Automated decision aids in future air traffic management: Human performance and mental workload

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Genehmigte Dissertation zur Erlangung des Grades eines Doctor rerum naturalium

(Dr. rer. nat.)

am Fachbereich 3: Humanwissenschaften

(Erziehungswissenschaften, Psychologie und Sportwissenschaft)

der Technischen Universität Darmstadt (D 17)

Tag der Einreichung: 11. Juni 2001

Tag der Prüfung: 17. Juli 2001

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Darmstadt, Juli 2001

Acknowledgements

This research was supported by Grants NAG 2-1096 ("Dynamic Automation Tools for Future Air Traffic Management") and NCC2-1247 ("Human Factors in Distributed Air Ground Traffic Management") from NASA Ames Research Center, Moffett Field, CA (Technical Monitors: Kevin Corker, Ph.D. and Richard Mogford, Ph.D.) awarded to Raja Parasuraman, Ph.D. Additional funding was provided by a grant from the Flughafenstiftung Frankfurt/Main, Germany awarded to Ulla Metzger.

I would like to thank all air traffic controllers that participated in my experiments. During the course of this work, I have developed a great appreciation of their profession and the services they provide.

No dissertation can be completed without the people that direct and later evaluate it. I would like to thank Prof. Dr. B. Ruettinger for his flexibility in supporting and accomodating my research endeavors abroad. I am indebted to Prof. Dr. R. Singer for his willingness to serve as a reader and evaluator of my dissertation on a short notice. I am most grateful to Prof. Dr. Raja Parasuraman for his support during my four great years in his lab and for providing a stimulating work environment full of opportunities joined with a great degree of professional and personal freedom.

Thanks are also due to Dr. Jürgen Sauer for valuable comments on a previous draft of my dissertation, Dr. Bernd Lorenz for encouraging and helpful discussions of my research, and my former colleagues at the Cognitive Science Lab, Diego Castaño, Jackie Duley, Scott Galster, and Tony Masalonis, for the fruitful, and sometimes heated discussions of our projects. My work has benefited from all of them.

Most of the work for this dissertation was done while I was abroad. While this has been a great opportunity for personal and professional development, I believe that it is only possible with a network of stable relationships - knowing that there is always someone to rely on. I would like to thank my friends and, most of all, my family for providing this network for me.

Finally, I am most thankful to Jörg for not just supporting, but encouraging me in all my ventures. His inspiration, both personally and professionally, has been invaluable.

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List of acronyms

ADS-B	Automatic Dependant Surveillance - Broadcast
ARTCC	Air route traffic control center
ASL	Applied Science Laboratories
ASRS	Aviation Safety Reporting System
ATC	Air traffic control
ATCo	Air traffic controller
ATM	Air traffic management
CDTI	Cockpit display of traffic information
COMPAS	Computer Oriented Metering, Planning and Advisory System
CPDLC	Controller-pilot digital datalink communication
CPTP	Conflict prediction and trial planning
CTAS	Center TRACON automation system
DD	Dynamic Density
ECG	Electro-cardiogram
EEG	Electro-encephalogram
ERP	Event-related potentials
FAA	Federal aviation agency
FF	Free flight
fMRI	Functional magnetic resonance imaging
FMS	Flight management syste,
FPL	Full performance level
GPS	Global positioning system
GPWS	Ground-proximity warning system
HRV	Heart rate variability
IFR	Instrument flight rules
M	Mean
MAT	Multi-attribute task battery
MSAW	Minimum safe altitude warning
NAS	National Airspace System

NASA	National Aeronautics and Space Agency
NASA-TLX	NASA-Task Load Index
NRC	National Research Council
OE	Operational error
OOTLUF	Out-of-the-loop phenomenon
PCR	Distance pupil-corneal reflection
PET	Positron emission tomography
PUMA	Performance and usability modeling in ATM
PVD	Plan view display
SA	Situation awareness
SAGAT	Situation awareness global assessment technique
SD	Standard deviation
SE	Standard error
SMEQ	Subjective mental effort questionnaire
STCA	Short-term conflict alert
SWAT	subjective workload assessment technique
SWORD	Subjective workload dominance technique
TRACON	Terminal radar control
URET	User request evaluation tool
VFR	Visual flight rules

