination changes coordination between stripless sector teams as well as within sector teams. Exchanging electronic proposals between teams instead of coordinating by phone may reduce errors related to mishearing or late auditory recognition (in case of noise due to pilot communication at the same time), as well as transmitting unclear information between sector teams. However, selection errors (clicking wrong values in the coordination menu by mistake) may occur instead. However, the impact of unsafe coordination proposals (incorrect information) is reduced by increased error detection and correction opportunities due to the Dynamic Scanning Tool, but only if the falsely selected value would be considered as an unsafe coordination.
Coordination within the team has also significantly changed in ‘stripless’ operations. Sharing coordination results in order to keep the flight strips up-to-date is no longer required. This reduces the possibility of recording or transmitting unclear information through verbal communication, leading to discrepancies between the coordination orally communicated and what is manually written on the flight strips in the ‘strip’ environment. Additionally, in case the radar executive has not been able to overhear the coordination, the radar planner may decide to postpone the notification of the updated result until there is sufficient opportunity to pass on the result. This reduces the possibility of prospective memory in ‘stripless’ operations. An additional benefit of electronic coordination is the reduced risk of forgetting temporary information or forgetting intended actions or plans. Incoming phone calls from other sectors may distract the controller temporarily from completing a task. With electronic coordination, controllers better plan and manage their cognitive attention.

However, accurate system input (e.g. CFL, heading, route or speed instructions) by the radar planner and other sectors is especially important in ‘stripless’ operations, as the radar executive cannot overhear the coordination when coordinated, and therefore has to rely on the accuracy of the system input by the radar planner. However, in ‘stripless’ operations, it is more difficult to cross-check if a coordination is indeed the same as the intended coordination by the radar planner. This means that the capability of the system to detect inaccurate input may have increased through system checks, but that instead, there may be a reduced capability for the radar executive to cross-check coordination proposals issued by the radar planner.

3.2.4. Monitoring and conformance management

*RE engages in flight progress monitoring and conformance management (Task 11)*

In ‘stripless’ operations, controllers are supported with the Monitoring Aids including Cleared Level Adherence Monitoring and Route Adherence Monitoring as well as frequency transfer reminders. The Cleared Level Adherence Monitoring and Route Adherence Monitoring supports controllers in timely visual detection and identification of potential deviations. Similarly, frequency transfer reminders may reduce the possibility of late visual detection and late visual identification of an aircraft near sector boundary requiring action through the display of a
reminder. It may also reduce the impact on operations through error recovery in case a controller forgets about the presence of an aircraft (forgetting temporary information) or is aware of the aircraft but forgets to transfer the aircraft (prospective memory failure), for example when distracted by other urgent tasks or high workload. Most importantly, the Monitoring Aids support controllers by increasing recovery opportunities through increased detection opportunities of errors elsewhere in the system, for example early detection of an unauthorized vertical deviation from an issued Cleared Flight Level, e.g. ‘level bust’, identified by the Cleared Level Adherence Monitoring function or a route deviation, identified by the Route Adherence Monitoring function. Monitoring Aids therefore particularly support controllers in managing non-routine and unexpected traffic situations.

3.2.5. Issuing instructions to the pilot

RE instructs pilot and updates system (Task 12)

In ‘stripless’ operations, a specific working method related to issuing instructions to pilots has been implemented. This working method is referred to as “click as you speak”. This working method was primarily intended to ‘force’ the controller to make her/his own analysis, for example prior to issuing an instruction to an aircraft and not to use the Dynamic Scanning Tool as a ‘what if’ tool. This working method, however, also reduces the risk of discrepancies between what is communicated to the pilot and the system inputs. Finally, the Dynamic Scanning Tool warns the controller when issuing unsafe clearances to the pilot. This working method, combined with the Dynamic Scanning Tool, thus reduce the possibility for transmitting and recording incorrect information. Incorrect clearances in the system, for example due to a selection error, which may not lead to unsafe situations, may further be detected by the Monitoring Aids in an early manner as the aircraft responds to a different instruction than what is entered in the system. Monitoring Aids further support controllers by creating error recovery opportunities in case a controller forgets to issue an instruction to the pilot or forgets to enter the instruction into the system.

3.2.6. Summary of results for all tasks
All tasks identified in the Cognitive Task Analysis were assessed on potential errors according to the TRACEr method. Figures 6a-d present the number of potential errors for ‘strip’ and ‘stripless’ environments for all the tasks (Task 1-12) identified in the Cognitive Task Analysis. The potential errors in a ‘stripless’ environment also include possible errors which have been introduced due to new tasks. In addition, Figures 6a-b list the number of errors that have been reduced in the ‘stripless’ environment compared to the ‘strip’ environment.

The results show that, overall, the number of potential errors related to all tasks has decreased. However, new support tools and electronic coordination have introduced new tasks related to detection of information. Therefore, although the possibility of no or late detection of potential conflicts have decreased, new potential sources of errors, related to timely detection of information on the radar screen have been introduced. Errors related to overhearing or mishearing have been reduced, mainly because the use of auditory modality has been reduced in ‘stripless’ operations. Overall, possible errors related to decision-making have been reduced in ‘stripless’ operations, thanks to controller support tools. However, this conclusion heavily relies on the assumption that prediction, provided by the Horizontal Scanning Tool, the Dynamic Scanning Tool and the Exit Conditions Assistance Tool (ECAT) provides sufficiently reliable information or that at least their accuracy can be assessed by controllers. With respect to execution tasks, there is a shift from errors related to transmitting/receiving unclear information towards selection errors, due to increased human-automation interaction. Overall, however, the number of potential errors related to execution has decreased thanks to the Dynamic Scanning Tool.

3.3 Analysis of mental workload reduction

All tasks identified by the Cognitive Task Analysis for ‘stripless’ operations were also assessed on potential reduced mental workload. The reduction of mental workload for routine tasks is perceived as one of the main benefits of ‘stripless’ operations (Le Roux, 2007). Mental workload has been defined in terms of the difference between the required capacity to manage tasks demands compared to the actual capacity to execute task demands (Moray 1979; Gopher and Donchin, 1986). In air traffic control, these task demands are dependent on airspace and traffic complexity factors, interface and equipment and procedural demands (Hillburn, 2004; Loft et al, 2007; Majumdar and Ochieng, 2002).
In total 233 tasks (excluding subtasks) were identified for ‘stripless’ operations using the Cognitive Task Analysis. Of those 233 tasks, we identified 104 tasks for which the execution may require reduced mental workload. Figure 7 shows the number of tasks for which the workload has reduced in a ‘stripless’ environment compared to a ‘strip’ environment. In ‘stripless’ operations, mental workload has been reduced in various ways. First of all, mental workload has been reduced by either reducing the load on the working memory, or by replacing laborious tasks with tasks involving less actions or require less time with respect to the execution. Some of the most important findings are discussed here.

Mental workload is reduced for assimilating the flight plan as all the required flight data is accessible on the radar screen (in the aircraft label, Entry and Exit windows) and information does not have to be transferred and memorized from the paper flight strips. Mental workload is also reduced for conflict detection and analysis. The Horizontal Scanning Tool, Crossing Tool and ECAT window allow tasks related to detection and analysis of crossing and exit conflicts to be shared, reducing the time required for detecting and analyzing these conflicts. Additionally, these tools continuously present aircraft status and conflict predictions in real time. Therefore, less working memory is required for remembering conflict information such as minimum separation and expected time until minimum separation.

Mental workload is further reduced due to shorter execution time required for initiating and responding to coordination as electronic coordination is faster than coordination by telephone. The system also allows tasks to be executed in parallel, and therefore more efficiently, for example by assessing multiple coordination proposals at the same time.

Finally, mental workload is reduced through the elimination of tasks related to paper Flight Process strips. Verbally transmitting coordination results, replacing new paper flight strips after receiving flight plan revisions and manually updating and rearranging paper flight strips are no longer part of ‘stripless’ operations.

4 Discussion

Paper flight strips support controllers with managing various cognitive tasks including traffic planning, assigning priorities and memorizing conflicts by re-ordering and positioning flight
strips. The fixed arrangement of Flight Process information, either electronically or on paper, was long viewed as non-replaceable. In particular, the flexibility of paper flight strips, and its visual and tactile memory functions have long been regarded as difficult to replace (Mackay et al, 1998; Mackay, 1999). However, ‘stripless’ technology seems to have successfully taken over the important functions of paper flight strips and even reduces or eliminates errors inherently associated with the use of paper flight strips.

‘Stripless’ operations heavily depend on continuous monitoring and accurate perception of presented conflict information as well as timely awareness of coordination results on the screen by the controllers. Possible new errors related to timely detection of information have been introduced based on the introduction of these new tasks. The results also showed that the reliability of the system is dependent on accuracy of the system input. The reliability of system input is managed through various ways. First of all, only the proposing sector can issue changes. Secondly, working methods in ‘stripless’, referred to as “click as you speak” guarantee that clearances and instructions are entered into the system at the same time when they are communicated to the pilot, preventing discrepancies between issued and entered clearances. Controllers are further supported by Monitoring Aids which alert controllers in case there is a discrepancy, for example when a controller forgets to input an clearance into the system or forgets to issue an instruction to the pilot. Finally, the Dynamic Scanning Tool alerts controllers in case of unsafe clearances or E-coordination proposals.

The analysis of workload reduction showed that mental workload in ‘stripless’ may be reduced for various tasks. To what extent the reduction in workload is actually detectable in real operations depends on various factors. For example, increased opportunities to detect conflicts may create a shift in the dynamic allocation of tasks within the sector team. Simulation trials of earlier versions of ‘stripless’ (FASTI, 2008) revealed that although the radar executive experienced a workload reduction, the radar planner experienced higher workload during increased traffic load. This could be explained due to improved opportunities to detect conflicts early, reducing the workload for the radar executive, but increasing workload for the radar planner (FASTI, 2008). Furthermore, freed up cognitive resources due to reduced workload may be used for other tasks, for example, further optimizing traffic trajectories and monitoring, which may improve performance (Metzger and Parasuraman, 2005). To what extent automated decision-support tools reduce mental workload, may be dependent on reliability of the support
tools as well as task demands. A study conducted by Metzger and Parasuraman (2005) showed that decision-support tools need to be reliable in order to effectively reduce workload.

Electronic coordination seems to be an effective means for coordinating flight changes between sectors. However, most coordination in upper airspace sectors in Enroute Control is standard and routine. More research is needed to understand how ‘stripless’ provides support during particular complex or non-standard situations. Such situations may require flexible and dynamic solutions as well as exchange of contextual information, which may be best transferred through voice coordination instead of electronic coordination as electronic coordination may not meet the required level of flexibility. This is in particular of interest when coordination will be performed fully electronically with telephone as alternative means for coordination.

Two final issues, related to peripheral awareness and trust in automation, which may need further study, will be shortly addressed.

**Peripheral awareness in ‘silent’ operations**

One of the major changes of ‘stripless’ is the reduced voice coordination in the control room. The results show that reduced voice coordination has eliminated many potential errors such as *mishearing*. It may also indirectly reduce *hearback* errors as the coordination between controllers is more silent. In addition, the radar planner may have more opportunities to overhear radar executive and pilot communications and thus may be more able to assist the radar executive by implicitly responding to incoming requests by pilots without the need for explicit requests by the radar executive. This is particularly beneficial as incoming requests generally occur during weather or turbulence situations, which are typically high workload conditions for the radar executive. However, voice coordination between controllers in the control room plays an important role for individual controllers to maintain situational awareness (Endsley, 1995) or ‘peripheral awareness’ (Heath and Luff, 1991; Macay, 1999) and to keep a listening ear. Observations in the ‘stripless’ environment showed that controllers still use explicit coordination within the team to pass on coordination results or to discuss traffic situations or plans, for example during non-routine situations or situations demanding urgent response. Future research should aim at understanding the conditions and situations controllers choose to engage in explicit coordination when coordination within the center is conducted fully electronically.
Trust in automation

One of the most frequent mentioned issues related to increasing the role of automation when designing cooperative human-machine systems such as the workspace of air traffic controllers is the notion of trust in automation. Trust may be impacted both by electronic coordination tools as well as conflict detection and analysis tools. Trust concerning the conflict detection tools is mainly ensured by the controller based algorithms underlying the predictions generated by the conflict detection tools. This ensures transparency and the ability to validate the predictions by the controller, according to their own mental calculations, at all times. One of the major factors likely to impact trust in conflict detection tools is the reliability of the predictions. Trust may be strongly affected by the reliability of the automation. Too much trust may also create overreliance or reduced vigilance, which is also referred to as complacency (Parasuraman and Manzey, 2010; Parasuraman and Wickens, 2008) to detect conflicts, which is a particular risk in case automation does fail, or provides inaccurate predictions. Trust in electronic coordination is ensured as it is clear for controllers which sector in the center sent the proposal. However, for future scenarios, when electronic coordination is conducted across Area Control Centers, potential lack of trust in incoming coordination requests and proposals may play a role. Area Control Centers may differ in working methods, controllers may have different mental models across ACCs and controllers do not know each other personally.

5 Limitations

Although this paper presents a thorough investigation and systematic analysis of potential cognitive errors, there are some limitations with respect to the analysis conducted. The main limitation of this study concerns the TRACEr method. Sometimes additional assumptions were necessary to make an assessment about possible errors. For example, the accuracy of the predictions of the support tools, in particular under weather situations, may highly influence controllers’ ability to make timely and accurate decisions. Another limitation of the TRACEr method is that it does not properly deal with dependencies between errors. For example, incorrect input in the system may create additional errors elsewhere in the system, therefore the assessment of particular errors is highly dependent on assumptions about the possibility of error elsewhere in the system.
The main limitation of the method is that it views human performance only in terms of cognitive error. Cognitive error reduction was not the main driver for the development of the ‘stripless’ system. Rather, the system was developed to support controllers efficiently with their tasks, and to develop support tools according to the controller’s needs (Le Roux, 2007). One of the main benefits of the system is that it supports controllers to accurately detect and anticipate future actions and system operational states, including the detection of errors or deviations elsewhere in the system. This goes beyond the concept of recovery opportunities: the ‘stripless’ system may not only support the perception and awareness of their own errors, but also the controller’s about other human agents in the system, including controllers and pilots. For example, ‘stripless’ particularly supports controllers under high workload conditions or high levels of uncertainty (unpredictability of traffic flows during difficult weather conditions) by early detection of aircraft deviations. This should not be described solely as increased recovery opportunities within the TRACEr method as it is about proactively identifying unwanted situations early, rather than detecting and correcting cognitive errors in the system. Secondly, at the individual level, the system allows controllers to deal with high variance in task demands and anticipating those demands through the ability of the system to identify complex situations or potential conflicts early and through reducing mental workload for routine tasks. Reduced workload may, in real operations however, not necessarily translate in increased mental capacity for evaluating conflicts, as this is largely dependent on operational decision-making related to sector capacity and accepted traffic loads.

This study has mainly analyzed controllers cognition at the individual level, and has not taken into account the dynamical nature of teamwork. ‘Stripless’ operations, in particular, support teamwork. For example, at team level, improved opportunities for distributing tasks and balancing workload are reported as most valuable benefits of the system (FASTI, 2008; Skyguide, 2010). However, more dynamic or flexible task distribution between controllers may also have some inherent risks. When controllers are able to distribute tasks dynamically between them, for example, depending on workload, there needs to be a clear understanding between the controllers concerning the actual distribution of tasks and responsibilities in order to avoid misunderstandings. Future research should therefore focus on understanding how the ‘stripless’ system supports performance at team level.
6 Acknowledgements

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Table 1. Overview of ‘stripless’ functionalities and support tools.

<table>
<thead>
<tr>
<th>Stripless tools</th>
<th>Description of the tool</th>
</tr>
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<tbody>
<tr>
<td><strong>Electronic coordination</strong></td>
<td></td>
</tr>
<tr>
<td>E-coordination window</td>
<td>Functionality allowing controllers of different sectors to electronically coordinate changes to the trajectory of a flight. The E-coordination tool is accessed by clicking on the aircraft label. This generates a prompt window (Figure 2) with several menus and options. The window allows controllers to send an electronic coordination proposal concerning the particular flight to another sector. The window allows controllers to propose a rate of descent/ascent, a flight level, a direct route or no need, as well as the opportunity to request the aircraft to contact the next sector frequency if not required at the sector frequency (see “flash”). A coordination proposal is used to propose a coordination for an aircraft approaching the sector, and proposes instructions to be executed by the upstream controller. A coordination proposal may concern a suggested flight level, suggested heading, direct or suggested speed.</td>
</tr>
<tr>
<td>Fh and Fx (Flash) function</td>
<td>The Flash function allows controllers to send over an aircraft to the next sector electronically. The flash function can be combined with an electronic coordination, for example a Flight Level, within the electronic coordination menu. This proposal will appear on the radar screen of the upstream sector as a coordination proposal (in blue) combined with “fh” in the aircraft label. The receiving sector executes the proposed coordination and sends the aircraft directly to the next sector, or specifically to the proposing sector with the “fx” option.</td>
</tr>
<tr>
<td><strong>Analysis support tool</strong></td>
<td></td>
</tr>
<tr>
<td>Crossing Tool</td>
<td>The Crossing Tool helps controllers in the analysis of the conflict and also the monitoring of a crossing situation. When using the Crossing Tool, the controller selects the two aircraft to be monitored against each other and the system extrapolates their positions to calculate the minimum separation between each other.</td>
</tr>
<tr>
<td><strong>Medium Term Conflict Detection tools</strong></td>
<td></td>
</tr>
<tr>
<td>Horizontal Scanning Tool</td>
<td>The Horizontal Scanning Tool (Figure 3) is a conflict detection function whose outcome is displayed on the radar screen, in the aircraft label and in a separate window which lists potential conflicts (encounters) having a horizontal separation of 10 nautical mile or 15 nautical mile or less (encounter threshold). The window lists aircraft callsigns as conflict pairs (highlighted in orange) and provides the controller with information concerning the minimum expected (horizontal) separation in nautical miles and the expected time in minutes when the separation is below the encounter threshold. Additionally, the trajectories are displayed in red where horizontal separation distance is less than 10 or 15 nautical miles, depending on controller preferred system settings.</td>
</tr>
</tbody>
</table>
| Exit Conditions Assistance | The Exit Conditions Assistance Tool (Figure 4) supports controllers in planning aircrafts through the sector in a timely manner by listing in windows all the aircrafts planned to exit at
**Tool (ECAT)**

The respective Exit Points and sorted according to their predicted exit times. The ECAT window presents the potential exit conflicts by marking the Exit Flight Levels of these flights red (also reflected in the labels) and presents controllers with a suggested solution. Exit conflicts generally concern non-compliance of the exit conditions (minimum of three minutes separation between aircraft or otherwise defined in agreements between centers).

**Dynamic Scanning Tool**

The Dynamic Scanning Tool (Figure 5) displays a prompt window when a controller enters a solution which, according to the system, is unsafe. This prompt window displays information about the potential crossings, including minimum distance and time until minimum distance is expected. The trajectories are marked in red where loss of separation is predicted. The controller is given the choice to accept the potential conflict(s) by pressing “valid” or to cancel the coordination by pressing “cancel”. If the controller clicks “cancel”, the input having triggered the Dynamic Scanning Tool conflict warning is not accepted by the system, and the controller needs to find a new solution. The Dynamic Scanning Tool does not propose any solutions to the conflicts detected. The Dynamic Scanning Tool is designed as a conflict detection tool triggered on certain inputs, and not as a continuous background monitoring.