They say that there dwelt at Naucratis in Egypt one of the old gods of that country, to whom the bird they call Ibis was sacred, and the name of the god himself was Theuth. Among his inventions were number and calculation and geometry and astronomy, not to speak of various kinds of draughts and dice, and above all, writing. The king of the whole country at that time was Thamus, who lived in the great city of Upper Egypt which the Greeks call Egyptian Thebes; the name they give to Thamus is Ammon. To him came Theuth and exhibited his inventions, claiming that they ought to be make known to the Egyptians in general. Thamus inquired into the use of each of them, and as Theus went through them expressed approval or disapproval, according as he judged Theuth's claims to be well or ill founded. It would take too long to go through all that Thamus is reported to have said for and against each of Theuth's inventions. But when it came to writing, Theuth declared: 'Here is an accomplishment, my lord the king, which will improve both the wisdom and the memory of the Egyptians. I have discovered a sure receipt for memory and wisdom.' 'Theuth, my paragon of inventors,' replied the king, 'the discoverer of an art is not the best judge of the good or harm which will accrue to those who practise it. So it is in this case; you, who are the father of writing, have out of fondness for your offspring attributed to it quite the opposite of its real function. Those who acquire it will cease to exercise their memory and become forgetful; they will rely on writing to bring things to their remembrance by external signs instead of their own internal resources. What you have discovered is a receipt for recollection, not for memory. And as for wisdom, your pupils will have the reputation for it without the reality: They will receive a quantity of information without proper instruction, and in consequence be thought very knowledgeable when they are for the most part quite ignorant. And because they are filled with the conceit of wisdom instead of real wisdom they will be a burden to society.'

From Plato, Phaedrus, translated by W. Hamilton (1973). London: Pinguin.

1. Overview

Rapidly increasing air traffic all over the world and economical considerations of the airlines are forcing radical changes in the air traffic control (ATC) system. Free Flight (FF) is a proposal in which authority for aircraft separation is transferred from the air traffic controller (ATCo) on the ground to the pilots in the air. The ATCo will manage traffic flows within a sector, but leave the detection and resolution of conflicts to the pilots. Nevertheless, ATCos will be required to oversee the system and intervene if necessary. This changes the role of the ATCo to an air traffic manager. The automation of higher-order cognitive functions such as decision-making or planning as well as new concepts of air traffic management (ATM) have been proposed to alleviate the pressure on the outdated system. In a high-risk environment like ATC, it is crucial to understand how the human operator in the system is affected by new procedures and automation tools. It is the ATCo who is ultimately held responsible for system safety. New concepts implemented with the goal to increase capacity and efficiency should at least be safety-neutral and, preferably, safety-enhancing. Although there has been much speculation about the consequences of automation and new procedures on ATCo and system performance, empirical evidence is scarce. The purpose of the present work was to provide empirical evidence on the effects of automation in future ATM on ATCo performance and mental workload. This serves to expand the knowledge on human interaction with automation of higher-order cognitive processes in the ATC and other environments and contributes to the design of safe and efficient human-machine systems.

The present work is comprised of ten chapters. After this brief overview, the next chapter will give a general introduction to the current situation in the ATC system and proposals such as FF and the introduction of advanced decision aids to support ATCo functions. How these proposals could affect the job of the ATCo will also be discussed. Chapter 3 addresses the issue of automation and gives an overview of its benefits and costs. In chapter 4, the concept of mental workload, its measurement and application to ATC will be covered. Chapter 5 reviews available empirical studies on the effects of automation on ATCo performance and mental workload in ATC. The apparatus of the experimental studies conducted and the measurement of dependent variables will be covered in Chapter 6. Chapters 7-9 represent the empirical part of this dissertation. Chapter 7 describes an empirical study that was carried out to investigate