**Monitoring Aids**

<table>
<thead>
<tr>
<th>Monitoring Aids</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cleared Level Adherence</td>
<td>Tool that monitors actual flight level of the aircraft against the Cleared Flight Level (CFL) given to the pilot and entered by the controller in the system. It provides a warning in the track label in case of non-conformance (e.g. the aircraft level does not change for a certain time after CFL input, the aircraft moves in the opposite direction to the input CFL, the aircraft levels-off before the CFL or the aircraft busts the CFL). The warning consists of the display of the CFL in orange warning colour.</td>
</tr>
<tr>
<td>Route Adherence Monitoring function</td>
<td>Monitoring aid to support controllers in detecting that an aircraft has deviated from the trajectory as known to the system. Controllers are warned for such deviations (heading field of the track label in orange warning colour). Alerts notify controllers that the current aircraft flight path deviates from the trajectory as known by the system.</td>
</tr>
<tr>
<td>Frequency reminder</td>
<td>Monitoring tool to warn controllers to send an aircraft on the frequency of the next sector (aircraft is approaching sector boundary). It displays a warning if not transferred at a defined time or distance before the Exit Point, when the exit conditions are satisfied (aircraft cleared to its planned Exit Level). The Frequency reminder supports the controller in identifying the appropriate time to transfer the aircraft to the next sector. If the controller responds late, the Frequency field will turn orange as a visual reminder.</td>
</tr>
</tbody>
</table>
Table 2. Internal error modes by TRACEr, adopting the definitions from Shorrock (2005; 2007).

<table>
<thead>
<tr>
<th>Internal error mode</th>
<th>Predictive question to identify</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Perception</strong></td>
<td></td>
</tr>
<tr>
<td>Mishear</td>
<td>Could the controller mishear a readback or transmission?</td>
</tr>
<tr>
<td>Mishearing a readback or transmission.</td>
<td></td>
</tr>
<tr>
<td>Mis-see</td>
<td>Could the controller misread, misperceive, or misidentify visual information?</td>
</tr>
<tr>
<td>Misreading, misperceiving, or misidentifying visual information.</td>
<td></td>
</tr>
<tr>
<td>No detection (auditory)</td>
<td>Could the controller fail to detect auditory information, or be late to recognize its significance?</td>
</tr>
<tr>
<td>Failing to detect, or being late to recognize the significance of a readback or transmission.</td>
<td></td>
</tr>
<tr>
<td>No detection (visual)</td>
<td>Could the controller fail to detect or identify visual information, or detect information too late to be effective?</td>
</tr>
<tr>
<td>Failing to detect or identify visual information, or detecting information too late to be effective.</td>
<td></td>
</tr>
<tr>
<td><strong>Memory</strong></td>
<td></td>
</tr>
<tr>
<td>Forget action</td>
<td>Could the controller forget to perform a planned task (prospective memory failure), or miss a step in a task sequence (including monitoring information/people)?</td>
</tr>
<tr>
<td>Forgetting to perform a planned task or missing a step in a task sequence (including monitoring information/people).</td>
<td></td>
</tr>
<tr>
<td>Forget information</td>
<td>Could the controller forget information or previous actions?</td>
</tr>
<tr>
<td>Forgetting information or previous actions.</td>
<td></td>
</tr>
<tr>
<td>Misrecall information</td>
<td>Could the controller misrecall temporary or longer-term information/actions.</td>
</tr>
<tr>
<td>Misrecalling temporary or longer-term information/actions.</td>
<td></td>
</tr>
<tr>
<td><strong>Judgement and decision-making</strong></td>
<td></td>
</tr>
<tr>
<td>Misprojection</td>
<td>Could the controller mis-project or misjudge spatial-temporal information in trying to maintain separation?</td>
</tr>
<tr>
<td>Misprojecting or misjudging spatial-temporal information in trying to maintain separation.</td>
<td></td>
</tr>
<tr>
<td>Poor decision or poor plan</td>
<td>Could the controller make a poor decision or inadequate plan?</td>
</tr>
<tr>
<td>Poor decision or inadequate plan.</td>
<td></td>
</tr>
<tr>
<td>Late decision or late plan</td>
<td>Could the controller form an acceptable decision or plan too late to be fully effective?</td>
</tr>
<tr>
<td>Acceptable decision or plan formed too late to be fully effective.</td>
<td></td>
</tr>
<tr>
<td>No decision or no plan</td>
<td>Could the controller fail to make a decision or plan for an aircraft?</td>
</tr>
<tr>
<td>No decision made or no plan formed for an aircraft.</td>
<td></td>
</tr>
<tr>
<td><strong>Action</strong></td>
<td></td>
</tr>
<tr>
<td>Selection error</td>
<td>Could the controller unintentionally mis-select or mis-position an object (e.g. manually or via a mouse pointer)?</td>
</tr>
<tr>
<td>Unintended manual selection or positioning.</td>
<td></td>
</tr>
<tr>
<td>Unclear information</td>
<td>Could the controller transmit or record unclear, vague or ambiguous information?</td>
</tr>
<tr>
<td>Transmitting or recording unclear, vague or ambiguous information.</td>
<td></td>
</tr>
<tr>
<td>Incorrect information</td>
<td>Could the controller Inadvertently transmit or recording incorrect information</td>
</tr>
<tr>
<td>Inadvertently transmitting or recording incorrect information.</td>
<td></td>
</tr>
<tr>
<td>Generic Task Type</td>
<td>Task description</td>
</tr>
<tr>
<td>------------------</td>
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</tr>
<tr>
<td><strong>Conflict detection and analysis</strong>&lt;br&gt; <em>Stripless tools: Horizontal Scanning Tool, Crossing tool, ECAT window</em></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>RP detects incoming aircraft and assimilates Flight Plan</td>
</tr>
<tr>
<td>2</td>
<td>RP detects potential conflict or service improvement</td>
</tr>
<tr>
<td>3</td>
<td>RP analyzes potential conflict and identifies solution or potential service improvement</td>
</tr>
<tr>
<td><strong>Coordination and updating system</strong>&lt;br&gt; <em>Stripless tools: Electronic coordination, Dynamic Scanning Tool</em></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>RP initiates coordination (proposal or request)</td>
</tr>
<tr>
<td>5</td>
<td>RP updates system and notifies RE</td>
</tr>
<tr>
<td>6</td>
<td>RP and RE respond to Dynamic Scanning Tool alert</td>
</tr>
<tr>
<td>7</td>
<td>RP receives coordination (proposal or request)</td>
</tr>
</tbody>
</table>
the changes in the aircraft label, confirming their awareness of the change.

### Assuming aircraft and tactical conflict detection and resolution
*Stripless tools: Horizontal Scanning Tool, Crossing tool, ECAT window*

<table>
<thead>
<tr>
<th>Step</th>
<th>Task</th>
<th>Description</th>
<th>Yes?</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>RE detects incoming aircraft, assimilates Flight Plan and assumes aircraft</td>
<td>The RE detects the aircraft and its planned trajectory through the sector and assumes the aircraft as soon as it calls on the frequency at the sector boundary.</td>
<td>Yes</td>
</tr>
<tr>
<td>9</td>
<td>RE detects potential conflict</td>
<td>The radar executive analyses the anticipated trajectory and recalls previously negotiated changes and future plans by RP.</td>
<td>Yes</td>
</tr>
<tr>
<td>10</td>
<td>RE analyzes potential conflict and identifies solution in tactical timeframe</td>
<td>The radar executive engages in conflict detection and analysis, identifies possible optimizations based on earlier plans or evaluation of the current situation and determines the plan for the trajectory through the sector.</td>
<td>Yes</td>
</tr>
</tbody>
</table>

### Aircraft progress monitoring and conformance management
*Stripless tools: Route Adherence Monitoring function, Cleared Level Adherence Monitoring function*

<table>
<thead>
<tr>
<th>Step</th>
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<th>Description</th>
<th>Yes?</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>RE flight progress monitoring and conformance management</td>
<td>The radar executive continuously monitors the performance and status of an aircraft in transit through the sector in order to timely execute the planned instructions and transfer of the aircraft. Monitoring supports controllers in timing instructions such as heading, speed and flight level instructions as well as instructions to change frequency. These tasks are primarily the responsibility of the radar executive. Conformance management is required when an aircraft may laterally deviate from its trajectory or when does not comply with level clearances leading to “level bust”.</td>
<td>Yes</td>
</tr>
</tbody>
</table>

### Aircraft instructions and transfer
*Stripless tools: Frequency reminder in radar display*

<table>
<thead>
<tr>
<th>Step</th>
<th>Task</th>
<th>Description</th>
<th>Yes?</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>RE instructs pilot and updates system</td>
<td>The radar executive instructs the pilot by giving (phased) instructions. When the aircraft reaches the sector boundary, the radar executive will hand over the aircraft to the next sector by instructing a frequency change to the pilot. In strip operations, the radar executive relies on the paper flight strips as a reminder for planned instructions to the pilot. In ‘stripless’ operations, the planned instructions are the coordination proposals (in blue text) in the aircraft label.</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Figure 1a. ‘Strip’ operations
Figure 1b ‘Stripless’ operations
Figure 2. Electronic coordination window

Figure 3. Horizontal Scanning Tool alert
Figure 4. Exit conditions assistance tool (ECAT)

Figure 5. Dynamic Scanning Tool alert
Figure 6a. Number of potential errors for ‘strip’ environment (possible errors) and ‘stripless’ environment (reduced and possible errors) for all perception tasks (Task 1-12) identified in the Cognitive Task Analysis.
Figure 6b. Number of potential errors for all memory tasks (Task 1-12) identified in the Cognitive Task Analysis.

Figure 6c. Number of potential errors for all judgment and decision-making tasks (Task 1-12) identified in the Cognitive Task Analysis.
Figure 6d. Number of potential errors for all *action execution* tasks (Task 1-12) identified in the Cognitive Task Analysis.

Figure 7. Frequencies of tasks for which the mental workload has been reduced, specified for each Generic Task (Task 1-12) as identified using the Cognitive Task Analysis.

7 References


Scientific paper 2

Predicting air traffic controllers’ workload: The indirect effect of traffic density on controller workload through traffic conflicts as a function of uncertainty

Predicting air traffic controller workload:
Uncertainty as the moderator of the indirect effect of traffic density on controller workload through traffic conflicts

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Abstract

Objective: Our study examines the impact of uncertainty on air traffic controller workload. We investigate if uncertainty moderates the relationship between traffic conflict and workload. Furthermore, we examine if the indirect effect of traffic density on workload via traffic conflict is conditional on the presence of uncertainty. Background: Although it is widely accepted that uncertainty impacts air traffic controller decision-making, little is known about how the presence of uncertainty in operations impacts controller workload. A better understanding how uncertainty impacts controller workload can improve workload prediction models for Enroute Air Traffic Control. Method: We collected data in a live operation environment, including workload ratings based on over-the-shoulder observations and real-time sector data. Hierarchical Linear Modelling was used to analyze the data. Results: Uncertainty interacts with traffic conflict in such a way that the relationship between traffic conflict and workload is strongest in the presence of uncertainty. Furthermore, uncertainty moderates the indirect effect of traffic density on workload via traffic conflict, that is, the mediating effect of traffic density via traffic conflict is conditional on the presence of uncertainty. Conclusion: Our results indicate that workload prediction tools based on traffic density metrics, which do not incorporate uncertainty, may underestimate workload under conditions of uncertainty leading to possible overload situations of air traffic controllers. Application: Sources of uncertainty which can be predicted in advance should be acknowledged in workload prediction models, taking into account possible interaction effect with other dynamic density metrics. This may increase the predictive power of these models.

Keywords: traffic conflict, traffic density, uncertainty, workload, Enroute Air Traffic Control

Précis: This study examines the impact of uncertainty on controller workload. The results show that uncertainty moderates the relationship between traffic conflict and workload and that the indirect effect of traffic density on workload via traffic conflict is conditional on the presence of uncertainty. Implications for workload prediction models are discussed.
INTRODUCTION

Enroute Air Traffic Control is a complex safety critical system, characterized by continuously changing levels of expected and unexpected task demands, which air traffic controllers need to manage, in order to maintain safe and efficient traffic flows (e.g. Loft, Sanderson, Neal, & Mooij, 2007; Malakis, Kontogiannis, & Kirwan, 2010). Workload, defined as the difference between the required capacity to manage tasks demands compared to the actual capacity to execute these task demands (Moray, 1979; Gopher & Donchin, 1986), is one of the most important factors which determine the capacity of the airspace (Majumdar & Ochieng, 2007; Majumdar, Ochieng, McAuley, Lenzi, & Lepadatu, 2004). The ability to predict workload is particularly important for strategic airspace management to make sure that workload levels stay within acceptable boundaries and to avoid possible overload situations (Djokic, Lorenz, & Fricke, 2010; Neal et al., 2014). Therefore, much progress has been made to identify task demands, in particular complexity factors, that generate mental workload for air traffic controllers (Hilburn, 2004; Loft et al., 2007; Mogford, Guttman, Morrow, & Kopardekar, 1995). Complexity may either stem from static complexity factors, originating from sector characteristics, or dynamic complexity factors, originating from traffic movements in the sector (Chatterji & Sridhar, 2001; Djokic et al., 2010; Kopardekar & Magyarits, 2003; Majumbar & Ochieng, 2007; Neal et al., 2014). Dynamic complexity factors, also referred to as dynamic density metrics (Loft et al., 2007) such as traffic density and traffic conflict metrics are important predictors for controller workload (Loft et al., 2007; Neal et al., 2014).

However, workload prediction continues to be a challenge because there are many factors creating workload (Loft et al., 2007; Neal et al., 2014). One of these factors which may account for the variability in workload in air traffic control is related to the level of uncertainty impacting operations. For example, adverse weather conditions create difficulties for controllers to predict the future state of the traffic (e.g. Averty, Guittet, & Lezaud 2008; Cummings & Tsonis, 2006). Uncertainty is therefore a fundamental aspect of air traffic control, generating additional task complexity for air traffic controllers (Averty et al., 2008; Cummings & Tsonis, 2006; Kontogiannis & Malakis, 2013), and can be regarded an additional dynamic complexity factor.

A few studies empirically investigated the main effects of uncertainty on controller workload. Prevot and colleagues (2012) and Neal and colleagues (2014) found that weather
conditions were associated with higher levels of workload. However, little is known about how uncertainty interacts with other dynamic complexity factors such as traffic conflicts.

This study contributes to the existing research by examining the interplay of dynamic complexity factors (traffic density, traffic conflicts, and uncertainty) on workload in Enroute air traffic control. As presented in Figure 1, we assume that the effect of traffic conflict is moderated by uncertainty. Furthermore, we aim to identify whether the indirect effect of traffic density on controller workload, mediated by traffic conflicts, is moderated by uncertainty. We adopt a unique approach by collecting real-time data in live operation environment and using multi-level analysis approach to take into account the nested structure of the data (cf. Neal et al., 2014).

![Figure 1. The hypothesized model.](image)

Our study has important implications for strategic airspace management. Workload prediction models, developed for strategic airspace management, are used to ensure that the workload of the air traffic controllers stays within the accepted boundaries. However, these workload prediction models often do not incorporate uncertainty, for example, generated by adverse weather. They therefore assume that the relationship between their predictors and workload do not vary depending on the amount of uncertainty influencing operations. This means that prediction tools might underestimate actual workload when uncertainty is high which, in turn, could lead to overload situations of the air traffic controllers generating safety risks.

**DYNAMIC COMPLEXITY FACTORS AS PREDICTORS OF WORKLOAD**

Traffic density is one of the strongest predictors of controller workload (Loft et al., 2007). Following Kopardekar and Magyarits (2003), we define traffic density as the number of aircraft...
divided by sector volume. Traffic density predicts workload due to the number of tasks related to manage the individual aircrafts through the sector (Loft et al., 2007) such as identifying, monitoring and instructing aircraft.

As stated by Loft et al. (2007), high traffic density may not necessarily reflect high workload for air traffic controllers because aircraft in close proximity do not always place the same amount of cognitive demand on a controller. Rather, it is the expected interaction of the aircraft based on their predicted trajectories which generate workload for controllers (e.g., Kirwan & Flynn, 2002; Loft et al., 2007). These interactions may generate traffic conflicts, which refers to situations where the minimum allowed separation distance is predicted to be lost between two or more aircraft at a certain time in the future (e.g., Boag, Neal, Loft, & Halford, 2006; Kirwan & Flynn, 2002).

Traffic conflicts are not independent from traffic density. The higher the traffic density, the more likely it is that two or more aircraft may interact based on their expected flight path through the sector. Therefore, Loft and colleagues (2007) have argued that the relationship between traffic count and workload is mediated by traffic conflicts. Similarly, we predict that traffic density causes workload not only directly due to aircraft control-tasks, but also indirectly through traffic conflicts in the sector, which need to be resolved.

Hypothesis 1: The relationship between traffic density and controller workload is partially mediated by traffic conflicts in the sector.

THE MODERATING ROLE OF UNCERTAINTY

Uncertainty is defined as a “sense of doubt that blocks or delays action” (Lipshitz and Strauss, 1997, p. 150). Three types of uncertainty can be distinguished: inadequate understanding (e.g., due to ambiguity), lack of (reliable) information, and undifferentiated alternatives (Lipshitz & Strauss, 1997). In air traffic control, these types of uncertainty originate from various sources. Winds may impact the predictability of aircraft performance, and in turn, the reliability of the predicted separation between aircraft by conflict detection tools (e.g., Cummings & Tsonis, 2006). Thunderstorms or turbulence increase the chance that pilots need to deviate from their trajectory unexpectedly. This results in difficulties for the controller to predict the most optimal strategic traffic solution (generating undifferentiated alternatives), as the effectiveness of the solution is dependent on these deviations in the tactical timeframe.
Uncertainty may also stem from other actors in the system due to ambiguity concerning (future) intentions or actions of neighboring sectors or the military. Finally, uncertainty may originate from system failures, creating situations where controllers need to make decisions based on conflicting, incomplete or missing information (Averty et al., 2008).

Uncertainty may moderate the relationship between traffic conflicts and workload. Typically, the controller conflict resolution process consists of three stages, 1) analyze, understand, and characterize the conflict, 2) determine the physically possible solutions, and 3) select an optimal solution for the current situation (Kirwan & Flynn, 2002). However, this process may be severely impacted when uncertainty impacts operations, for example when controllers have to deal with missing or conflicting information, when a traffic conflict cannot be accurately predicted due to variability of aircraft performance, or when the effectiveness of a planned solution cannot be accurately assessed in advance. In such situations, controllers critically (re)assess the situation by searching for new information, adjust priorities and select responses which may include back-up or contingency plans (Malakis et al., 2010). In contrast, during conditions characterized by low uncertainty, traffic conflicts may require only limited cognitive resources, as the future traffic situation is easy to predict and the assessment of the validity of separation plans requires little cognitive effort (e.g. Kirwan & Flynn, 2002). The relationship between traffic conflicts and workload therefore depends on the degree or level of uncertainty impacting operations. Thus, it can be expected that relationship between traffic conflicts and workload is stronger for conditions where uncertainty is present.

**Hypothesis 2:** Uncertainty moderates the relationship between traffic conflicts and controller workload such that the relationship between traffic conflicts and workload is stronger when uncertainty is present.

Finally, we expect uncertainty to aggravate the relationship between traffic density and workload via traffic conflicts when uncertainty is present, because uncertainty exacerbates the cognitive effort related to solving traffic conflicts, generated by traffic density. In contrast, when uncertainty is absent, the cognitive effort required to solving conflicts will be less, because air traffic controllers have high levels of experience allowing them to resolve traffic conflicts without much cognitive effort. Thus, the indirect effect of traffic density on workload via traffic
conflict is conditional, depending on the presence of uncertainty. Logically derived from Hypothesis 1 and 2, Hypothesis 3 is formulated as follows:

**Hypothesis 3:** Uncertainty moderates the mediating effect of traffic density and workload via traffic conflict, in such a way that the mediation effect is strongest when uncertainty is present.