ATCo performance and mental workload under different levels of traffic with and without assistance of a decision aid. The purpose was to study whether automation could compensate for performance decrements brought about by FF and increased traffic. Chapter 8 describes a study investigating the effects of a decision aid with different types of automation feedback and different levels of traffic density on ATCo performance, mental workload, and visual attention. Chapter 9 examines ATCo performance, mental workload, and visual attention under conditions when the automation was reliable, unreliable and when ATCos were performing manually. Finally, chapter 10 discusses the findings of the experiments as they apply to a model of performance and workload in ATC. Implications for a better understanding of human-automation interaction and the design of a safe ATC system are derived.

2. The air traffic control system

2.1 The challenge of modernizing the ATC system

Commercial air travel is increasing at a rapid rate both in the US and throughout the world, putting tremendous pressure on the ATC system. By some estimates, air travel in the US will increase up to 100% over the next decade (Aviation Week & Space Technology, 1998). Flight delays in the air and on the ground caused by the insufficient capacity of the outdated ATC system have become very common in recent years. While in the past, runways represented the bottleneck limiting the capacity of the system, unprecedented amounts of traffic have now led to a saturation of the en route airspace as well. The high cost of flight delays, reduced airline profit margins (e.g. resulting from the US Airline Deregulation Act in 1978), as well as passenger inconvenience and dissatisfaction have led to international efforts to increase ATC capacity and efficiency.

Enhancing ATC efficiency and capacity is necessary, but cannot be accepted at the cost of safety. Although the airspace system has an impressive safety record, there is a need to increase safety even further. If traffic continues to grow as predicted and the accident rate (i.e. accidents per number of aircraft) remains the same, the number of accidents will increase. According to one estimate, if the accident rate remains as it is today, in the near future there will be one major commercial airline accident every week in some part of the world (Aviation Week and Space Technology, 1998). The recent call for a five-fold improvement in safety by the White House Commission on Aviation Safety and Security (1997) or the strategic goal of the US Federal Aviation Administration (FAA) of reducing fatal aviation accident rates by 80% by the year 2007 (FAA, 2000) was motivated by the need to avoid such a scenario. Thus, the increase in capacity and efficiency has to be matched with an increase in safety (Perry, 1997; Wickens, Mavor, Parasuraman, & McGee, 1998a; Eurocontrol, 1998). This poses a considerable challenge. The ATC system is already operating at or near its limits. Traffic is reaching a level where ATCos can no longer handle traffic safely. ATCo workload, which is already high in many airspace sectors, may increase unacceptably and be a limiting factor in an attempt to increase capacity. These factors have led to the growing realization that the ATC system cannot remain the way it is today but must change in fundamental ways. Consequently, many new concepts for ATM have been proposed (RTCA, 1995; Eurocontrol, 1998; Wickens et al., 1998a).

2.2 Proposals for modernization

The ATCo's role in the airspace system is to assure the "safe, orderly, and expeditious flow of traffic" (ICAO, 1993) through the airspace. The most important task of the ATCo is to prevent collisions between aircraft, both on the ground and in the air. Under current conditions, a number of procedures and rules assist ATCos to accomplish this. These will now be described briefly. For more detailed treatments of ATC the reader may refer to Nolan (1990) or Luffsey (1990).

Except for aircraft flying under visual flight rules (VFR), typically very small aircraft flown by recreational pilots that are allowed to maneuver freely as long as they stay at certain altitudes, aircraft are managed and controlled by ATC. All aircraft flying under instrument flight rules (IFR) are required to file a flight plan to announce their intended flight path en route to their destination. This is typically done by pilots or airline dispatchers before take-off. The flight plan is then approved by ATC, with or without revisions, and the pilots must follow it. It is entered into the ATC system and distributed to the ATCo in form of a flight strip about 20 minutes before the flight enters an ATCo's sector. If pilots wish to deviate from the intended flight plan (e.g. because of weather or turbulence), they must both inform and get permission from ATC. In addition, pilots usually cannot fly the most direct and fuel-efficient route (i.e. the great circle) to their destination. The airspace is structured by airways and jet routes, like highways in the sky, and flights are assigned to airways (at lower altitudes) and jet routes (at higher altitudes) that take them from their origin to their destination. In the current system, ATC has both authority over and responsibility for the events in the airspace. Together with the requirement to have all deviations from the intended flight plan approved by ATC, the airspace structure limits the areas where potential conflicts can occur to the points where airways and jet routes converge. This makes it feasible for the ATCo to assure safety. However, the rigid structure and rules restrict the pilots in their maneuvering, routing, and scheduling, often not allowing them and the airlines to fly the fastest and most fuel-efficient routes. The system of routes, for example, was designed to accommodate air traffic patterns many years ago (i.e. before the airline deregulation) and has not been updated to account for the change in current route preferences. In addition, ATCos often cannot accommodate pilot requests for deviations from their intended flight paths in favor of more efficient routes because the ATCos are already working at their capacity limit.

Another problem of the current ATC system is congestion on the radio frequencies that ATCos and pilots use to communicate with each other. Because each aircraft is required to make certain routine transmissions, the number of transmissions is directly related to the number of aircraft. With the expected increase in traffic over the next few years, it will not be long before the communication system breaks down. If frequencies are congested, pilots cannot contact ATCos (and vice versa) and have to make several attempts before they can finally communicate. This increases pilot and ATCo workload unnecessarily. Digital controller-pilot data link communication (CPDLC) has been suggested as a solution to this problem. Instead of verbally transmitting routine messages, messages would be transmitted digitally and displayed or even printed on cockpit and ATC displays. Radio frequencies would be reserved for emergency transmissions and transmissions that are relevant to other pilots (e.g. pilot weather and turbulence reports).

The outdated ATC equipment has not kept up with technological advances on the flight deck. Modern technologies such as the flight management systems (FMS) have capabilities (e.g. estimating times of arrival, calculating the most fuel-efficient routes) well beyond the capabilites of technology on the ground. This mismatch in technologies between the air and the ground does not allow pilots and airlines to make use of their expensive and sophisticated on-board equipment as much as they would like in order to save money (e.g. through reducing flight time and fuel consumption). This has caused the airlines, industry, and government to propose the modernization of the airspace system with new ways of conducting ATC and assuring the safety in the airspace. Among the proposals for modernization are the concept of FF and the introduction of automation. FF refers to a new concept of ATM in which pilots will be given the freedom to choose their own heading, altitude, and speed in real time without being restricted by ATC instructions or outdated route structures. While under current ATC procedures, pilots are required to strictly follow the ATCos' instructions, under FF conditions, pilots flying under IFR would be allowed to maneuver freely and possibly deviate from their course without even notifying the controller much like pilots flying under VFR. The RTCA (1995) defined FF as

"a safe and efficient flight operating capability under instrument flight rules (IFR) in which the operators have the freedom to select their path and speed in real time. Air traffic restrictions are only imposed (1) to ensure separation, (2) to preclude exceeding airport capacity, (3) to prevent unauthorized flight through special use airspace, and (4) to ensure safety

of flight. Restrictions are limited in extent and duration to correct the identified problem. Any activity which removes restrictions represents a move toward free flight."

FF relies heavily on automation support both in the cockpit and on the ground. In fact, it would allow the airlines for the first time to make full use of their investment in expensive on-board equipment such as cockpit displays of traffic information (CDTI).