**METHOD**

**The setting**

The data was collected through observation of Enroute Air Traffic Control teams during live operations. The observations were held at an Enroute Area Control Center (ACC) in central Europe, in upper control sectors L1 through L6. The sectors share the same geographical area, but differ in altitude and volume. Sectors can be merged up to three sectors during the day, depending on traffic levels. Data were collected for seven out of the 12 possible sector combinations. The sessions were held from 5:00am to 16:00pm Local Time with varying availability of military airspace within the sector. Each sector is managed by a team of two controllers: a radar executive and a radar planner. The radar executive is in charge of the communication with the aircraft and managing traffic conflicts within the sector. The radar planner in the sector is responsible for coordinating traffic solutions with neighboring sectors and solving traffic conflict in a strategic manner (i.e., before the aircraft enter the sector). Although they have different responsibilities, their tasks are highly interdependent (Corver & Aneziris, 2014).

**Participants**

The participants in this study were air traffic controllers (*N* = 45) all licensed to work in the enroute sectors of the ACC. Age, gender, and experience were not recorded to maintain the anonymity of the controllers. Participation in the study was voluntary.

**Procedure**

Two observers, blinded for our hypotheses, independently rated the workload of one of the two controllers. The two observers, both male, had more than 10 years of working experience in Enroute Air Traffic Control and were also familiar with controller performance evaluations. The observers rated workload at five minute intervals. The sessions had an duration of 10 to 20
minutes, thus subdividing each session into two to four sub-sessions, after which workload was rated. The observers rotated positions randomly, observing either the radar executive or the radar planner. The allocation of the observer across the two positions was balanced ($\chi^2 (1, N = 108) = 0.59, ns$). At the end of the session, both observers evaluated the individual performance of the controller they observed. In addition, they monitored for uncertainty impacting operations during their observations, and provided a shared rating of uncertainty at the end of the session.

**Sample description**

In total, 61 sessions were observed. Because a few controllers preferred a different ‘look-ahead’ time setting of their conflict detection tools, traffic conflicts could only be computed for 54 of the 61 sessions. The remaining 54 sessions were used for this analysis. Workload ratings subdivided each session into two to four sub-sessions, for which an average traffic density and traffic conflicts was calculated. This resulted in a total of 176 sub-sessions. For each sub-session, workload ratings were provided for both positions, thus, generating $N = 334$ workload ratings. The means, standard deviations and correlations among the variables are presented in Table 1.
### Table 1
*Means, Standard Deviations, and Correlations Between Study Variables*

<table>
<thead>
<tr>
<th></th>
<th>M</th>
<th>SD</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
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<th>6</th>
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<th>10</th>
<th>11</th>
<th>12</th>
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</thead>
<tbody>
<tr>
<td>1. Traffic density</td>
<td>0.30</td>
<td>0.17</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Traffic conflict</td>
<td>1.02</td>
<td>1.12</td>
<td>0.43</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Sub-session duration</td>
<td>300.05</td>
<td>38.73</td>
<td>0.00</td>
<td>-0.09</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Military activity</td>
<td>0.62</td>
<td>0.49</td>
<td>0.12</td>
<td>0.17</td>
<td>0.04</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Controller workload</td>
<td>1.50</td>
<td>0.52</td>
<td>0.26</td>
<td>0.28</td>
<td>0.05</td>
<td>0.10</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>6. Observer</td>
<td>0.50</td>
<td>0.50</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>-0.13</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>7. Controller position</td>
<td>0.50</td>
<td>0.50</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>-0.11</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>8. Actor performance</td>
<td>0.81</td>
<td>0.39</td>
<td>-0.19</td>
<td>-0.21</td>
<td>0.00</td>
<td>-0.13</td>
<td>-0.02</td>
<td>-0.30</td>
<td>-0.07</td>
<td>1.00</td>
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<tr>
<td>9. Partner performance</td>
<td>0.81</td>
<td>0.39</td>
<td>-0.19</td>
<td>-0.21</td>
<td>0.00</td>
<td>-0.13</td>
<td>-0.17</td>
<td>0.30</td>
<td>0.07</td>
<td>-0.12</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>10. Uncertainty</td>
<td>0.50</td>
<td>0.50</td>
<td>0.05</td>
<td>0.01</td>
<td>0.01</td>
<td>-0.04</td>
<td>0.06</td>
<td>0.00</td>
<td>0.00</td>
<td>-0.14</td>
<td>-0.14</td>
<td>1.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11. Sector volume</td>
<td>45.00</td>
<td>17.13</td>
<td>-0.77</td>
<td>-0.24</td>
<td>-0.03</td>
<td>-0.16</td>
<td>-0.13</td>
<td>0.00</td>
<td>0.00</td>
<td>0.13</td>
<td>0.13</td>
<td>-0.08</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>12. Sector average FL</td>
<td>328.80</td>
<td>35.86</td>
<td>0.67</td>
<td>0.22</td>
<td>0.03</td>
<td>0.10</td>
<td>0.21</td>
<td>0.00</td>
<td>0.00</td>
<td>-0.02</td>
<td>-0.02</td>
<td>0.06</td>
<td>-0.83</td>
<td>1.00</td>
</tr>
</tbody>
</table>

*Note.* Cronbach’s alpha ….. Correlations are sub-session level correlations (N =334). Correlations $r \geq .11$ being significant at $p \geq .05$ and $r \geq .14$ being significant at $p \geq .01$.

* $a_0$ = not active; 1 = active.
* $b_1$ = low; 2 = medium; 3 = high.
* $c_0$ = Observer 1; 1 = Observer 2.
* $d_0$ = Radar Planner; 1 = Radar Executive.
* $e_0$ = less than excellent performance; 1 = excellent performance.
* $f_0$ = uncertainty absent; 1 = uncertainty present.
Measures

Traffic density. The average traffic density for each sub-session was calculated by computing the average number of aircraft under control per minute and dividing this by the sector volume.

Traffic conflict. Two types of traffic conflict were recorded: horizontal crossings and exit conflicts. A horizontal crossing involves a potential conflict of two or more aircraft, with a horizontal separation of 10 nautical miles or less predicted within a ‘look-ahead’ time of the next 10 minutes. Exit conflicts concern non-compliance of the exit conditions (e.g., less than three minutes separation between two aircraft). Traffic conflict was calculated as the average number of active horizontal crossings and exit conflicts per minute.

Uncertainty. Uncertainty was measured using a 5-item Likert scale (Appendix A). The items were chosen in order to capture as many different sources of uncertainty as possible whilst acknowledging the different types of uncertainty, thus forming a composite (or: formative) scale of various sources of uncertainty. The scale was subsequently recoded into a dichotomous variable, indicating 0 = “no uncertainty present” and 1 “uncertainty present”, allowing us to discriminate between conditions where uncertainty was absent versus present to simplify analyses.

Workload. We measured workload on a 3-point scale (“low”, “medium” and “high”) as an indicator of required effort to execute the tasks. The ratings were entered electronically on a small laptop. This method is similar to other workload measures including the Air Traffic Workload Input Technique (ATWIT; Stein, 1985) and the Instantaneous Self–Assessment (ISA) technique (Eurocontrol, 2002; Eurocontrol 2003) which measure workload (self-reported or rated by observers) on a single 5-point scale item. One-dimensional scales for workload are a commonly applied method to measure workload in simulations in ATC Environment (Eurocontrol, 2002). The observers were asked to rate the workload of the controller they were observing based on the full scope of the task demands they were responding to (e.g. traffic monitoring, decision-making and traffic planning, coordinating traffic, executing system entries, instructing aircraft).

Control variables
For all analyses, we controlled for variables on all levels of the analysis. On the sub-session level (Level 1), military activity was included as a covariate because the availability of military airspace increases the airspace volume and allows the controllers the ability to give aircraft direct routings, as a way to resolve conflicts. Furthermore, the duration of the sub-session was included as a control variable. On the controller level (Level 2), we assessed controller performance with six items on a 6-point rating scale (Appendix B). The scale was recoded into a dichotomous variable, indicating 0 = “less than excellent performance” and 1 “excellent performance”. Because controller’s workload is influenced by his or her own performance (actor performance), as well as by the performance of their partner (partner performance), we included these variables as separate predictors in the model, following the approach as proposed by the Actor Partner Interdependence Model (Kenny, Kashy, & Cook, 2006). Finally, on the controller level, we created a variable indicating the observer. On the session level (Level 3), we entered sector volume and sector average flight level as control variables. Sector volume may mainly influence workload because larger sectors offer more maneuver possibilities (Kirwan & Flynn, 2002) without the need to coordinate with other sectors. Furthermore, sectors with a lower average flight level generally have a higher percentage of descending or ascending aircraft that may cross flight levels of other aircraft.

**Analytical approach**

We used Hierarchical Log-Linear Modelling to test Hypothesis 1 and 2. Hierarchical Linear Models accommodate the nested structure of the data due to the non-independent observations, which is neglected by ordinary least square (OLS) regression models (Raudenbush & Bryk, 2002). All the variables (except the dichotomous variables) were grand centered (Hofmann & Gavin, 1998; Kreft & de Leeuw, 1998). The Hierarchical Log-Linear Models were analyzed using HLM v7.0 (Raudenbush, Bryk, & Congdon, 2004).

To test the mediation effect as described in Hypothesis 1, we adopted the steps described by Baron and Kenny (1986). To test the moderation described in Hypothesis 2, we built up our model using an incremental approach and added a cross-level interaction effect as a last step. We tested model improvements with a likelihood ratio statistic (Aguinis, Gottfredson, & Culpepper 2013; Raudenbush & Bryk, 2002). To test Hypothesis 3, a moderated mediation model was used,
using the SPSS macro PROCESS, based on single level bootstrapping (Preacher, Rucker, & Hayes, 2007).

**RESULTS**

**Preliminary Analyses**

To conduct multilevel analyses, there needs to be variance on all levels (Hofmann, 1997; Raudenbush & Bryk, 2002). This requirement was fulfilled: 57.6% of the total variance was within sub-session (Level 1), 6.4% between controllers (Level 2) and 36.0% between sessions (Level 3), indicating that the application of Hierarchical Log-Linear Modelling is appropriate.

**Test of Hypotheses**

In Hypothesis 1, we proposed that traffic conflicts mediates the relationship of traffic density on controller workload. The results of the Hierarchical Log-Linear Mediation analysis are presented in Table 2.
### Table 2

*Hierarchical Log-Linear Mediation analysis for traffic density on controller workload via traffic conflicts and single level bootstrap re-sampling results (PROCESS).*

<table>
<thead>
<tr>
<th>Mediation analysis (HLM)</th>
<th>Estimate</th>
<th>SE</th>
<th>t</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traffic density predicts workload</td>
<td>1.32</td>
<td>0.33</td>
<td>4.04 ***</td>
</tr>
<tr>
<td>Traffic density predicts traffic conflict</td>
<td>3.60</td>
<td>0.76</td>
<td>4.71 ***</td>
</tr>
<tr>
<td>Traffic density predicts workload controlled for traffic conflict</td>
<td>1.06</td>
<td>0.34</td>
<td>3.10 **</td>
</tr>
<tr>
<td>Traffic conflict predicts workload controlled for traffic density</td>
<td>0.07</td>
<td>0.03</td>
<td>2.14 *</td>
</tr>
</tbody>
</table>

*Estimation of indirect effect based on single level bootstrap re-sampling (PROCESS)*

<table>
<thead>
<tr>
<th></th>
<th>Estimate</th>
<th>SE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indirect effect of traffic density on controller workload via traffic conflict</td>
<td>0.27</td>
<td>0.10</td>
</tr>
<tr>
<td>LL 95% CI</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td>UL 95% CI</td>
<td>0.49</td>
<td></td>
</tr>
</tbody>
</table>

*Note.*  *p < .05.*  ** *p < .01.*  *** *p < .001.*

a Bootstrap re-sampling = 5000; *N* = 334.

Standard errors are robust standard errors (HLM) and standard errors based on the HC3 estimator (PROCESS)
Table 2 shows that traffic density, without traffic conflicts in the model, has a positive and significant effect on controller workload ($\gamma = 1.32$, $p < .001$). Furthermore, traffic density positively predicted traffic conflicts ($\gamma = 3.60$, $p < .001$). Finally, the effect of traffic density on controller workload was reduced ($\gamma = 1.06$, $p < .01$) when controlling for traffic conflicts, indicating a partial mediation of traffic conflicts on the relationship of traffic density and controller workload. In addition, the estimation of the indirect effect based on single level bootstrapping (bootstrapping samples= 5000), using PROCESS for SPSS (Preacher & Hayes, 2004) showed that the indirect effect was significant ($\beta = 0.27$, 95% CI [0.08, 0.49]). Thus, data supported Hypothesis 1.

Hypothesis 2 proposes that uncertainty moderates the effect of traffic conflicts on controller workload. Table 3a shows the results of our analyses.
### Table 3a

**Multilevel Moderated Mediation Analysis**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Null model</th>
<th>Model 1 Random Intercept and Fixed Slope</th>
<th>Model 2a Random Intercept and Fixed Slope</th>
<th>Model 2b Random Intercept and Random Slope</th>
<th>Model 3 Cross-Level Interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>1.51 0.05 30.38 ***</td>
<td>1.74 0.17 10.44 ***</td>
<td>1.52 0.21 7.39 ***</td>
<td>1.52 0.19 7.89 ***</td>
<td>1.53 0.19 7.86 ***</td>
</tr>
<tr>
<td>Control variables</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sector duration</td>
<td>0.00 0.00 0.71</td>
<td>0.00 0.00 1.30</td>
<td>0.00 0.00 1.40</td>
<td>0.00 0.00 1.55</td>
<td></td>
</tr>
<tr>
<td>Military activity</td>
<td>0.13 0.09 1.45 *</td>
<td>0.12 0.08 1.53</td>
<td>0.11 0.07 1.50</td>
<td>0.11 0.07 1.51</td>
<td></td>
</tr>
<tr>
<td>Controller position</td>
<td>-0.01 0.05 -0.15</td>
<td>-0.01 0.05 -0.15</td>
<td>-0.01 0.05 -0.15</td>
<td>-0.01 0.05 -0.15</td>
<td></td>
</tr>
<tr>
<td>Controller observer</td>
<td>-0.11 0.05 -2.17 *</td>
<td>-0.11 0.05 -2.16 *</td>
<td>-0.11 0.05 -2.16 *</td>
<td>-0.11 0.05 -2.16 *</td>
<td></td>
</tr>
<tr>
<td>Actor performance</td>
<td>-0.11 0.11 -0.97</td>
<td>0.12 0.09 2.09</td>
<td>0.11 0.09 2.09</td>
<td>0.11 0.09 2.07</td>
<td></td>
</tr>
<tr>
<td>Partner performance</td>
<td>-0.20 0.09 -2.37 *</td>
<td>-0.08 0.10 -0.86</td>
<td>-0.06 0.10 -0.66</td>
<td>-0.09 0.10 -0.92</td>
<td></td>
</tr>
<tr>
<td>Sector volume</td>
<td>0.01 0.01 1.82</td>
<td>0.02 0.00 3.52 ***</td>
<td>0.02 0.00 3.72 ***</td>
<td>0.02 0.00 3.45 **</td>
<td></td>
</tr>
<tr>
<td>Sector average FL</td>
<td>0.01 0.00 2.61 *</td>
<td>0.01 0.00 2.19 *</td>
<td>0.01 0.00 2.28 *</td>
<td>0.00 0.00 2.13 *</td>
<td></td>
</tr>
<tr>
<td>Predictors</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uncertainty</td>
<td>0.06 0.09 0.66</td>
<td>0.02 0.09 0.22</td>
<td>0.06 0.09 0.67</td>
<td>0.06 0.09 0.67</td>
<td></td>
</tr>
<tr>
<td>Traffic density</td>
<td>1.06 0.34 3.10 **</td>
<td>1.26 0.34 3.70 ***</td>
<td>1.14 0.35 3.26 ***</td>
<td>1.14 0.35 3.26 ***</td>
<td></td>
</tr>
<tr>
<td>Traffic conflict</td>
<td>0.07 0.03 2.14 *</td>
<td>0.09 0.04 2.54 *</td>
<td>0.01 0.04 0.29</td>
<td>0.01 0.04 0.29</td>
<td></td>
</tr>
<tr>
<td>Traffic conflict x uncertainty</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-2 X Log</td>
<td>435.22</td>
<td>413.32</td>
<td>394.61</td>
<td>391.39</td>
<td>387.54</td>
</tr>
<tr>
<td>Df</td>
<td>4</td>
<td>12</td>
<td>15</td>
<td>17</td>
<td>18</td>
</tr>
<tr>
<td>Δ -2 X Log</td>
<td>21.90 **</td>
<td>18.71 ***</td>
<td>3.22 ns</td>
<td>3.85 *</td>
<td></td>
</tr>
<tr>
<td>ΔDf</td>
<td>8</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Level 1 intercept variance (SE)</td>
<td>0.16 0.40</td>
<td>0.16 0.39</td>
<td>0.15 0.38</td>
<td>0.14 0.38</td>
<td>0.14 0.38</td>
</tr>
<tr>
<td>Level 2 intercept variance (SE)</td>
<td>0.02 0.13</td>
<td>0.01 0.09</td>
<td>0.01 0.10</td>
<td>0.01 0.10</td>
<td>0.01 0.10</td>
</tr>
<tr>
<td>Level 3 intercept variance (SE)</td>
<td>0.10 0.31</td>
<td>0.08 0.28</td>
<td>0.07 0.27</td>
<td>0.07 0.26</td>
<td>0.07 0.26</td>
</tr>
<tr>
<td>Level 3 slope variance (SE)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.01 0.08</td>
</tr>
</tbody>
</table>

*Note.* *p < .05. **p < .01. ***p < .001.

All standard errors are robust standard errors.
To test Hypothesis 2, we built up our model according to the incremental approach as described. Model 1, which included the control variables on all levels, showed a better fit than the null model ($\chi^2 (12) = 413.32, \Delta \chi^2 (8) = 21.90, p < .01$). Of the control variables entered, sector average flight level was positively associated workload ($\gamma = 0.01, p < .05$). Furthermore, performance of the partner controller (-0.20, p < .05) was negatively associated with workload. Thus, the lower the performance of your partner, the higher your workload. Finally, there was a main effect of observer ($\gamma = -0.11, p < .05$), indicating there was some difference between the two raters in the prediction of workload. In Model 2a, we added the main effects of the predictors in the model. Model 2a had a better fit compared to Model 1, ($\chi^2 (15) = 394.61, \Delta \chi^2 (3) = 18.71, p < .001$). Traffic density showed a positive association with workload ($\gamma = 1.06, p < .01$), as did traffic conflicts ($\gamma = 0.07, p < .05$). However, there was no main effect of uncertainty ($\gamma = 0.06, p = \text{n.s.}$). In order to test the interaction effect as proposed in Hypothesis 2, we first tested if the slope for traffic conflict varied significantly across the sessions (Hox, 2010; Snijders & Bosker, 2012). Adding the random slope effect in Model 2b, however, did not significantly increase the fit of the model ($\chi^2 (17) = 391.39, \Delta \chi^2 (2) = 3.22, p = \text{n.s.}$). Following advice by LaHuis and Ferguson (2009) and Aguinis et al. (2013), we proceeded to test the interaction effect. The interaction effect was added as a last step (Model 3). Model 3 showed a better fit compared to Model 2b, ($\chi^2 (18) = 387.54, \Delta \chi^2 (1) = 3.85, p < .05$).

The regression estimates of the interaction effect in Model 3 showed that the interaction effect of traffic conflicts and uncertainty ($\gamma = 0.13, p < .05$) predicted controller workload. Figure 2 indicates that, in line with hypothesis 2, in the presence of uncertainty, traffic conflict positively predicts workload, whereas in conditions of no uncertainty, the effect of traffic conflicts on workload is weaker. Thus, workload is highest under higher levels of traffic conflicts and in the presence of uncertainty. Additional simple slope analysis (c.f. Preacher, Curran, & Bauer, 2006) confirmed these findings: in the presence of uncertainty, traffic conflict positively predicts workload (slope = 0.17, $z = 4.53, p < 0.001$, whereas in absence of uncertainty, traffic conflicts did not predict workload (slope = 0.02, $z = 0.36, \text{ns}$). Thus, Hypothesis 2 was supported.
In order to test the moderated mediation as described in Hypothesis 3, Model 3 was run in PROCESS with the bootstrapping approach. Table 3b reports the unstandardized regression coefficients and 95% confidence interval.

Table 3b

<table>
<thead>
<tr>
<th></th>
<th>Effect</th>
<th>SE</th>
<th>Lower limit</th>
<th>Upper limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncertainty absent</td>
<td>0.02</td>
<td>0.13</td>
<td>-0.23</td>
<td>0.30</td>
</tr>
<tr>
<td>Uncertainty present</td>
<td>0.47</td>
<td>0.12</td>
<td>0.27</td>
<td>0.73</td>
</tr>
</tbody>
</table>

*Note. Bootstrap sample size=5000 (N=334); Unstandardized regression coefficients are reported.*

The results show that uncertainty moderates the positive indirect effect of traffic density on controller workload via traffic conflicts. More specifically, traffic conflicts mediate the relationship between traffic density on workload when uncertainty is present, indicated by a significant indirect effect of traffic conflicts, β = 0.47, 95% CI [0.27, 0.73]. However, when uncertainty is absent, traffic conflict does not mediate the relationship between traffic density and workload, which was indicated by a non-significant indirect effect of traffic conflict, β = 0.02, 95% CI [-0.23, 0.30]. This suggests that the contribution of traffic conflicts generated by traffic

*Figure 2. Interaction effect between traffic complexity and uncertainty on controller workload.*
density on workload is only significant when uncertainty is present. As we expected the mediating relationship of traffic conflict to be stronger in the presence of uncertainty, but not to disappear when uncertainty is absent, Hypothesis 3 was partially confirmed.

**DISCUSSION**

**Conclusion**

Our study examined the impact of uncertainty on air traffic controller workload. The live operational setting of our study provided a unique opportunity to study uncertainty in real context.

Data confirmed most of our hypotheses. In line with Loft et al. (2007), we could confirm a mediation effect of traffic density on workload via traffic conflicts. The identification of mediation effects between dynamic complexity metrics allows for the identification of further moderators and thus needs to be considered when developing predictive workload models for enroute air traffic control.

Furthermore, in line with our expectations, we found that uncertainty interacts with traffic conflicts to predict workload such that the relationship between traffic conflicts and workload is stronger in the presence of uncertainty. This is in line with arguments put forward by Hilburn & Flynn (2005) and Majumdar & Ochieng (2007) that (dynamic) complexity factors may interact to predict workload. The interaction effect between traffic conflict and uncertainty can be explained by the additional cognitive demands associated with managing traffic conflicts under conditions of uncertainty (e.g., Cummings & Tsonis, 2006; Hilburn & Flynn, 2005; Kontogiannis & Malakis, 2013). Controllers need to search for information, formulate back-up plans and engage in additional coordination when managing traffic conflicts under conditions of uncertainty (e.g., Kontogiannis & Malakis, 2013). In contrast, in absence of uncertainty, most traffic conflicts require little cognitive effort and associated workload for air traffic controllers, due to controllers high level of expertise and experience (e.g., Kirwan & Flynn, 2002).

Finally, our findings also provided partial support for our final hypothesis. We found that uncertainty indeed moderates the mediating effect of traffic conflicts. However, the results showed that there is only an indirect effect of traffic density on workload via traffic conflicts when uncertainty is present. The findings confirm that the relative contribution of traffic conflicts
on workload cannot be seen as static. The effect of traffic conflict generated by traffic density is conditional on the amount of uncertainty influencing operations.

**Limitations and future research**

Our study has some limitations. First of all, although multilevel modelling was able to address the non-interdependencies of the data, we could not take into account all interdependencies in the data: the air traffic controllers participated in our research in more than one session as the pool of controllers was not large enough to have observations with unique controllers for each session. This means that interdependencies of the data, due to controller characteristics not measured in our study (e.g. experience), is not accounted for in our model. Secondly, we made no distinction between the two controller positions in our analyses. For this reason, future research should investigate if our findings can be replicated for both positions. Thirdly, our study only assessed the impact of uncertainty on traffic conflict, which was limited to two types of traffic conflicts: horizontal crossings and exit conflicts. Future research should examine further interactive effects between uncertainty and other static and dynamic complexity metrics.

There are also some limitations regarding the generalizability of the study across other air traffic control settings, as such settings may differ considerably from the setting under study in terms of controller composition (e.g. single manned sector operations), static and dynamic complexity factors as well as automation levels. For example, in lower enroute control, controllers need to align traffic flows and hand off aircraft with sufficient separation to approach control using speed and heading instructions. Dynamic complexity factors in lower enroute control are therefore likely to be different. Thus, future research in other settings should study possible interaction effects of uncertainty with dynamic complexity factors which are typical for those air traffic control settings.

Finally, future research should focus on developing measures which allow the measurement of uncertainty. Although uncertainty cannot always be predicted (e.g. emergency scenarios), weather conditions can provide useful indicators for the measurement of uncertainty.

**Practical implications**
The results of our study have important implications for the development of controller workload models. Our results indicate that workload prediction tools which have not incorporated uncertainty may underestimate workload under conditions of high uncertainty, leading to possible overload situations of the air traffic controller, generating safety risks. Future workload models of enroute air traffic control should acknowledge uncertainty, as well as interactive effects between traffic conflict and uncertainty as predictors of controller workload. Including uncertainty and their interactive effects with other dynamic complexity factors may increase the predictive power of these models, in particular under conditions of uncertainty. The results also have implications assessing controller workload in future air traffic scenarios as envisioned in SESAR (SESAR JU, 2012) and NextGen (FAA, 2014). Although these programs aim to minimize uncertainty (Grote, 2009) by reducing tactical conflicts in operations through the implementation of trajectory-based ATC operations, uncertainty, for example due to weather, can never be fully removed from tactical operations. Uncertainty will therefore continue to influence controller workload in trajectory-based ATC operations, for example when negotiating with pilots in case planned trajectories cannot be met due to adverse weather. Uncertainty should therefore be considered as a predictor of controller workload in future trajectory-based operations, and possible interactive effects of uncertainty with other (dynamic) complexity factors, identified as critical for trajectory-based operations, should be identified.

Acknowledgements

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Key points

- Although uncertainty has been acknowledged as an important aspect of air traffic control, little is known about how uncertainty influences controller workload.
• We collected data in an Enroute Air Traffic Control Center during live operations and used a hierarchical linear modeling approach to analyze the data.
• Uncertainty moderates the indirect effect of traffic density on workload via traffic conflict such that the effect of traffic conflict is aggravated under conditions of uncertainty.
• Uncertainty should be considered in workload prediction models for enroute air traffic control as it will improve the predictive power, in particular under conditions of uncertainty.
APPENDIX A

Uncertainty rating scale

To what extent did the following events occur during previous session:

<table>
<thead>
<tr>
<th>Event</th>
<th>Rating Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Weather conditions (e.g. winds) greatly impacted AC performance</td>
<td>0 1 2 3 4 5 6</td>
</tr>
<tr>
<td>2) Sector information (e.g. military airspace availability) was conflicting</td>
<td>0 1 2 3 4 5 6</td>
</tr>
<tr>
<td>3) Actions of surrounding ACC sectors (e.g. planned execution of coordination, deviations from procedures) were difficult to predict.</td>
<td>0 1 2 3 4 5 6</td>
</tr>
<tr>
<td>4) Unexpected behavior by aircraft: deviations from routing.</td>
<td>0 1 2 3 4 5 6</td>
</tr>
<tr>
<td>5) Unexpected behavior by aircraft: deviations from issued CFL</td>
<td>0 1 2 3 4 5 6</td>
</tr>
</tbody>
</table>

APPENDIX B

Controller performance rating scale

Please rate the performance of the controller you just have observed.

I - SITUATION AWARENESS

<table>
<thead>
<tr>
<th>Event</th>
<th>Rating Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) RE/RP maintained sufficient awareness of aircraft and their positions</td>
<td>1 2 3 4 5 6</td>
</tr>
<tr>
<td>2) RE/RP corrected own errors or made improvements in a timely manner</td>
<td>1 2 3 4 5 6</td>
</tr>
<tr>
<td>3) RE/RP was always ahead of the traffic</td>
<td>1 2 3 4 5 6</td>
</tr>
</tbody>
</table>

II - PRIORITIZING AND PLANNING

<table>
<thead>
<tr>
<th>Event</th>
<th>Rating Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>4) RE/RP took actions in an appropriate order of importance</td>
<td>1 2 3 4 5 6</td>
</tr>
</tbody>
</table>
5) RE/RP engaged timely in preplanning control actions

Note. The items, with minor adaptions, originate from the Subject Matter Expert Observer Rating Form For En Route Operations (Allendoerfer & Galushka, 1999) and the SHAPE questionnaire (Jeannot, Kelly, & Thompson, 2003).

References


Hilburn, B. (2004). *Cognitive Complexity in Air Traffic Control: A Literature Review.* Retrieved from Center for Human Performance Research:
http://www.chpr.nl/index_htm_files/CXLIT.pdf


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Gudela Grote is a full professor of work and organizational psychology at ETH Zurich, Switzerland. She received her PhD in industrial/organizational psychology from Georgia Institute of Technology, Atlanta, in 1987.
Scientific paper 3

Uncertainty management in Enroute Air Traffic Control. Implications for automation design

UNCERTAINTY MANAGEMENT IN ENROUTE AIR TRAFFIC CONTROL:
A FIELD STUDY EXPLORING CONTROLLER STRATEGIES AND REQUIREMENTS FOR AUTOMATION

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ABSTRACT

The management of uncertainty is a critical aspect of Air Traffic Control. This study investigates: 1) The sources of uncertainty in Enroute Air Traffic Control, 2) the strategies that Air Traffic Controllers adopt to cope with uncertainty, and 3) the requirements for system design which support controllers in following these strategies.

This study identifies three types of uncertainty coping strategies: reducing uncertainty, acknowledging uncertainty and increasing uncertainty. The RAWFS heuristic (Lipshitz and Strauss 1997) and anticipatory thinking (Klein et al. 2007) were used to identify reduction and acknowledgement strategies. Recent suggestions by Grote (2015) were used to further explore to identify strategies that increase uncertainty. The data was collected using a field study in two Enroute Air Traffic Control Centers, involving “over the shoulder” observation sessions, discussions with air traffic controllers and document analysis.

The results show that controllers, in addition to reduction and acknowledgement of uncertainty, may deliberately increase uncertainty in order to increase flexibility for other actors to meet their operational goals. Furthermore, the results discuss system design recommendations which allow controllers to follow these different uncertainty coping strategies. System design recommendations discussed include 1) the design of alerts and forcing functions; 2) transparency of prediction tools, and 3) system flexibility as requirement for acknowledging and increasing uncertainty. The study discusses implications of the findings for the future Air Traffic Management scenarios as envisioned within the SESAR Joint Undertaking (SESAR JU 2012) and NextGen (FAA 2014) operational concept.

Keywords Uncertainty management, coping with uncertainty, air traffic control, adaptive strategies, system design, Naturalistic decision-making.
1. Introduction

Air Traffic Management is a highly regulated industry, which aims at minimizing uncertainties (c.f. Grote 2004; Grote 2009) through airspace design, standardized procedures (e.g. communication phraseology, standard routings) and coordination agreements between Air Navigation Service Providers, in order to increase the predictability of operations. However, these efforts do not eliminate uncertainty from Air Traffic Control operations. Rather, uncertainty is considered a fundamental feature of Air Traffic Control operations, as data required for decision-making may often be incomplete, unreliable or ambiguous (Averty et al. 2008). Uncertainty, defined as a “sense of doubt that blocks or delays action” (Lipshitz and Strauss 1997, p. 150), therefore heavily influences controller decision-making. For example, winds may cause variability of aircraft performance, which, in turn, may cause unreliable traffic conflict predictions (e.g. Averty et al. 2008; Cummings and Tsonis 2006). Furthermore, thunderstorms and turbulence may create uncertainty concerning the availability of airspace (flight levels and traffic routes) and preferences of pilots concerning their preferred trajectory through the sector. The management of uncertainty, that is how controllers anticipate and respond to uncertainty, is therefore an important aspect of controllers’ task work strategies (Malakis et al. 2010).

According to the RAWFS heuristic, decision-makers cope with uncertainty by adopting two types of coping mechanisms: reducing uncertainty and acknowledging uncertainty (Lipshitz and Strauss 1997). Strategies reducing uncertainty aim to decrease uncertainty, for example, by searching for additional information or by engaging in assumption based reasoning. Strategies acknowledging uncertainty include strategies that take uncertainty into account rather than aim to reduce it. Acknowledgement of uncertainty may take place when uncertainty cannot be (further) reduced, for example because it is too costly (Lipshitz and Strauss 1997). Examples of acknowledging uncertainty are weighing pros and cons between different options, adapting plans, and developing backup plans. Several recent studies have shown that the RAWFS heuristic is successful in explaining how decision-makers cope with uncertainties in team contexts. For example, the RAWFS heuristic has been used to explain adaptive strategies of firefighting teams (Lipshitz et al. 2007) and hostage negotiating police teams (Van den Heuvel et al. 2014) in context of uncertainty.
In addition to the reduction strategies identified by the RAWFS heuristic, several other naturalistic decision-making theories have shed light on how decision-makers create an understanding of the situation during highly complex, dynamic and uncertain conditions.

Firstly, *anticipatory thinking* (Klein et al. 2007) based on *sensemaking* (Weick 1995), describes various uncertainty *reduction* strategies which explain how decision-makers select attention and how they detect when something is wrong, such as difficulties, problems or threats in the environment (Klein et al. 2007; Klein et al. 2006a). A related theory is the *data/frame* theory of *sensemaking* (Klein et al. 2006b). Similar to anticipatory thinking, it is based on *sensemaking* (Weick 1995). It describes how decision-makers establish a mental picture of the situation by constructing and elaborating a “frame” and how they question and reframe these frames when new information is inconsistent with the existing frame (Klein et al. 2006b). Although the data/frame theory primarily describes how decision-makers *reduce* uncertainty, the model has some overlap with *acknowledging* uncertainty, as it explains how decision-makers respond, and make decisions by adapting frames. Two recent studies (Malakis et al. 2013; Malakis and Kontogiannis 2014) have illustrated how air traffic controllers (Tower Control) reduce uncertainty through *sensemaking* using the data/frame theory of *sensemaking* (Klein et al. 2006b). Similarly, Malakis and Kontogiannis (2013) acknowledged the overlap with decision-making and planning.

Secondly, the R/M Model (Cohen et al. 1996) argues that decision-makers reduce uncertainty by actively *critiquing* their mental model of the situation, goals and responses. Critiquing allows decision-makers to check their models for incompleteness, unreliable assumptions and possible conflicts, by searching for additional information to verify assumptions (Cohen et al. 1996). Malakis et al. (2010) have successfully illustrated how Enroute air traffic controllers reduce uncertainty using the recognition/metacognition (R/M) Model (Cohen et al. 1996). Similar to the data/frame theory, the R/M Model mainly describes the mechanisms that drive reduction strategies (searching information and verifying assumptions) while at the same time, having an overlap with acknowledging uncertainty.

Given the current knowledge on how controllers cope with uncertainty in air traffic control, some questions remain. Firstly, although recent studies have provided much insight into how controllers *reduce* uncertainty and the dynamic processes underlying these reduction strategies, less is known about the variety of strategies that controllers adopt to *acknowledge* uncertainty. Secondly, more
recently, researchers have argued that, in some situations, uncertainty may actually be preferred, as it allows flexibility and generates options, suggesting that decision-makers may also adopt strategies which *increase* uncertainty (Grote 2015). Thirdly, although much is known about the trade-offs related to managing traffic complexity (e.g. Kirwan and Flynn 2002; Kontogiannis and Malakis 2013), previous studies have not provided much insight into the *contingencies* and *trade-offs* that determine the favorability of uncertainty coping strategies. Finally, little is known about the requirements for automation that support controllers in coping with uncertainty. In this paper, we aim to identify the requirements for system design and automated functions (e.g. radar display, information systems and controller support tools), that optimally supports controllers with reducing, acknowledging and increasing uncertainty. Understanding system requirements are particularly important to increase the flexibility of the operational system, in particular during conditions of high levels of uncertainty.

Specifically, we aim to advance the understanding of how controllers manage uncertainty in Enroute Air Traffic Control by answering the following questions:

1. What are the sources of uncertainties in air traffic control, and what are the issues they generate for air traffic controllers?
2. What are the tactics and underlying strategies used by air traffic controllers when deciding to reduce, acknowledge or increase uncertainty?
3. What contingency factors and trade-offs influence the adoption of these strategies?
4. What are the requirements for system design to support controllers in following different strategies for uncertainty management?

Coping with uncertainty cannot be studied without taking into account the interplay between traffic complexity and uncertainty. Adapting traffic plans as a response to uncertainty often involve changes to trajectory of aircraft, thus automatically reducing the complexity of the traffic at the same time. This means that although traffic plans are a direct response to uncertainty, for example, adverse weather, these strategies also reduce complexity because the traffic situation is altered. Similarly, traffic plans can be used primarily with the aim to reduce complexity (e.g. resolving traffic conflicts, regardless of the level of uncertainty involved in the conflict) but will, of course, indirectly also acknowledge uncertainty because it removes uncertainty/doubt about the
traffic conflict. We will therefore focus on the interplay of uncertainty and complexity in the discussion of our results.

In this paper, we aim to identify the various strategies that describe how controllers reduce, acknowledge or increase uncertainty, rather than the underlying process, as has been described by the data/frame theory (Klein et al. 2006b) and the R/M Model (Cohen et al. 1996). We will therefore use the RAWFS heuristic and anticipatory thinking as a starting point to identify reduction and acknowledgement strategies and discuss the results in context of the data/frame theory (Klein et al. 2006b) and the R/M Model (Cohen et al. 1996) in the discussion.

This paper is structured as follows: Firstly, we will provide an overview of the sources of uncertainties which can be encountered in Enroute Air Traffic Control, grouped by the action requirements they generate for controllers. Secondly, we aim to identify the coping strategies that controllers adopt to manage uncertainty, in view of a) different sources of uncertainty, and b) existing theories in naturalistic decision-making, including the RAWFS heuristic (Lipshitz and Strauss 1997) and anticipatory thinking (Klein et al. 2007). In addition, we aim to identify whether controllers increase uncertainty and if so, under which conditions. Thirdly, we will pay particular attention to the contingency factors that influence controller preferences with respect to these coping strategies, as well as the trade-offs related to controllers’ operational goals. Fourthly, we will discuss the results with respect to requirements for automation, which supports controllers in coping with uncertainty in Enroute Air Traffic Control. Finally, we will discuss the implications of our study for future Air Traffic Management operations as envisioned in the SESAR Joint Undertaking (SESAR JU 2012) and NextGen (FAA 2014) operational concept.