Instead of staying on assigned airways and jet routes, which limit fuel efficiency, aircraft can take shortest-path routes and take advantage of favorable winds or avoid unfavorable winds. The airspace under FF conditions will be less structured. Conflicts are no longer restricted to the points where airways and jetroutes cross, but could occur at any point in a sector. A flight plan will be available to ATCos, but not as a basis for separation, only for the management of the traffic flow. In the maturest case of FF, separation authority will fully shift to the cockpit. As a consequence, ATC will become ATM in which the ATCo remains to manage traffic flows and oversee separation. ATC restrictions will only become necessary in the four cases mentioned above. FF provides the user with the flexibility of VFR flights while maintaining the protection of the current system. It was assumed that this could be achieved by the integration of advanced airborne (e.g. Global Positioning System, GPS) and ground-based technologies as well as new procedures to permit the use of optimum routing and tactical separation. Thus, FF is not just a change in procedures; it goes hand in hand with the introduction of new technology and advanced automation, both on the ground and on the flight deck.

A recent report by the US National Research Council (NRC; Wickens et al., 1998a) proposed automation as a means to increase efficiency and reduce controller workload. The rationale was to provide ATCos with automation in order to free resources that the ATCo could use to fulfill user requests (e.g. for direct routes). To date, ATC automation has involved relatively low-level functions associated with data collection and integration (e.g., aircraft data blocks on the radar display, automated hand-offs) and alerts (e.g. minimum safe altitude warning, MSAW, or short-term conflict alerts, STCA). However, automation technology has steadily advanced in complexity and sophistication over time. Recent advances in technology will lead to dramatic changes in the quality of the aids available to ATCos. A new generation of automated tools will assist and could replace certain aspects of the controller's decision-making and planning activities (Parasuraman, Duley, & Smoker, 1998) such as the detection and resolution of conflicts between aircraft or between aircraft and restricted airspace.

The introduction of FF and automation represent a radical change in the way ATCos currently operate and will significantly impact their jobs. The role of the ATCo will change from actively controlling traffic to monitoring separation in a high-density airspace and intervening in potential conflicts only if the pilots fail to resolve them on their own. Hence, the ATCo's role is to act as a back-up to the system in case something goes wrong. This could lead to a much higher monitoring and scanning load for the ATCo and reduced conflict detection performance because controllers constantly have to reevaluate the situation for aircraft that might have changed their course and be in conflict with other aircraft. In addition, ATCos will have to monitor and work the datalink display to exchange information. While in the current system ATCos have both authority over and responsibility for the aircraft in their airspace, ATCos under FF will have the responsibility, but not full authority over aircraft. Even though the emphasis of this work is on automation, FF and automation are considered jointly for several reasons. First, FF and automation both can lead to a transfer of some aspects of decision-making authority from the ATCo to another agent, either pilots or automation, putting the ATCo in a monitoring role. Therefore, the consequences of FF and automation for the ATCo are similar. Second, while automation could be introduced into the ATC system on its own, FF will not be feasible without automation. FF is heavily based on the use of automation, both on the ground and in the air. Together, they will create a highly efficient and dense airspace. Third, it is important to study automation in the context it will be used because its implications (e.g. reliability) could be different under FF than under current conditions. How automation affects the en route ATCo as a crucial part of the airspace system and its performance under FF conditions is the topic of this work.

3. Automation

3.1 Definition

Before discussing the concept of automation, the term should be clearly defined. While sometimes the term automation is used for mere additions of technology (e.g. typing on a computer keyboard instead of typing on a typewriter), Parasuraman and Riley (1997) defined automation as

"any device or system that accomplishes (partially or fully) a function that was previously carried out (partially or fully) by a human operator".

This definition emphasizes the replacement of a human function by a machine function. Typing on a typewriter versus a computer keyboard requires the same human function (i.e. typing) and does not constitute automation according to this definition. However, using the spell checker of a word-processing software does constitute automation. The human function of searching for incorrectly spelled words and deciding on the correct spelling is replaced by the spell checking function of the program.

3.2 Models of automation

Automation is not an all-or-nothing concept. Human functions can be automated at different levels. Sheridan (1987) proposed 10 levels of automation between full manual control to full automation. At the lowest level of automation, no assistance to the human is provided at all by a computer or any other machine. At the highest level, the computer decides everything and acts autonomously, ignoring the human. Table 3.1 shows the levels of human and machine control that lie between these two extremes.