2. Theoretical background

2.1. Sources of uncertainty

Uncertainty can be classified in three different types of uncertainty (Lipshitz and Strauss 1997). First of all, uncertainty may originate from a lack of information (Lipshitz and Strauss 1997). This type of uncertainty originates when information is either lacking, partially lacking or unreliable (Lipshitz and Strauss 1997). Information may be unreliable because the source (either a system, or human operator) cannot be relied on, or because values underlying options lack precision (Hansson 1996). Secondly, according to Lipshitz and Strauss (1997), uncertainty may also concern a lack of understanding (i.e. inability to understand or comprehend information due to ambiguity,
equivocality or novelty). Although experienced air traffic controllers may only very sporadically encounter novel situations, traffic situations containing ambiguity (aircraft intentions, preferences of neighboring sectors) are inherent to routine and non-routine operations. Thirdly, uncertainty may also originate from the inability to make a decision due to *undifferentiated alternatives*, meaning that decision-makers cannot differentiate alternatives because predicted outcomes are equally (un)preferable (Lipshitz and Strauss 1997), despite the availability of information and the ability to understand the information.

Furthermore, Lipshitz and Strauss (1997) argued that uncertainty can be classified in terms of its *source* (i.e. what is causing uncertainty) and the *issue* arising from uncertainty (i.e. the impact of uncertainty on the decision-maker). For example, an unexpected deviation of an aircraft may be caused by different sources, such as adverse weather, or a discrepancy between issued and executed aircraft control instructions. In this paper we will refer to issue as *action requirement* from this point onwards.

### 2.2. Strategies aimed at reducing uncertainty
#### 2.2.1. Reduction strategies within the RAWFS heuristic

The RAWFS heuristic (Lipshitz and Strauss 1997) identified two main strategies that controllers use to reduce uncertainty: “Reduction” and “Assumption based reasoning”. Tactics within “Reduction” include, for example, *searching for additional information* (e.g. by asking for advice or opinions) or *relying on (in)formal rules* (e.g. procedures, shared working methods). Tactics within “Assumption based reasoning” include tactics which explain how decision-makers “fill the gaps”, by using *assumptions* to reduce uncertainty i.e. how they create an understanding when information is missing, using their expertise and previous experience. An example of assumption based reasoning is *mental simulation*, which is a combination of prediction and the use of assumptions (Klein and Crandall 1995; Lipshitz and Strauss 1997).

#### 2.2.2. Anticipatory thinking

*Anticipatory thinking* has been proposed by Klein and colleagues (2007) to explain how decision-makers select attention and detect possible threats or problems during recognition-primed decision making tasks. Anticipatory thinking allows decision-makers to detect problems during uncertain and ambiguous conditions in order to prepare a response. Anticipatory thinking is therefore
considered essential for planning and replanning (Klein et al. 2007). According to Klein and colleagues (2007), anticipatory thinking is a form of sensemaking based on mental simulation, which prevents fixating and supports vigilance. Klein and colleagues (2007) identified three different types of anticipatory thinking: pattern recognition, trajectory tracking and convergence. Pattern recognition refers to how decision-makers detect patterns and how they compare it with stored patterns in order to detect abnormalities and deviations as cues for intervention (Klein et al. 2007). Trajectory tracking refers to extrapolating situations and actively comparing observed and required future states, in order to identify pro-active responses (Klein et al. 2007). Trajectory tracking may be similar to task monitoring. According to Osman (2010), task monitoring reduces uncertainty by testing predictions about the future state, using the feedback to update a decision-maker’s understanding about the environment. Convergence refers to the cognitive process of creating connections between events in order to understand how these events interrelate (Klein et al. 2007).

2.3. Strategies aimed at acknowledging uncertainty

Acknowledgement strategies within the RAWFS Heuristic

In contrast to strategies that reduce uncertainties, strategies that acknowledge uncertainties do not influence the level of uncertainty, rather, these strategies explain how decision-makers accept uncertainty by taking uncertainty into account (Lipshitz and Strauss 1997). The RAWFS Heuristic identifies two main strategies that acknowledge uncertainty: “Weighing pros and cons” and “Forestalling”. Weighing pros and cons describe the strategies that controllers adopt when comparing or choosing between competing options, whereas forestalling refers to strategies that aim to improve readiness in order to prepare adverse outcomes or worst case scenarios, for example, by buffering resources or creating back-up or contingency plans. In addition, Lipshitz and Strauss (1997) identified avoiding irreversible action (for example, by engaging in adaptive planning). Contingency plans have been recognized as an important element of responding to evolving uncertainty (Malakis et al. 2010). In addition, adaptive planning has been recognized as an important strategy in the context of uncertainty (Kontogiannis 2010).

2.4. Strategies aimed at increasing uncertainty
Grote (2015) suggested that increasing uncertainty may also be a viable option in uncertainty management. Using flexible rules and speaking up as examples, she argued that increasing uncertainty can add adaptive capacity, for instance by avoiding premature convergence in decision-making. Taking up this proposal, we were interested to see whether controllers ever use strategies to increase uncertainty and if so, under which conditions.

2.5. Automation requirements

In this study we also investigate in what ways automation positively supports controllers in managing uncertainty. Up to now, uncertainty and automation have mainly been discussed in terms of how uncertainty may impact the reliability of automation, raising various issues with respect to trust and vigilance (e.g. Parasuraman and Manzey 2010; Parasuraman and Wickens 2008). In addition, automation may also have limitations with respect to conflict resolution support due to the inability of automation to take into account naturalistic decision-making models, including human trade-offs and subjective evaluation of possible outcomes (Cummings and Tsonis 2006; Parasuraman and Wickens 2008), which may particularly become relevant during conditions of uncertainty. To support controllers with estimating the impact of uncertainty on a future predicted state (for example, an aircraft), automation may also provide support by visualizing uncertainty, for example on human-machine interfaces, such as radar displays. Nicholls (2001) has discussed various ways how to graphically present and visualize uncertainty for air traffic control operations. Nicholls (2001), at the same time, acknowledges the limitations of presenting uncertainty graphically and argues that automation should take into account the individualistic preferences of controllers with respect to the representation of uncertainty as well as the individualistic nature of preferred coping strategies. We will take these arguments by Nicholls (2001) as a starting point for our research by investigating how automation can support controllers in managing uncertainty by supporting different coping strategies.

3. Methods

3.1. Methods of data collection

An ethnographic approach was chosen by conducting a field study in two Enroute Area Control Centers (ACC). Field studies in naturalistic settings are the recommended approach to study (macro) cognitive functions, because these functions are often highly dependent on external factors and contingencies and complex interactions, which can only be observed and studied in
real operational settings (Hutchins 1995; Xiao 2005). Field studies are therefore considered the recommended approach to study uncertainty management (Klein et al. 2003; Lipshitz et al. 2001). Ethnographic studies have been successfully applied to study a wide range of cognitive and collaborative processes within Air Traffic Control operations. Examples of previous studies involved the function of paper flight strips (Mackay 1999), controller-flight deck collaboration (Sharples et al. 2007), and the study of cognitive models (Soraji et al. 2012).

The methods used within this field study included:

- “Over the shoulder” observations, supported by detailed field notes;
- Discussion sessions with controllers during breaks and after shifts;
- Document analysis (study of operational procedures, simulation studies and evaluation reports of operational concepts).

### 3.2. The setting

The “over the shoulder” observations were conducted in two Enroute Area Control Centers (ACC’s). Field study 1 was conducted at the Zürich Area Control Center (ACC) in lower and upper airspace sectors, covering altitudes between 11,000 and 66,000 feet (FL110-660), for a total duration of 80 hours. Field study 2 was conducted at the upper Enroute sectors of the Geneva Area Control Center, covering altitudes between 25,000 and 66,000 feet (FL250-660), for a duration of 50 hours. The observations were conducted by the first author of this study.

In Enroute air traffic control, airspace is divided in airspace blocks. These airspace blocks, referred to as airspace sectors, are bounded by a geographical boundaries and a lowest and highest flight level and are managed by a team of two air traffic controllers: a radar executive and a radar planner. The main goal of the air traffic control team is to provide safe and efficient air navigation service to aircraft within their sector by optimizing traffic flows and maintaining separation between aircraft (1000 feet vertically due to reduced separation minima, and 5 nautical miles horizontally), according to the standards mandated by the International Civil Aviation Organization (ICAO 2007).

The radar executive and the radar planner are responsible for different tasks within the team. The radar executive is in charge of identifying and instructing the aircraft and detecting, identifying
and solving possible traffic conflicts within the sector in a *tactical* timeframe, which we refer to as tactical traffic solutions. The *radar planner* is responsible for solving traffic conflicts in a *strategic* timeframe with neighboring sectors, before the aircraft enter the sector, which we refer to as strategic traffic solutions. Furthermore, the radar planner is responsible for coordinating tactical traffic solutions with neighboring sectors when traffic solutions within their own sector are not available. Although the radar planner and the radar executive have different responsibilities, they share high levels of task interdependency: the radar planner needs to be continuously ahead of the needs and preferences of the radar executive. In addition, the radar planner supports the radar executive with tactical conflict management and monitoring whenever backup support is required, supporting the balance of workload within the team.

Both ACCs, at the time of observation, were equipped with different levels of automation. In the ZRH sectors, controllers are supported with *planning and measuring tools*, which support controllers with developing traffic plans and monitoring the traffic situation. *Planning tools* include speed vectors (vector in the aircraft label giving controllers visual information about heading and speed), extrapolated speed vectors and a planning tool. The *planning tool* allows controllers to extrapolate a trajectory to a certain point, which then provides controllers with estimates of the extrapolated trajectory. The *measuring tool* supports controllers in measuring distances between aircraft, between trajectories, or other critical points.

In the GVA sectors, controllers were additionally supported by *controller support tools*, including, amongst others:

- *Electronic coordination tools (E-coordination)*, which support the exchange of coordination proposals between the upper sectors of GVA ACC;
- *Medium Term Conflict Detection tools (MTCD)*, which support controllers with the detection and analysis of exit conflicts (ECAT window) and horizontal crossings (Horizontal Scanning Tool, HST);
- *Analysis support tools*, which support controllers with the analysis of a crossing of two aircraft on the same flight level (Crossing Tool);
- *Monitoring tools*, which support controllers in detecting aircraft deviations, including a lateral deviation (Route Adherence Monitoring function), or a vertical deviation (CLAM).

A full overview of “stripless” functionalities and controller support tools are presented in Table 1.
3.3. Data collection

During the “over the shoulder” observations, field notes were written down and elaborated with comments made by the controllers. Drawings and sketches recorded specific traffic situations. Particular attention was directed at understanding the sources of uncertainty, how controllers detected and responded to uncertainty, and how the automation supported controllers in following different strategies for uncertainty management. During the breaks and after the observations, the first author was able to engage in discussions with the controllers. These discussions focused on gaining further understanding of traffic situations which had occurred, or to gain further understanding of the overall system, including controller support tools and other functionalities of the system.

4. Results

In this section, we analyze the data in three steps. In the first part of the analysis, we will discuss the different sources of uncertainty and the action requirements they generate for controllers. Because action requirements related to uncertainty may be caused by different underlying sources, we will discuss uncertainty grouped by action requirements and present examples of underlying sources for each of those action requirements. In the second part of the analysis, we will explore the strategies and the underlying tactics that controllers adopt, as well as the contingency factors and the trade-offs that influence the adoption of these strategies. In the third part of the analysis, we will discuss the requirements for automation that support the controllers in coping with uncertainty in Enroute Air Traffic Control operations.

4.1. Sources of uncertainty

Table 2 represents our findings with respect to the sources of uncertainty in Enroute Air Traffic Control and the action requirements they generate for controllers. The action requirements were classified in four categories: 1) aircraft and sector information; 2) procedures; 3) traffic situation, and 4) aircraft future preferred trajectory. Example sources for each of these action requirements are presented.

4.1.1. Aircraft and sector information
First of all, *missing, ambiguous, incomplete, conflicting or unreliable* aircraft and sector information may impact the work of controllers. *Missing* flight plan data (or “estimates”) may occur when the system fails to automatically send the flight plan data of an aircraft approaching the sector. System data may also be *conflicting*, for example, when the system generates conflicting information concerning the availability of airspace delegated by the military. In case of radar failures, flights may only be tracked by one single radar, decreasing the reliability of information concerning an aircraft’s position. In case of a transponder failure, aircraft data, such as altitude and other information used as input for conflict detection and monitoring tools, are not automatically sent to the controllers workstation, thus requiring manual tracking (or: correlation) using pilot information. Transponder failure also generates unreliability of controller support tools which use transponder information as input. Uncertainty may also originate from a *lack of information* related to the capacity or traffic in neighboring sectors. Controllers stated that sufficient insight into the capacity, traffic and workload of neighboring sectors is particularly important for efficient coordination.

4.1.2. Procedures

Procedural uncertainty may exist when there is doubt amongst the controllers if a traffic situation is according to procedures. As an example, during one of the observations, the military occupied more airspace than usual for military exercises, meaning that separation needed to be provided vertically, rather than horizontally. This situation created *ambiguity* for the controllers, as they were unsure if the situation was according to procedures with respect to airspace management.

4.1.3. Traffic situation

Traffic conflict predictions (e.g. anticipated minimum separation and time until minimum separation is reached) are never static. In particular under high levels of uncertainty (e.g. variability of aircraft performance due to winds or unknown aircraft parameter settings), traffic conflict predictions may not be accurate. In addition, future possible trajectory changes, requested by pilots due to turbulence or thunderstorms, may cause a predicted traffic conflict to expire, meaning that active intervention becomes unnecessary as the situation resolves itself automatically. Furthermore, an aircraft may not make its agreed exit conditions, due to poor aircraft performance. These factors may cause *undifferentiated alternatives* concerning the control
action to be implemented: to intervene or not, and if so, when to intervene and what solution to implement.

4.1.4. Aircraft future (preferred) trajectory

Controllers may also be uncertain about an aircraft’s future (preferred) flight path through their sector. For example, the actual trajectory of an aircraft may deviate from what was instructed to the pilot. Such deviations may vary in their level of predictability. In case of strong winds, some degree of deviation from the coordinated trajectory is more or less anticipated by controllers, whereas a level bust or lateral deviation may occur unexpectedly, for example due to a discrepancy between instructed and entered flight instructions by the pilot, leading to level bust or lateral deviation from trajectory.

4.2. Reducing uncertainty

The reduction strategies and underlying tactics are described and summarized in Table 3.

4.2.1. Collecting additional information

An important strategy of controllers to reduce uncertainty is search for additional information, for example, by consulting and comparing different information systems. When information systems provide conflicting or missing system information, controllers may call other sectors or military to obtain more accurate or up-to-date information. Often, while controllers search for additional information, decisions related how to solve a traffic situation are usually postponed. However, in most cases, traffic plans are created at the same time, suggesting that reduction and acknowledgement of uncertainty within teams may take place in parallel. For example, controllers will defer traffic plans requiring military airspace until conflicting information related to the availability of airspace is resolved, while at the same time developing traffic plans which avoids the use of military airspace, in case a direct routing using military airspace may not be possible. Similarly, under conditions of adverse weather, controllers will generally defer plans that involve the use of airspace which may be impacted by turbulence, until controllers have a sufficient understanding about the weather conditions in the sector, while at the same time engaging in traffic planning avoiding the use of this airspace.

4.2.2. (In)formal rules of conduct
Another important reduction strategy for controllers is to rely on (in)informal rules of conduct. This strategy seemed to be particularly associated with procedural uncertainty: controllers prefer to do what is “common sense” or “do what is safe” in case, 1) the situation deviates from procedures due to other actors in the system, 2) the applicable procedure is unknown, or 3) the applicable procedure is known but the situation does not allow the applicable procedure to be followed. This strategy seems to be particularly preferred when controllers have little time to respond (the urgency is high) and when consulting the procedure manual is too time consuming.

For example, during one session, controllers identified that the military occupied more airspace than usual for military exercises. Instead of directly reducing uncertainty by searching for procedural information, the radar executive preferred to reduce uncertainty by relying on informal rules of conduct by doing “what is safe”, immediately followed by acknowledging uncertainty by developing adapted traffic plans to safely separate the traffic.

4.2.3. Anticipatory thinking

Pattern detection
Controllers detect patterns, by directing attention to visual cues and detecting a need for intervention by comparing observed patterns with stored patterns. For example, when a controller detects an aircraft deviation from routing, the controller will compare the observed situation with the controller’s stored patterns about how, for example, winds impact aircraft deviations from routings. Based on this comparison, the controller assesses whether the deviation requires needs intervention or not.

Trajectory tracking
In case of a potential traffic conflict, for example a horizontal crossing, the controller assesses the minimum separation and the time until the minimum separation is reached by extrapolating the traffic situation. Similarly, controllers may extrapolate the future trajectory of an aircraft in case it may not be making its planned exit conditions. Controllers rely on mental simulation as well on available support tools, for example, (extrapolated) speed vectors and, in case of a horizontal crossing, the Horizontal Scanning Tool and Crossing Tool. In addition, experience may support assumption based reasoning to determine the reliability of the support tools.
In case of adverse weather, controllers converge information obtained from various sources to identify inconsistencies and interdependencies. For example, in order to identify the impact of adverse weather conditions, controllers need to obtain information from various sources, including weather information displays, weather visualization on the radar display, pilot requests for deviations, observed aircraft behavior (deviations) and information obtained from pilots. Information from pilots may be obtained by either by requesting reasons for observed deviations as part of conformance management, or by proactively requesting pilots their requested flight level. Controllers then converge the obtained information in order to establish an understanding concerning the usability of routings and flight levels. In addition, it allows controllers to detect inconsistencies in the data, in order to question the established mental picture about the location of the weather and the preferences of pilots.

4.3. Acknowledging uncertainty

The acknowledgment strategies and underlying tactics are described and summarized in Table 4.

4.3.1. Weighing pros and cons (trade-offs)

After the radar planner has identified a traffic situation to be managed (e.g. traffic conflict or an opportunity for optimization of the traffic), the radar planner acknowledges uncertainty by deciding: 1) whether to intervene or not to intervene; 2) when to intervene, to implement the solution in a strategic or in a tactical timeframe, and 3) what traffic solution to implement within the strategic or tactical timeframe. As there may be more than one suitable traffic solution, controllers may be confronted with undifferentiated alternatives, in particular under conditions of uncertainty, such as adverse weather conditions.

Strategic versus tactical traffic solution

If the radar planner decides to intervene, the radar planner will need to decide between a strategic or a tactical traffic solution. Traffic solutions in a strategic timeframe often include a coordination of a new flight level, a direct routing or different sector exit conditions with the subsequent sectors, whereas traffic solutions in a tactical timeframe are solved by more fine-tuned solutions, e.g. (phased) flight level instructions, change of heading or speed. Controllers will generally
decide between a strategic and a tactical solution by making trade-offs “weighing pros and cons” between the various operational goals.