For example, at a low level of automation, a spell checker could assist the writer in searching for words that are spelled incorrectly, and highlight the words. The writer would then have to decide on the correct spelling of the word perhaps by using a dictionary and make the correction manually. At a moderate level of automation, the spell checker could search for incorrectly spelled words and suggest the correct way of spelling. The writer would then have to decide if he or she wants to accept the suggested spelling (level 5). At the highest level of automation, the spell checker replaces the incorrect spelling with the correct spelling without even notifying the writer that incorrectly spelled words were replaced.

Table 3.1: Levels of automation (Sheridan and Verplank, 1978; Sheridan, 1992)

THE COMPUTER…		
HIGH	10.	decides everything, acts autonomously, ignoring the human.
	9.	informs the human only if it, the computer, decides to
	8.	informs the human only if asked, or
	7.	executes automatically, then necessarily informs the human, and
	6.	allows the human a restricted time to veto before automatic execution, or
	5.	executes that suggestion if the human approves, or
	4.	suggests one alternative
	3.	narrows the selection down to a few, or
	2.	offers a complete set of decision/action alternatives, or
Low	1.	offers no assistance: human must take all decisions and actions.

However, automation cannot only occur at different levels. It can also support different stages of information processing and decision-making from perception and information acquisition to action implementation. Parasuraman, Sheridan, and Wickens (2000) expanded the original one-dimensional concept of levels of automation and suggested that the 10 levels originally proposed by Sheridan and Verplank (1978) best characterize automation for decision-making and action selection, but that automation can be applied to other stages of information-processing as well. The proposed types of automation are automation in the process of (1) information acquisition (e.g. through attention guidance), (2) information analysis (e.g. through inference), (3) decision selection, and (4) action implementation. Figure 3.1 shows the resulting model of levels and types of automation that corresponds roughly to the stages of human information-processing including sensation, perception, response selection, and response execution. Automation of types 2 and 3 is typically characterized as decision-aiding (Wickens & Hollands, 2000).