Controllers seem to prefer a tactical solution instead of a strategic solution, when:

- The most optimal solution will be more apparent in the tactical timeframe, when the traffic conflict may resolve itself in the tactical timeframe, or when the radar planner is uncertain about the preference of the radar executive or the pilot (efficiency);
- There are sufficient viable options or simple solutions within the tactical timeframe (risk/safety);
- The radar executive will have sufficient capacity to deal with the tactical conflict (workload/capacity);
- Flexibility (e.g. possibility to adapt a plan in tactical timeframe) is preferred over stability/predictability (flexibility versus stability);

The trade-off between flexibility versus stability seems to be particular relevant when deciding between a strategic versus a tactical solution. For example, strategic solutions may generate stability (by increasing the predictability of the trajectory). However, implementing a strategic solution, for example, by expediting traffic through direct routings may also cause disruption. For example, a direct routing may disrupt the expected arrival sequence in the approach sector. Thus, in this case, efficiency may be traded off against stability. Similarly, controllers may sometimes prefer flexibility by opting for a tactical solution which allows flexibility due to the possibility to adapt it in the tactical timeframe. However, a more elegant solution in the tactical timeframe usually involves higher levels of workload for the radar executive (e.g. radar executive provides aircraft instructions and monitors of execution of the solution). Thus, in this case, workload may be traded off against flexibility.

Traffic solutions within strategic or tactical timeframe

Similar trade-offs are adopted when weighing pros and cons between traffic solutions within the strategic or tactical time frame, i.e. controllers weigh pros and cons between traffic solutions which are all within the strategic or all within the tactical time frame, taking into account trade-offs between operational goals.

4.3.2. Adaptable plans
Under conditions of uncertainty, controllers may prefer to adapt existing traffic plans in response to uncertainty (e.g. adverse weather). These adaptations in traffic plans are primarily a response to cope with uncertainty, rather than a direct response to traffic complexity (e.g. traffic conflicts) or efficiency of traffic flows. Adaptable strategic traffic plans provide controllers with the flexibility to deal with unpredictable sources of uncertainty which may impact the traffic flows. For example, the radar executive may dynamically adjust plans based on (un)availability of flight levels in the sector due to turbulence and adjust traffic flows and the location of holding circles depending on the location of the adverse weather (e.g. thunderstorms).

4.3.3. Forestalling

Controllers may also engage in forestalling, in order to prepare for possible adverse outcomes, by 1) creating contingency or backup plans, 2) creating buffer zones in traffic flows, 3) increasing safety margins, and 4) maximizing operational control.

Contingency or backup plans

Under high levels of uncertainty, controllers may share contingency or backup plans. Backup plans are explicitly shared within the sector team when the likelihood of implementing a backup plan is high, e.g. due to high levels of uncertainty. When a backup plan involves other sector teams, the radar planner will proactively share or coordinate this backup plan with other sectors, which then includes information about the task distribution between the sectors. For example, a controller communicated to a neighboring sector the following backup plan: “That flight level is ok, if he doesn’t make it send it on a heading and I will advise Military”. It should be noted that even if backup plans are not explicitly shared, it does not mean that they do not exist. As one controller stated: “There is always a back-up plan”.

Creating buffers zones in traffic flows (loose coupled plans)

Controllers may prefer to create buffer zones in traffic flows when aligning traffic for approach, i.e. increasing the separation between aircraft within traffic flows. Controllers may apply this tactic in particular when aircraft performance is difficult to predict, for example, due to winds.

Increasing tactical safety margins

An alternative way for controllers to create buffers is to increase tactical safety margins beyond the minimum separation distance. Controllers seem to prefer this tactic when the behavior of a
particular aircraft cannot be fully anticipated, for example, because its trajectory through the sector is unknown or possible deviations from an intended trajectory cannot be predicted. For example, a controller mentioned that in case there is a crossing involving an aircraft flying under Visual Flight Rules ("VFR flights"), controllers may increase the separation (beyond the minimum separation) between an aircraft and a VFR flight, to "be on the safe side", when getting into contact with VFR flight is too costly with respect to time and coordination requirements.

**Maximize operational control**

Controllers may prefer to maximize operational control by requesting an aircraft on their frequency, or by keeping an aircraft on their frequency, by deliberately delaying handoff at the sector boundary. Controllers use this tactic when there is uncertainty about the intentions or behavior of another aircraft which is not under their control. For example, during one of the observation sessions, there was uncertainty concerning the trajectory of an aircraft, which could possibly generate a future traffic conflict. Although the traffic situation had already been resolved with the neighboring center, the actual implementation of the traffic solution was, for unknown reasons to the controllers, delayed by the neighboring center. The controllers responded to this situation by not handing off their aircraft to the subsequent sector at the sector boundary, in order to remain in control of the situation. The controllers stated afterwards: “We preferred to keep our aircraft on our frequency until we were sure that separation could be assured in the future, as we were just not sure what he [the aircraft under control of the neighboring center] was going to do”.

A similar tactic would involve controllers contacting an aircraft flying under Visual Flight Rules (VFR flight), in case of an emergency situation.

**4.4. Increasing uncertainty**

The strategies related to *increasing* uncertainty and underlying tactics are described and summarized in Table 5.

**4.4.1. Creating flexibility through delegation of control within specific boundaries**

In addition to strategies aiming to reduce or acknowledge uncertainty, we also identified that controllers, on some occasions, prefer to increase uncertainty, as a means to increase the flexibility of operations for neighboring sectors and pilots. Increasing uncertainty is preferred when controllers favor flexibility over stability and predictability. For example, controllers may prefer to
increase uncertainty related to an aircraft’s trajectory through the sector, if it enables subsequent sectors or pilots more flexibility to obtain their goals and objectives. In such cases, controllers define specific boundaries or conditions within which they accept uncertainty.

Releasing an aircraft

A tactic within this strategy refers to the delegation of control by releasing an aircraft to the next sector well before the aircraft reaches the sector boundary by sending the aircraft to the frequency of the subsequent sector. This means that the aircraft, while still in the previous sector, is under control of the next sector. In most cases, restrictions may apply to the release which are issued simultaneously with the release by the previous sector. For example, an aircraft may be released for descent or turn only, depending on limitations due to other traffic. A release allows the subsequent sector to initiate descent/ascent or turn before the aircraft reaches the sector boundary. This increases flexibility for subsequent sectors by allowing more maneuvering space and time for conflict resolution or traffic optimization and thus allows extra operational degrees of freedom for subsequent actors to obtain their operational goals. However, a release increases uncertainty for controllers in the current sector, as the aircraft in their sector is not under their direct command and the trajectory of the aircraft will be dependent on the plans of the subsequent sector. A sector will only release an aircraft under conditions that it will not impact other aircraft. Controllers may prefer to increase uncertainty related to the aircraft’s trajectory through their sector depending on trade-offs, e.g. if it supports the next sector with adhering to their operational goals (e.g. efficiency or traffic conflict resolution).

Enabling flexibility for pilots: pilot discretion

Controllers may provide pilots the opportunity to execute the instruction at their discretion, leaving the decision latitude to the pilot concerning the timing of the implementations as well as the speed and rate of climb/descent. This creates flexibility for the pilot to adhere to their operational goals (e.g. avoiding weather or increasing comfort in case of turbulence).

4.5. Contingency factors

We have additionally focused on contingency factors that may influence the adoption of uncertainty coping strategies. The results indicate three relevant contingency factors: predictability of uncertainty, urgency of response and available resources.
4.5.1. Predictability of uncertainty

The first factor that influences the adoption of strategies is the predictability of the source of uncertainty. For example, for controllers, thunderstorms are relatively predictable, whereas turbulence is not. The results indicate that uncertainty with lower levels of predictability require more anticipatory thinking due to their unpredictable nature. For example, in case of turbulence, controllers may engage more in anticipatory thinking (e.g. convergence) because controllers need to obtain information from various sources (pilot requests) in order to build a mental picture of the usability of the airspace. In addition, the level of predictability may limit the ability to acknowledge uncertainty via strategic traffic plans.

4.5.2. Urgency of response

The second factor involves time pressure, i.e. the urgency of the response. Time pressure may limit the possibilities to engage in uncertainty coping strategies which are more time consuming, shifting preference towards adopting strategies that facilitate a quick response to the situation. Taking the earlier presented situation as an example, the controllers preferred to keep their aircraft on the frequency rather than calling the neighboring center, which was very busy, to ask why the aircraft coming to their sector was not yet responding to previously coordinated instructions. Instead, controllers preferred to acknowledge uncertainty by maximizing control and formulating a backup plan.

4.5.3. Available capacity and resources

The third factor, availability of capacity and resources influences the adoption of uncertainty management strategies. For example, controllers will only release an aircraft or enable pilot discretion when the required airspace for the release is available (e.g. no interfering traffic).

4.6. Automation requirements

Finally, we identified how the operational system, including information displays, human-machine enhancements (various integrated functionalities) and controller support tools, allow controllers in following the different strategies for uncertainty management.

Table 7 supports an overview of examples for each strategy. The results show that the system supports controllers with reducing, acknowledging and increasing uncertainty in various ways.
Firstly, the system supports controllers by providing reliable, real-time information and allowing controllers to quickly obtain insight into the sector characteristics of neighboring sectors as well as the limitations and constraints (e.g. traffic) of other sectors. The system also supports controllers with anticipatory thinking, for example, by visualizing movements and direction of aircraft, visualizing aircraft for different flight levels and visualizing horizontal crossings and exit conflicts. In addition, various tools, including speed vectors, extrapolated speed vectors and planning tool support the mental simulation of future states of aircraft, as well as their possible interaction with other aircraft. Secondly, the system also supports controllers with acknowledging uncertainty, for example, by supporting controllers with developing and implementing adaptable traffic plans. Thirdly, the system supports controllers by increasing uncertainty by enabling delegation of control (e.g. release), in order to increase flexibility of other actors in the system, while respecting a balance between autonomy and control. For example, the delegating controller is able to set restrictions to the sector requesting the release, as well as have the availability to regain control if needed.

4.7. Air Traffic Controller complexity and uncertainty management model

Figure 1 illustrates the Air Traffic Controller complexity and uncertainty management model, based on the findings presented in the previous sections.
First of all, the model differentiates between complexity and uncertainty in the strategic and tactical phase. Uncertainty impacting operations in the tactical phase is the uncertainty which is created in the tactical phase (e.g. weather conditions impacting traffic in tactical phase) as well as any residual uncertainty impacting tactical operations which was not or could not be managed in the strategic phase. Similarly, the traffic complexity impacting operations in the tactical phase originates from the traffic complexity that has (deliberately) not been resolved in a strategic timeframe, and the traffic complexity which originates from any (un)expected disturbances in the tactical time frame.

Secondly, the model acknowledges:

- Strategies directed to reduce complexity in the strategic or tactical phase (e.g. by implementing traffic solutions), which may also indirectly acknowledge uncertainty in the tactical and strategic phase;
• Strategies directed to *acknowledge* complexity in the strategic or tactical phase (e.g. strategies directed at moderating/buffering the cognitive demands or workload required to managing complexity);
• Strategies directed to *reduce* or *acknowledge* uncertainty in the strategic or tactical phase, which may also *indirectly reduce the complexity* of the traffic (e.g. adaptable traffic plans, increase of safety margins);
• Strategies directed to *increase* uncertainty to increase flexibility of operations (e.g. release of an aircraft to the next sector before the sector boundary).

Example strategies for each of these four categories are presented in Table 6.

Thirdly, the model shows that controllers choose their cognitive and collaborative strategies depending on the trade-offs they make with respect to their operational goals. We identified four important operational goals, which function as *trade-offs* when choosing strategies to manage traffic complexity (e.g. traffic conflicts) and uncertainty:

• **Risk/Safety:** Associated risks related to the solutions in the strategic or tactical timeframe.

• **Efficiency/Service:** The efficiency of the solution (fuel burn, miles flown) and the preferred level of service.

• **(Future) Workload/Capacity:** The (future) workload required for the implementation of the traffic solution in relation to available capacity.

• **Flexibility/Stability:** The required level of flexibility versus stability for other actors in the system.

Although the results so far only illustrated these trade-offs for traffic solutions when controllers are confronted with undifferentiated alternatives, these trade-offs may influence all uncertainty management strategies. For example, a release depends on a *trade-off* between the *expected cost/benefits* of the release. The benefits in terms of increased operational freedom (flexibility) are traded off against the costs related to the release (e.g. possible constraints (risk) and the effort related to coordinating such a release (workload)). For example, when an aircraft is close to the
sector boundary, controllers will decide against a release as there is a negative cost/benefit trade-off: the benefits of increased flexibility do not outweigh the costs in terms of workload involved in the coordination and the monitoring of the execution of the release.

5. Conclusion and discussion

5.1. Sources

This study was the first study to provide a detailed overview of the sources of uncertainties, and the action requirements they generate for air traffic controllers in Air Traffic Control. The results show that all types of uncertainty (lack of information, lack of understanding and undifferentiated alternatives) can be identified but that the types of uncertainty are confounded with their source: incomplete information originates mainly from system sources, whereas undifferentiated alternatives are mainly generated by uncertainty related to the traffic situation. Furthermore, the results show that some sources of uncertainty may generate more than one action requirement (issue) at the same time. For example, thunderstorms may generate uncertainty with respect to the availability of airspace as well as uncertainty about the most optimal traffic solution. This is in line with Hansson (1996), who stated that a lack of understanding may generate difficulties with respect to decision-making, because options or outcomes of options are unclear or unknown. We believe that the presented overview is useful for future studies investigating uncertainty in air traffic control. Up to now, sources and action requirements (issues) have often been used interchangeably to refer to uncertainty in air traffic control. Therefore, this overview may facilitate the understanding of uncertainty, which, in turn, may support discussions on uncertainty in current as well as future Air Traffic Management operations as envisioned within SESAR and NextGen.

5.2. Tactics and underlying strategies: reducing uncertainty

The results showed that the uncertainty coping strategies as described by the RAWFS Heuristic (Lipshitz and Strauss 1997) and anticipatory thinking (Klein et al. 2007) could be identified as air traffic controller strategies in Enroute Air Traffic Control. Anticipatory thinking has long been recognized in air traffic control as an important strategy during perception and decision-making tasks. For example, earlier studies argued that separation assessment heavily relies on visual mental cues and the processing of patterns (e.g. Averty et al. 2008; Nunes and Mogford 2003; Xu and Rantanen 2003). Pattern detection is supported by mental abstractions to reduce traffic complexity. The use of mental abstractions may involve the grouping of traffic into traffic flows,
groups of interacting aircraft, critical points (e.g. Histon et al. 2002) and assignment of aircraft into “in conflict” or “not in conflict” (e.g. Kirwan and Flynn 2002; Niessen and Eyferth 2001; Rantanen and Nunes 2005). In addition, several authors also argued that the extrapolation of the future position of an aircraft not only relies on perceptual information but also experience (Averty et al. 2008; Boag et al. 2006; Xu and Rantanen 2003). For example, controllers use previous knowledge and experience about how winds impact the reliability of the traffic predictions.

Finally, the findings with respect to anticipatory thinking partially replicate earlier findings of Malakis and Kontogiannis (2013) and Malakis and Kontogiannis (2014), who illustrated how air traffic controllers reduce uncertainty through sensemaking. This finding is not surprising, as anticipatory thinking reflects different types of strategies that support sensemaking (Malakis and Kontogiannis 2014; Klein 2006b).

5.3. Tactics and underlying strategies: acknowledging uncertainty

Less research has focused on the variety of strategies that controllers use to acknowledge uncertainty. The results showed that controllers use a wide variety of acknowledgement strategies, including adaptive planning, and various forestalling tactics (e.g. the use of loose coupled plans (e.g. buffering)), maximizing operational control and increasing safety margins) to acknowledge uncertainty. Up to now, loose-coupled plans in air traffic control have mainly been discussed in context of error detection (Kontogiannis and Malakis 2009) instead as an uncertainty coping mechanism. Furthermore, although adaptable planning (e.g. replanning) has been acknowledged as an important adaptive strategy in response to uncertainty (Kontogiannis 2010), previous studies did not present specific strategies for air traffic control. In our study, replanning was rarely observed. Replanning refers to the implementation of new plans after an original plan has failed (e.g. Kontogiannis 2010). A possible explanation for this finding is that replanning may not be a preferred strategy for controllers due to the increased time pressure and decreased options in the tactical timeframe (e.g. Kontogiannis 2010).

5.4. Tactics and underlying strategies: increasing uncertainty

Our study also found support for recent arguments by Grote (2015), who stated that decision-makers, under specific conditions, may sometimes prefer to increase uncertainty, rather than to reduce or to acknowledge it. We identified two strategies, aircraft release and pilot discretion, which increase uncertainty for controllers related to the aircraft’s predicted trajectory through their
sector. We found that controllers use these strategies as a means to enable flexibility for subsequent sectors and pilots. The increased flexibility, in turn, allows controllers of subsequent sectors and pilots to adhere to their operational goals. Increasing uncertainty has, up to now, not been identified as a coping strategy in air traffic control.

5.5. Contingencies

Furthermore, our research stressed that there are three contingency factors influencing the adoption of uncertainty coping strategies: the predictability of uncertainty (to what extent controllers can anticipate uncertainty), the urgency of the response (to what extent their response is time critical) and the availability of resources. Lipshitz and Strauss (1997) already argued similarly, that decision-makers tend to use acknowledgement strategies when reduction strategies are either too costly or not feasible. However, the results showed that these contingencies do not only influence a shift from reduction to acknowledgement strategies, but that these contingency factors mainly influence the choice between different reduction or acknowledgement strategies. In addition, the results showed that controllers initiated various uncertainty coping strategies in parallel, enabled by dynamic task distribution within the team. This means that the same source of uncertainty may lead to different responses by controllers depending on the controller position and the (dynamic) task distribution within the team.

5.6. Trade-offs

Risk/safety, efficiency and workload have long been identified as the most important trade-off factors (e.g. Hilburn 2004; Kirwan and Flynn 2002; Loft et al. 2007; Malakis et al. 2010), in context of traffic complexity. In particular, these trade-offs have been discussed in context of explaining how controllers choose between strategic and tactical traffic solutions (e.g. Athenes et al. 2002; Kontogiannis and Malakis 2013; Loft et al. 2007). For example, Athenes and colleagues (2002) referred to this trade-off as the late/accurate/costly versus early/imprecise/economical control actions. Our study contributed to these earlier findings by discussing these trade-offs in the context of uncertainty. Furthermore, our results suggest that these trade-offs similarly apply for uncertainty coping strategies as well as complexity coping strategies. Finally, in addition to these three trade-off factors, our study has identified a fourth trade-off: (loss/gain of flexibility/stability, which can be traded-off to other outcomes (risk/safety, efficiency, workload). We illustrated this trade-off with various examples.
5.7. Air Traffic Controller complexity and uncertainty management model

Our findings have been summarized in the “Air Traffic Controller complexity and uncertainty management model”. The model acknowledges: 1) the mutual influence of complexity and uncertainty coping strategies, and 2) the influence of automation, contingencies and trade-offs that determine the adoption of these strategies. A limitation of the model is that it does not provide insight into the meta-cognitive mechanisms behind these strategies, as illustrated by the data/frame theory (Klein 2006b) and the R/M model (Cohen et al. 1996). These models, however, nicely complement this model. For example, the R/M model explains how controllers may adapt trade-offs and coping strategy by critiquing goals and responses.

5.8. Automation

In line with proposals by Nicholls (2001), we have argued that automation should support controllers in following different strategies for uncertainty management. The results showed that current air traffic control automation is designed to optimally support uncertainty management strategies through controller support tools and human-machine interface enhancements as well as overall system design. In this section, we will discuss the results in context of existing design proposals for automation, including the concept of transparency and appropriate reliance (Lee and See 2004).

5.8.1. Design of alerts and forcing functions

In general, it has been widely acknowledged that automation can be a threat to anticipatory thinking as it may increase the risk on fixation (De Keyser and Woods 1990) and reduce vigilance, also referred to as complacency (Parasuraman and Manzey 2010; Parasuraman and Wickens 2008) due to passivity induced by automation (Klein et al. 2007). We have identified that air traffic control automation is designed to counter these effects. First of all, we identified that automating detection of uncertainty is only preferred when 1) the data behind these functions are more or less stable and reliable (deviation from coordinated route) and, 2) failure to detect the uncertainty has a high impact on safety (e.g. not noticing unexpected deviations from trajectory). Furthermore, vigilance is managed in system design by carefully deciding the timing and the sensitivity of these alerts to support controller vigilance as well as trust in automation. Finally, the design of these alerts must take into account various trade-offs. For example, notifications in color may
sometimes be missed, whereas animated alerts may have disadvantages in terms of their intrusiveness and cognitive costs related to processing these alerts (Imbert et al. 2014).

5.8.2. Transparency of automation

Furthermore, we identified transparency of automation as an important design consideration to support controllers with uncertainty, while, at the same time, preserving controllers' skills (c.f. Leroux 1999). To illustrate this, the conflict prediction tools available to the controllers in this study are based on human algorithms, in favor of integrating more sophisticated weather models into these prediction tools, which may increase the reliability of the predictions under more adverse weather conditions. This has several advantages. First, it reduces fixating and increases vigilance by stimulating manual trajectory tracking through mental simulation and assumptions, supporting comparison between the predicted versus actual state, and allowing controllers to understand the impact of weather. These findings support the notion of transparency and the concept of appropriate reliance (Lee and Moray 1994; Lee and See 2004). Appropriate reliance states that the understanding of humans concerning the capabilities of automation should match the actual capability of the automation, allowing humans to decide when it is reliable and when it is not (Lee and Moray 1994; Lee and See 2004). We argue that this transparency does not only support appropriate reliance, but also supports uncertainty reduction strategies, and, in turn, reduces fixation and increases vigilance. This finding is in line with earlier arguments by Averty and colleagues (2008), who stated that reducing uncertainty to a maximum is not a primary concern for controllers, as they, instead, prefer to accept a certain degree of uncertainty.

5.8.3. System flexibility as requirement for acknowledging and increasing uncertainty

Finally, controllers are supported with acknowledging and increasing uncertainty due to the possibility to implement traffic plans which involve high levels of flexibility, for example, through the delegation of airspace (while acknowledging a balance between authority and control) and a dynamic use of airspace (e.g. changing routings and holdings).

6. Limitations of study

We acknowledge some limitations of this study. First of all, data were collected exclusively in Enroute Air Traffic Control sectors, suggesting limitations for external validity to other
environments. Some of the findings, in particularly automation requirements, are specific to Enroute Air Traffic Control environments, although they can be translated to other command and control environments. Furthermore, the limited hours of observation means that the list of strategies and underlying tactics may not be exhaustive. In addition, we did not observe emergency scenarios or other highly abnormal situations, which are typical scenarios for high levels of uncertainty (Malakis et al. 2010; Kontogiannis and Malakis 2013). Finally, our study did not investigate the influence of team cognition (e.g. team mental models, team situation awareness) on uncertainty management (e.g. a team’s ability to anticipate and to respond to uncertainty) as an aspect of adaptive team performance (c.f. Burke et al. 2006). Future research could, for example, further explore the influence of a teams’ externalized cue-strategy associations (c.f. Fiore et al. 2010) on a team’s ability to manage uncertainty.

7. Implications for future concepts of operation

Future ATM concepts, as envisioned within SESAR (SESAR JU 2012) and NextGen (FAA 2014) aim to increase the efficiency and predictability of Air Traffic Management through the implementation of 4D business trajectories. Although these programs aim to minimize uncertainty, uncertainty cannot be completely eliminated from future operations (Malakis and Kontogiannis 2014; Nicholls 2001). In particular during non-routine events (e.g. adverse weather or emergency situations), controllers may be confronted with undifferentiated alternatives, e.g. whether or not to intervene (Dekker and Woods 1999). In addition, controllers may experience higher levels of ambiguity concerning the pilot’s intended flight path, which may increase the difficulty in estimating the likelihood of meeting the negotiated conditions of the 4D trajectory. Similar arguments were presented by Malakis and Kontogiannis (2014) and Nicholls (2001). We therefore believe that uncertainty management should be taken into consideration in the future design requirements of SESAR and NextGen operations. As sources of uncertainty will likely be different in future operations, it is important to gain a better insight into the sources of uncertainty in all flight phases, and the preferred strategies, in order to identify future requirements for automation.

Particular attention should be focused on understanding the requirements for increasing uncertainty, for example by understanding how to balance authority and control (Boy and Grote 2009; Boy and Grote 2011; Straussberger et al. 2008) between controllers and pilots and
controllers/pilots and automation, but also between the ground controllers involved in the 4D trajectory.

8. Acknowledgements

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Table 1. Overview of controller support tools (adapted from Corver and Aneziris 2014)

<table>
<thead>
<tr>
<th>Stripless tools</th>
<th>Description of the tool</th>
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<tbody>
<tr>
<td><strong>Electronic coordination</strong></td>
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<tr>
<td>E-coordination tool</td>
<td>Functionality allowing controllers of different sectors to electronically coordinate changes to the trajectory of a flight, e.g. by proposing a rate of descent/ascent, a flight level, or a direct route.</td>
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<tr>
<td><strong>Medium Term Conflict Detection tools</strong></td>
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<tr>
<td>Horizontal Scanning Tool</td>
<td>The Horizontal Scanning Tool is a conflict detection function whose outcome is displayed on the radar display, in the aircraft label and in a separate window which lists potential conflicts (encounters) having a horizontal separation of 10 nautical mile or 15 nautical mile or less (encounter threshold).</td>
</tr>
<tr>
<td>Exit Conditions Assistance Tool (ECAT)</td>
<td>The Exit Conditions Assistance Tool supports controllers in planning aircraft through the sector in a timely manner by listing all aircraft planned to exit at an exit point, sorted according to their predicted exit times. Potential exit conflicts are identified by highlighting the exit flight levels of these flights. In addition, controllers are presented with a suggested solution. Exit conflicts arise if exit conditions (typically three or more minutes of separation between aircraft, or as specified in letters of agreement between centres) cannot be complied with.</td>
</tr>
<tr>
<td>Dynamic Scanning Tool</td>
<td>The Dynamic Scanning Tool displays a prompt window when a controller enters a solution which, according to the system, is unsafe. This prompt window displays information about the potential crossings, including minimum distance and time until minimum distance is expected. The trajectories are marked in red where loss of separation is predicted.</td>
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<tr>
<td><strong>Analysis support tool</strong></td>
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<tr>
<td>Crossing Tool</td>
<td>The Crossing Tool helps controllers in the analysis of a potential conflict situation and with the monitoring of a crossing situation. When using the Crossing Tool, the controller selects the two aircraft to be monitored against each other and the system extrapolates their positions to calculate the minimum separation between them.</td>
</tr>
<tr>
<td><strong>Monitoring Aids</strong></td>
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<tr>
<td>Cleared Level Adherence Monitoring function (CLAM)</td>
<td>Monitoring aid that monitors actual flight level of the aircraft against the Cleared Flight Level (CFL) given to the pilot and entered by the controller in the system. It provides a warning in case of a deviation.</td>
</tr>
<tr>
<td>Route Adherence Monitoring function</td>
<td>Monitoring aid to support controllers in detecting that an aircraft has deviated from the trajectory as known to the system. An alert warns the controller if the current aircraft flight path deviates from the trajectory as expected by the system.</td>
</tr>
<tr>
<td>Action requirement (issue)</td>
<td>Example source</td>
</tr>
<tr>
<td>---------------------------------------------------------------</td>
<td>--------------------------------------------------------------------------------</td>
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<tr>
<td>System information (Aircraft and sector information)</td>
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<tr>
<td>Aircraft trajectory through the sector</td>
<td>System failures, e.g. missing estimates of flight (flight plan details)</td>
</tr>
<tr>
<td>Aircraft position</td>
<td>Radar failure (loss of signal of primary or secondary radar)</td>
</tr>
<tr>
<td>Aircraft altitude</td>
<td>Transponder failure</td>
</tr>
<tr>
<td>Availability of civilian airspace</td>
<td>Turbulence, Thunderstorms</td>
</tr>
<tr>
<td>Availability of military airspace</td>
<td>Conflicted information provided by the system</td>
</tr>
<tr>
<td>Capacity of neighboring sectors</td>
<td>System limitations, e.g. limits of radar coverage</td>
</tr>
<tr>
<td>Procedures</td>
<td></td>
</tr>
<tr>
<td>Procedural course of action</td>
<td>Unanticipated deviation of procedures by other actors in the system</td>
</tr>
<tr>
<td></td>
<td>Applicable procedure unknown</td>
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<tr>
<td>Traffic situation (Traffic conflict, separation distance and exit conditions)</td>
<td></td>
</tr>
<tr>
<td>Traffic conflict and/or separation distances</td>
<td>Missing or unknown flight parameters (pilot settings) and aircraft performance variability (e.g. due to winds).</td>
</tr>
<tr>
<td></td>
<td>Adverse weather (e.g. thunderstorms)</td>
</tr>
<tr>
<td>Aircraft adherence to negotiated entry and exit agreements</td>
<td>Missing or unknown flight parameters (pilot settings) and aircraft performance variability (e.g. due to winds).</td>
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<tr>
<td>Aircraft future flight path</td>
<td>Military aircraft in military airspace, VFR flight.</td>
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<td>---------------------------</td>
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<tr>
<td>Aircraft intentions</td>
<td>Aircraft with technical problems (emergency)</td>
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<td></td>
<td>Unknown intentions neighboring sectors</td>
</tr>
<tr>
<td></td>
<td>Thunderstorms, turbulence</td>
</tr>
<tr>
<td>Non-conformance of aircraft</td>
<td>Discrepancy between instructed versus executed instruction, turbulence, thunderstorms, winds</td>
</tr>
<tr>
<td>Aircraft preferred future trajectory through the sector</td>
<td>Turbulence, thunderstorms</td>
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<tr>
<td></td>
<td>Special flight or emergency flight</td>
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</tbody>
</table>
Table 3. Uncertainty coping strategies: reducing uncertainty

<table>
<thead>
<tr>
<th>Coping strategy</th>
<th>Tactic within strategy</th>
<th>Description of tactic and behavioral markers</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reduction strategies</strong></td>
<td></td>
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</tbody>
</table>
| Reducing | Collecting additional information | When information is unreliable, conflicting or missing, controllers may collect additional information by 1) consulting information systems; 2) call neighboring (military) sectors on the phone; 3) contact aircraft on the frequency, in order to resolve the uncertainty.  
*Examples:*  
- The radar planner calls the previous center to obtain the missing flight plan data.  
- The radar planner calls military on the phone to clarity the conflicting information concerning the availability of military airspace.  
- The radar executive obtains information about the location of thunderstorm and turbulence by requesting pilots their future preferred routing during adverse weather. |
| Relying on informal rules of conduct | | When there is procedural uncertainty, because the situation is not according to procedures, or the applicable procedure is unknown, controllers may shift to using informal rules of conduct by doing what is safe, and what makes sense, whilst relying on a shared common sense between controllers.  
*Example:*  
- When the military uses more airspace than usual for military exercises, controllers ensure that separation is provided vertically (do “what is safe”), rather than horizontally (standard procedure). |
| **Anticipatory thinking** | Pattern recognition | Controllers engage in selective attention and detect need for intervention (cues) based on detected deviations from expected patterns and comparison with stored patterns.  
*Example:*  
- The radar executive detects an aircraft deviation from routing. Based on the controller’s experience (stored patterns), the controller assesses whether the deviation requires action or if it is an (expected) deviation due to wind that does not need conformance management. |
| **Trajectory tracking** (including mental simulation) | | Controllers extrapolate the future traffic situation using *mental simulation* supported by controller support tools and *assumption based reasoning*.  
*Example:*  
- Controller assesses a horizontal crossing using mental simulation and assumptions based on experience (e.g. impact of wind on the reliability of traffic conflict prediction), in combination with predictions obtained from speed vectors, extrapolated speed vectors, and the Crossing Tool. |
| Convergence | | Controller combines information from various sources in order to create an understanding of the availability of routes and flight levels in the sector.  
*Example:*  
- Controllers form a mental picture of the weather situation in the sector by combining and integrating information from pilots, requests from pilots, weather display and traffic movements in order to identify the useable flight levels in the sector. |
### Table 4. Uncertainty coping strategies: acknowledging uncertainty

<table>
<thead>
<tr>
<th>Coping strategy</th>
<th>Tactic within strategy</th>
<th>Description of tactic and behavioral markers</th>
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</table>
| **Acknowledging uncertainty** | Weighing pros and cons | The radar planner decides between implementing a strategic traffic solution or tactical traffic solution, to be implemented by the radar executive in the tactical timeframe.  
*Example:*  
The radar planner weighs pros and cons by taking into account various trade-offs when deciding between a strategic or tactical traffic solution:  
- A strategic plan, which avoids workload in tactical timeframe, but is more static and possibly less efficient.  
- A tactical plan, which creates workload in the tactical timeframe, but is more precise and possibly more efficient. |
| | Weighing solutions within strategic or tactical timeframe using trade-offs | The radar planner or radar executive chooses between different traffic solutions within the strategic or tactical timeframe.  
*Example:*  
The radar planner/radar executive weighs pros and cons by taking into account trade-offs when choosing between various options within the strategic or tactical timeframe. |
| **Adaptable plans** | | Controllers dynamically decide on the usability of the airspace and adapt plans using alternative routing and location of holdings depending on the location of the adverse weather (e.g. thunderstorms). |
| **Forestalling (improving readiness)** | Creating buffer zones in traffic flows (plan coupling) | Controllers maintain extra spacing between aircraft within traffic flows in order to accommodate possible future deviations from aircraft performance due to winds. |
| | Contingency or backup plan | Controllers develop specific backup plans in case the original plan fails. Backup plans may be shared explicitly within the team as well as between sector teams. |
| | Increasing safety margins | Controllers increase the safety margins (or minimum separation distance) between two aircraft as a precaution in case they are unsure about the behavior of an aircraft. |
| **Maximize operational control** | | Controllers prefer to maximize operational control by being in contact with an aircraft in case a traffic situation may result in a potential loss of separation.  
*Examples:*  
- Controllers may prefer to keep an aircraft on frequency instead of transferring to the next frequency in order to provide timely separation if needed.  
- Controllers request to get in contact with a VFR flight in case a traffic situation may result in a potential loss of separation. |
Table 5. Uncertainty coping strategies: increasing uncertainty

<table>
<thead>
<tr>
<th>Coping strategy</th>
<th>Tactic within strategy</th>
<th>Description of tactic / Behavioral marker</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increasing uncertainty</td>
<td>Aircraft release</td>
<td>Controllers grant a release of an aircraft to the next sector before it reaches the sector boundary, creating additional time and space for the subsequent sector to manipulate the aircraft in order to 1) allow the subsequent sector to acknowledge uncertainty; 2) enable flexibility for the subsequent sector to adhere to their operational goals, e.g. by expediting an aircraft after obtaining control.</td>
</tr>
<tr>
<td>Creating flexibility through delegation of control within specific boundaries</td>
<td>Pilot discretion</td>
<td>Controllers may give pilots the opportunity to execute the instruction at their discretion, thus leaving the actual trajectory through the sector (e.g. initiation of descent and descent rate) up to the pilot, in order to adhere to their operational goals (e.g. comfort, economy)</td>
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<tr>
<td>Strategy</td>
<td>Timeframe</td>
<td>Tactics within strategy</td>
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<tr>
<td><strong>Complexity management</strong></td>
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<td>Reducing complexity which may indirectly</td>
<td>Strategic</td>
<td><strong>Strategic traffic plans</strong></td>
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<td>acknowledge uncertainty</td>
<td>timeframe</td>
<td>Acknowledge complexity by solving possible traffic conflicts in a strategic timeframe:</td>
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<tr>
<td></td>
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<td>• Coordinate new flight level outside sector</td>
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<td>• Coordinate different exit conditions (exit flight level or exit waypoint)</td>
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<td>• Coordinate direct routing</td>
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<td>Tactical</td>
<td><strong>Tactical traffic plans</strong></td>
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<td></td>
<td>timeframe</td>
<td>Acknowledge complexity by solving possible traffic conflicts in a tactical timeframe:</td>
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<td>• Separate aircraft vertically (minimum of 1000ft separation)</td>
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<td>• Separate aircraft horizontally (minimum of 5 nm), then descent through each other’s level</td>
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<td>• Separate aircraft using heading, speed, or send aircraft on diverging tracks</td>
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<tr>
<td>Acknowledging complexity</td>
<td>Strategic and tactical timeframe</td>
<td><strong>Use of mental abstractions</strong></td>
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<td>• Grouping traffic into traffic flows, conflict pairs, aircraft on the same flight level</td>
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<td>• Identification of critical points (waypoints, conflict points)</td>
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<td>• Assignment of aircraft into “in conflict” or “not in conflict”</td>
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<td><strong>Optimization of work process</strong></td>
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<td>• Leaving measuring and planning tools active to support monitoring functions</td>
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<td>• Suppressing irrelevant information</td>
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<td></td>
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<td>• Optimizing layout (location of windows, avoid cluttering of information on radar display, e.g. aircraft label information)</td>
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<td><strong>Workload management</strong></td>
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<td>• Reducing workload for repetitive functions to free up cognitive capacity for complexity</td>
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<tr>
<td>Reducing uncertainty</td>
<td>Strategic and tactical timeframe</td>
<td><strong>Reducing</strong></td>
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<td></td>
<td>• Searching for additional information</td>
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<td>• (In)formal rules of conduct</td>
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<td></td>
<td></td>
<td>• Anticipatory thinking</td>
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<td></td>
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<td>• Assumption based reasoning</td>
</tr>
<tr>
<td>Acknowledging which may indirectly reduce</td>
<td>Strategic and tactical timeframe</td>
<td><strong>Weighing pros and cons (trade-offs)</strong></td>
</tr>
<tr>
<td>complexity</td>
<td></td>
<td>• Weighing pros and cons when choosing between traffic solutions:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Weighing strategic versus tactical traffic solutions using trade-offs</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Weighing options within strategic or tactical timeframe using trade-offs</td>
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<tr>
<td></td>
<td></td>
<td><strong>Adaptive planning</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Forestalling</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Creating buffer zones in traffic flows (plan coupling)</td>
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<tr>
<td></td>
<td></td>
<td>• Contingency or backup plans</td>
</tr>
<tr>
<td></td>
<td><strong>Tactical</strong></td>
<td>Forestalling</td>
</tr>
<tr>
<td></td>
<td>timeframe</td>
<td>• Increasing safety margins</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Maximize operational control</td>
</tr>
<tr>
<td>Increasing</td>
<td>Strategic</td>
<td><strong>Flexibility through delegation of airspace/control</strong></td>
</tr>
<tr>
<td>timeframe</td>
<td></td>
<td>• Releasing aircraft</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Delegation of airspace flight levels to other sectors</td>
</tr>
<tr>
<td></td>
<td><strong>Tactical</strong></td>
<td><strong>Increasing operational freedom to pilot</strong></td>
</tr>
<tr>
<td></td>
<td>timeframe</td>
<td>• Enabling flexibility for pilot to execute instructions; pilot discretion</td>
</tr>
<tr>
<td>Uncertainty management strategy</td>
<td>Example system design features supporting uncertainty management</td>
<td></td>
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<tr>
<td>---------------------------------</td>
<td>---------------------------------------------------------------</td>
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</tr>
</tbody>
</table>
| Collecting additional information | - The system provides *real-time* and accurate data.  
- The system allows insight into relevant *sector characteristics* on demand through functions that support the visualization of sector characteristics (e.g. routings, country boundaries, waypoints).  
- The system supports visualization of *limitations and constraints* of neighboring sectors, including the availability of airspace, current capacity/workload of neighboring sectors. |
| Anticipatory thinking | Pattern recognition  
- The system supports *timely detection of missing, conflicting or unreliable information* through (visual) system notifications or alerts (e.g. in case of radar failure).  
- Automation functions support visualization of traffic on different flight levels, traffic to the same exit points (ECAT window) etc.  
- Aircraft labels support detection of patterns (past trajectory, supporting identification of traffic flows; arrow if aircraft is in vertical evolution etc.).  
- Conflict detection tools (HST, ECAT and DST) support the detection of traffic conflicts.  
- Monitoring tools (CLAM and MONA) support the timely identification of aircraft deviations (lateral or vertical). |
| Trajectory tracking and mental simulation |  
- Automation functions reduce *fixating* (e.g. aircraft elements on radar display supporting controllers with tracking aircraft progress (e.g. by presenting continuous data).  
- Automation functions supports *vigilance*. Traffic predictions and conflict prediction tools follow human algorithms, supporting controllers in critiquing and validating these predictions.  
- Speed vectors, extrapolated speed vectors and planning tools supporting *mental simulation* of the future trajectory on demand.  
- Conflict analysis tool supports mental simulation of potential future crossing of two aircraft against each other by extrapolating future trajectories.  
- Measuring tools support detection of discrepancy between planned and actual state. |
| Convergence |  
- System supports convergence of data, for example, optional visualization of weather (weather radar image) on top of the traffic picture. |
| Planning: Weighing pros and cons | Weighing pros and cons (trade-offs)  
- Visualization of sector characteristics of neighboring sectors (traffic situation, traffic complexity as an indicator of workload, availability of flight levels) across sectors.  
- What-if trajectories (planning tools) to generate options.  
- System allows insight into trade-offs (e.g. insight into sector conditions and limitations, delay of aircraft). |
| Adaptive plans | Developing adaptive plans  
- Controllers use planning tools to simulate possible alternative trajectories (e.g. headings).  
- Ability to develop plans and propose possible solutions *independently* across sectors, supported by E-coordination.  
- System supports controllers in implementing adaptive plans (e.g. ability to change routings and assign location of holding circles during adverse weather). |
| Forestalling | Maximizing operational control  
- System allows controllers to remain in control if deemed necessary, for example by keeping aircraft on frequency. |
| Delegation of control or airspace | Aircraft release  
- System allows delegation of airspace, supported with clear delegation procedures and balance between autonomy/control mechanisms. |
9. References


Federal Aviation Administration (FAA) (2012) FAA’s NextGen implementation plan, August 2014, Federal aviation administration


Xu X, Rantanen EM (2003) Conflict detection in air traffic control: a task analysis, a literature review, and a need for further research. Proc of the 12th International Symposium on Aviat Psychology. Dayton, USA
APPENDIX
### Appendix A. Task descriptions of controller tasks in Enroute Air Traffic Control
(adopted from: Corver & Aneziris, 2014)

<table>
<thead>
<tr>
<th>Generic Task Type</th>
<th>Task description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conflict detection and analysis</td>
<td></td>
</tr>
<tr>
<td>1 RP detects incoming aircraft and assimilates Flight Plan</td>
<td>The radar planner detects the aircraft and assimilates flight plan before the aircraft enters the sector. The radar planner visualizes the lateral and vertical trajectory through the sector.</td>
</tr>
<tr>
<td>2 RP detects potential conflict or service improvement</td>
<td>The radar planner scans the sector for any transit or exit conflicts which might be expected based on the predicted trajectory through the sector. The radar planner also scans for possible optimizations of the trajectory.</td>
</tr>
<tr>
<td>3 RP analyzes potential conflict and identifies solution or potential service improvement</td>
<td>The radar planner analyzes the conflict and decides to coordinate a solution/optimization, plan a solution to be implemented by the radar executive in a later phase, or do nothing.</td>
</tr>
<tr>
<td>Coordination and negotiation</td>
<td></td>
</tr>
<tr>
<td>4 RP initiates coordination (proposal or request)</td>
<td>The radar planner coordinates changes with other sectors if required.</td>
</tr>
<tr>
<td>7 RP receives coordination (proposal or request)</td>
<td>The radar planner receives a coordination proposal or request from other sectors (phone or electronically).</td>
</tr>
<tr>
<td>Assuming aircraft and tactical conflict detection and resolution</td>
<td></td>
</tr>
<tr>
<td>8 RE detects incoming aircraft, assimilates Flight Plan and assumes aircraft</td>
<td>The RE detects the aircraft and its planned trajectory through the sector and assumes the aircraft as soon as it calls on the frequency at the sector boundary.</td>
</tr>
<tr>
<td>9 RE detects potential conflict</td>
<td>The radar executive analyses the anticipated trajectory and recalls previously negotiated changes and future plans by RP.</td>
</tr>
<tr>
<td>10 RE analyzes potential conflict and identifies solution in tactical timeframe</td>
<td>The radar executive engages in conflict detection and analysis, identifies possible optimizations based on earlier plans or evaluation of the current situation and determines the plan for the trajectory through the sector.</td>
</tr>
<tr>
<td>Aircraft progress monitoring and conformance management</td>
<td></td>
</tr>
<tr>
<td>11 RE flight progress monitoring and conformance management</td>
<td>The radar executive continuously monitors the performance and status of an aircraft in transit through the sector in order to timely execute the planned instructions and transfer of the aircraft. Monitoring supports controllers in timing instructions such heading, speed and flight level instructions as well as instructions to change frequency. These tasks are primarily the responsibility of the radar executive. Conformance management is required when an aircraft may laterally deviate from its trajectory or when does not comply with level clearances leading to “level bust”.</td>
</tr>
<tr>
<td>Aircraft instructions and transfer</td>
<td></td>
</tr>
<tr>
<td>12 RE instructs pilot and updates system</td>
<td>The radar executive instructs the pilot by giving (phased) instructions. When the aircraft reaches the sector boundary, the radar executive will hand over the aircraft to the next sector by instructing a frequency change to the pilot. In strip operations, the radar executive relies on the paper flight strips as a reminder for planned instructions to the pilot. In “stripless” operations, the planned instructions are the coordination proposals (in blue text) in the aircraft label.</td>
</tr>
</tbody>
</table>
## Appendix B: Controller Support Tools in “stripless” operations
(adopted from: Corver & Aneziris, 2014)

<table>
<thead>
<tr>
<th>Stripless tools</th>
<th>Description of the tool</th>
</tr>
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<tbody>
<tr>
<td><strong>Electronic coordination</strong></td>
<td></td>
</tr>
<tr>
<td>E-coordination window</td>
<td>Functionality allowing controllers of different sectors to electronically coordinate changes to the trajectory of a flight. The E-coordination tool is accessed by clicking on the aircraft label. This generates a prompt window with several menus and options. The window allows controllers to send an electronic coordination <em>proposal</em> concerning the particular flight to another sector. The window allows controllers to propose a rate of descent/ascent, a flight level, a direct route or no need, as well as the opportunity to request the aircraft to contact the next sector frequency if not required at the sector frequency (see “flash”). A coordination <em>proposal</em> is used to propose a coordination for an aircraft approaching the sector, and proposes instructions to be executed by the upstream controller. A coordination proposal may concern a suggested flight level, suggested heading, direct or suggested speed.</td>
</tr>
<tr>
<td>Fh and Fx (Flash) function</td>
<td>The Flash function allows controllers to send over an aircraft to the next sector electronically. The flash function can be combined with an electronic coordination, for example a Flight Level, within the electronic coordination menu. This proposal will appear on the radar screen of the upstream sector as a coordination proposal (in blue) combined with “fh” in the aircraft label. The receiving sector executes the proposed coordination and sends the aircraft directly to the next sector, or specifically to the proposing sector with the “fx” option.</td>
</tr>
<tr>
<td><strong>Analysis support tool</strong></td>
<td></td>
</tr>
<tr>
<td>Crossing Tool</td>
<td>The Crossing Tool helps controllers in the analysis of the conflict and also the monitoring of a crossing situation. When using the Crossing Tool, the controller selects the two aircraft to be monitored against each other and the system extrapolates their positions to calculate the minimum separation between each other.</td>
</tr>
<tr>
<td><strong>Medium Term Conflict Detection tools</strong></td>
<td></td>
</tr>
<tr>
<td>Horizontal Scanning Tool</td>
<td>The Horizontal Scanning Tool is a conflict detection function whose outcome is displayed on the radar screen, in the aircraft label and in a separate window which lists potential conflicts (encounters) having a horizontal separation of 10 nautical mile or 15 nautical mile or less (encounter threshold). The window lists aircraft callsigns as conflict pairs (highlighted in orange) and provides the controller with information concerning the minimum expected (horizontal) separation in nautical miles and the expected time in minutes when the separation is below the encounter threshold. Additionally, the trajectories are displayed in red where horizontal separation distance is less than 10 or 15 nautical miles, depending on controller preferred system settings.</td>
</tr>
<tr>
<td>Exit Conditions Assistance Tool (ECAT)</td>
<td>The Exit Conditions Assistance Tool supports controllers in planning aircrafts through the sector in a timely manner by listing in windows all the aircrafts planned to exit at the respective Exit Points and sorted according to their predicted exit times. The ECAT window presents the potential exit conflicts by marking the Exit Flight Levels of these flights red (also reflected in the labels) and presents controllers with a suggested solution. Exit conflicts generally concern non-compliance of the exit conditions (minimum of three minutes separation between aircraft or otherwise defined in agreements between centers).</td>
</tr>
<tr>
<td>Dynamic Scanning Tool</td>
<td>The Dynamic Scanning Tool displays a prompt window when a controller enters a solution which, according to the system, is unsafe. This prompt window displays information about the potential crossings, including minimum distance and time until minimum distance is expected. The trajectories are marked in red where loss of separation is predicted. The</td>
</tr>
</tbody>
</table>
controller is given the choice to accept the potential conflict(s) by pressing “valid” or to cancel the coordination by pressing “cancel”. If the controller clicks “cancel”, the input having triggered the Dynamic Scanning Tool conflict warning is not accepted by the system, and the controller needs to find a new solution. The Dynamic Scanning Tool does not propose any solutions to the conflicts detected. The Dynamic Scanning Tool is designed as a conflict detection tool triggered on certain inputs, and not as a continuous background monitoring.

**Monitoring Aids**

<table>
<thead>
<tr>
<th>Monitoring Aids</th>
<th>Function</th>
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<tbody>
<tr>
<td>Cleared Level Adherence Monitoring function (CLAM)</td>
<td>Tool that monitors actual flight level of the aircraft against the Cleared Flight Level (CFL) given to the pilot and entered by the controller in the system. It provides a warning in the track label in case of non-conformance (e.g. the aircraft level does not change for a certain time after CFL input, the aircraft moves in the opposite direction to the input CFL, the aircraft levels-off before the CFL or the aircraft busts the CFL). The warning consists of the display of the CFL in orange warning colour.</td>
</tr>
<tr>
<td>Route Adherence Monitoring function</td>
<td>Monitoring aid to support controllers in detecting that an aircraft has deviated from the trajectory as known to the system. Controllers are warned for such deviations (heading field of the track label in orange warning colour). Alerts notify controllers that the current aircraft flight path deviates from the trajectory as known by the system.</td>
</tr>
<tr>
<td>Frequency reminder</td>
<td>Monitoring tool to warn controllers to send an aircraft on the frequency of the next sector (aircraft is approaching sector boundary). It displays a warning if not transferred at a defined time or distance before the Exit Point, when the exit conditions are satisfied (aircraft cleared to its planned Exit Level). The Frequency reminder supports the controller in identifying the appropriate time to transfer the aircraft to the next sector. If the controller responds late, the Frequency field will turn orange as a visual reminder.</td>
</tr>
</tbody>
</table>
## Appendix C: Overview of automation issues addressed in papers

<table>
<thead>
<tr>
<th>Automation issues</th>
<th>Paper</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>New tasks mean new possible risks</td>
<td>Paper 1</td>
<td>Isaac <em>et al.</em> (2002); Kirwan (2001)</td>
</tr>
<tr>
<td>Change of modalities/ Peripheral awareness</td>
<td>Paper 1</td>
<td>Stedmon <em>et al.</em> (2007)</td>
</tr>
<tr>
<td>Trust</td>
<td>Paper 1, 3</td>
<td>Averty <em>et al.</em> (2008); Parasuraman &amp; Manzey (2010); Parasuraman &amp; Wickens (2008)</td>
</tr>
<tr>
<td>Vigilance</td>
<td>Paper 1 and 3</td>
<td>Parasuraman &amp; Manzey (2010); Parasuraman &amp; Wickens (2008)</td>
</tr>
<tr>
<td>Automation may keep the controller “out of the loop” (disengagement).</td>
<td>Paper 1</td>
<td>Kirwan (2001); Leroux (1999); Parasuraman, Sheridan, and Wickens (2000)</td>
</tr>
<tr>
<td>Fixation errors</td>
<td>Paper 3</td>
<td>De Keyser &amp; Woods (1990)</td>
</tr>
<tr>
<td>Designing alerts and notifications, poorly designed automation notifications,</td>
<td>Paper 3</td>
<td>Imbert <em>et al.</em> (2014); Leveson (2004)</td>
</tr>
<tr>
<td>sensitivity of alarms</td>
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<tr>
<td>Human trade-offs and preferences: challenges to integrate them into the system</td>
<td>Paper 3</td>
<td>Cummings &amp; Tsonis (2006); Kirwan &amp; Flynn (2002a; 2002b); Parasuraman &amp; Wickens (2008);</td>
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<tr>
<td>(CD &amp; R).</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Matching authority and control</td>
<td>Paper 3</td>
<td>Boy &amp; Grote (2009); Boy &amp; Grote (2011); Straussberger <em>et al.</em> (2008)</td>
</tr>
</tbody>
</table>
Appendix D: Statement of Ethics & Informed Consent

Statement of Ethics & Informed Consent

Nature and Purpose of Activity

Thank you for volunteering to participate in the ETH study.

This study has 4 primary objectives:

1) Investigate how team coordination, decision-making and situation awareness is supported by the operational system – including controller support tools – and working methods in Enroute sectors in Geneva and Zürich.
2) Investigate how controller teams distribute tasks to manage workload in stripless sectors depending on task characteristics and how working methods and system design support this task distribution.
3) Investigate how controller teams build and maintain team situation awareness during varying levels of traffic complexity and uncertainty.
4) To compare performance and team situation awareness between stripless equipped sectors in GVA versus the current upper sectors in ZRH.

Important note: We are not interested in evaluating individual performance or comparing performances between teams. Our main research objective is to understand controller strategies to deal with challenging and complex situations, to understand how the operational system effectively supports controllers in these situations and how the operational system supports efficient coordination and team situation awareness.

Participation

All Skyguide controller working in GVA and ZRH Enroute control sectors are eligible for participation. Participation with this research is voluntary.

Procedures

As part of the observational study, you may be randomly approached by two of your colleague controllers who will act as independent observers during one of the session you are working as an on-duty controller, for a maximum duration of 20 minutes. The observers will a) record all observable interaction between you and your partner and b) observe team situation awareness during these 20 minutes.

During the observations, you should not interact with the observers nor will they interact with you: it will be a silent, over-the-shoulder observation. The observers do not have any responsibilities with respect to the observed session, they are only passive observers.

Finally, a few weeks after observations, we will ask your support by answering a short questionnaire by email. This questionnaire will include questions concerning complexity factors of airspace sectors you are working in and how you evaluate these complexity factors as well as a few other questions.

Time investment

We expect that the time investment will be roughly: 5-10 minutes in total to answer the questionnaire by email.

Discomforts and Risks

We anticipate no discomfort or risks during the observation.

Benefits

Your participation in this study, for which we are very grateful, provides no direct benefit to you. However, it benefits Skyguide as well as general research purposes. Skyguide expects to use this data to aid in the development of future systems and its implementation, more specifically, the implementation of Stripless in ZRH Enroute sectors.
Participant’s Responsibilities
The results of this effort depend greatly on conducting your normal way of work and on your attention and honest responses to the questionnaire.
If there is something you do not understand in the questionnaire, please ask a researcher. In addition, to avoid biasing the results, please do not discuss the study with other potential participants until the study is completed.

Participant’s Assurances
Researchers from the ETH Zürich maintain strict standards regarding participant confidentiality and informed consent. We base our standards on the Ethical Principles in the Conduct of Research with Human Participants by the American Psychological Association (APA). The APA standards conform to the following principles.

- Your participation in this study is voluntary. You may choose not to participate, or to withdraw from the observation, for any reason, without consequence. You have the right to stop your participation at any time once the session has started and the observers have initiated with observing. If you would like to do so, please notify the ETH researcher or observers. No consequences exist when withdrawing from participation. In addition, the observers can also terminate the observation if they believe it is in the best interest of the situation.
- Your responsibilities will be made clear by the researchers or observers: you will not have any additional responsibilities during your work. We only would like you to fill out a questionnaire before and after the observation session, at any time convenient for you.
- We will keep your identity anonymous. We will code your identity (for questionnaire as well as observation) with an unrecognizable participant number. This number is only known to the researchers. Also, we won’t associate your name with data contained in any report or briefing. To facilitate your anonymity, please do not write your name or any other identifying marks on your questionnaires. Please do not share your participant code with anyone other than the researchers. Finally, we will also replace the session time and date with an unrecognizable session code so that data cannot be connected to a particular session.
- We will keep the data collected from the questionnaires and observation anonymous. The raw data collected in this assessment will become the property of the ETH. Only researchers from the ETH will analyze the data. We will not make any individual session data available to Skyguide. We will only present aggregate (summarized) statistics in briefings and reports. These will include averages, standard deviations, and other summary statistics.

If you any have questions about this study or need to report any adverse conditions, you may contact the researchers conducting the study, the primary investigators Sifra Corver (scorver@ethz.ch) or Prof. Gudela Grote (ggrote@ethz.ch). You may also contact Montserrat Mendoza montserrat.mendoza@skyguide.ch (Skyguide) at any time with questions or concerns.

I have read this consent document. I understand its contents, and I freely consent to participate in this study under the conditions described.

Participant: (print) ________________________________
(sign) ________________________________ Date: ___________

Researcher ETH: (sign) ________________________________ Date: ___________

Witness (observer): (sign) ________________________________ Date: ___________

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Weinbergstrasse 56/58
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8092 Zürich, Switzerland
Sifra Corver
Tel. +41 446327083
scorver@ethz.ch
Appendix E: Curriculum Vitae

Name: Sifra Christina Corver
Date of birth: December 30, 1980
Place of birth: Den Haag (The Hague), Netherlands
Nationality: Dutch

Education

2008 – 2014 PhD in Human Factors and Organizational Psychology, ETH Zürich, Department Management Technology and Economics.

1999 – 2007 Leiden University, Social and Organisational Psychology, specialized in Accident analysis and Risk- and Safety management.

Work Experience

2008 – 2014 ETH Zürich, Department Management Technology and Economics (D-MTEC)
In collaboration with skyguide, Switzerland
Organization, Work and Technology Group
PhD in Human Factors/Organizational Psychology

2011 Imperial College London
Research Center for Transport Studies
Guest researcher

2007 - 2008 TNO Quality of Life
Knowledge for Business
Safe and healthy business

2005 Dutch Safety Board
Internship Student & Safety analyst
Publication list

Research papers


Conference papers