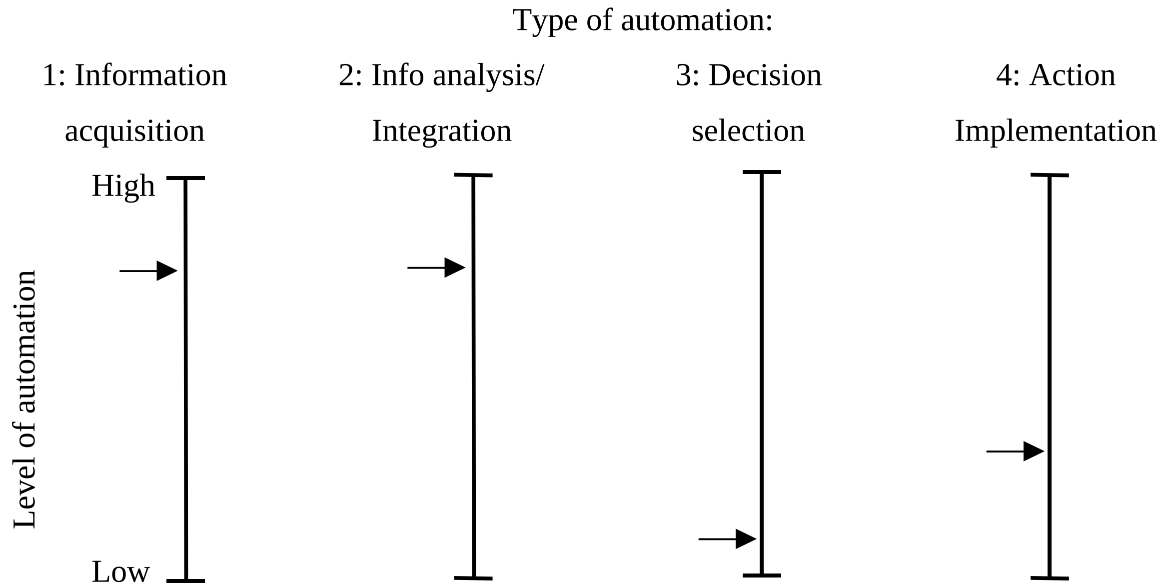


Figure 3.1: Types and levels of automation

The concept of levels and types of automation raises the design issue how to choose the appropriate level and type of automation for a particular application. First, a different level of automation can be chosen for each type of automation (e.g. high level automation for information acquisition, low level for information analysis). However, regardless of the type or level of automation, the associated human performance consequences should be evaluated before implementing the automation. The human performance consequences should represent the primary evaluative criteria. In addition, secondary evaluative criteria have to be considered. These could be issues such as the reliability of automation, cost and risks of action outcomes, ease of system integration, implementation cost, or liability issues. The assessment of primary and secondary evaluative criteria are part of an iterative design process until an appropriate solution is found (Parasuraman et al., 2000; Parasuraman, 2000).

For example, high levels of automation for information acquisition might be acceptable given the high reliability of current automation technologies. On the other hand, high-level automation, particularly of decision making and action selection, can lead to adverse human performance effects discussed further below (Parasuraman & Riley, 1997). For example, automation beyond level 6 on the decision scale would mean that a particular decision is automatically made by the computer, with the human operator being informed only subsequently. This might be appropriate for low-risk functions, such as automated hand-offs between airspace sectors. It may also be necessary when decisions need to be made faster than the human is capable of, for example when certain emergency events occur in a nuclear power plant (Moray, 1986) or when there is an engine malfunction prior to the critical aircraft speed for take-off (Inagaki, 1999).

3.3 Human performance consequences of automation: Costs and benefits

Automation has many benefits. It can spare humans from carrying out dangerous functions such as the handling of hazardous materials like nuclear waste or the recovery of material from the ocean floor after an aircraft accident. Automation can also carry out functions that are impossible for humans to perform in a timely manner (e.g. the decision to continue or abort the takeoff of an aircraft after an engine failure; Inagaki, 1999) or impossible to perform at all due to physical disabilities (e.g. reading for the blind). Automation can take over functions that the human is capable of carrying out, but are burdensome, fatiguing or error-prone (e.g. complex mathematical calculations). Automation does not necessarily have to fully take over human work; it can also aid the human in functions that are vulnerable such as some working memory processes (Wickens, Gordon & Liu, 1998b). As Wickens (2000) points out, even if the automation does not have immediate benefits for performance, it could reduce workload and therefore be beneficial.

In the aviation system, automation has also had many beneficial effects on workload and safety. The ground-proximity warning system (GPWS) is a good example of the beneficial effects of automation on safety. It warns pilots when aircraft come in close proximity to the ground (e.g. close to mountains). Terrain strike accidents have been drastically reduced since GPWS became mandatory in 1974 (Wiener & Curry, 1980). The capability for automated hand-offs has reduced ATCo workload and freed resources for other, more important tasks. Automation can also bring large economic benefits, for example through aircraft fuel conservation, reduced travel times, and a reduction in crew size from three to two persons in most automated cockpits. However, these benefits have not come without a cost.

As suggested (Parasuraman et al., 2000; Parasuraman, 2000), human performance consequences should be the primary evaluative criterion for designing an automated system. This raises the issue of what some of the human performance consequences of automation are, both positive and negative. In the cockpit and other human-machine systems, advances in technology (e.g. microprocessor technology) make automation a reasonable alternative to manual control. To automate functions because it is technologically feasible is considered a technology-centered approach. To automate functions in order to support the human while leaving the human operator to perform functions that humans are good at is considered a human-centered approach (Billings, 1997).

Wiener et al. (1980) were among the first to point out disadvantages of a technology-centered approach to automation in the aircraft cockpit and questioned that automation could reduce human error by removing the human operator. In addition to the many psychosocial implications of automation (e.g. job satisfaction, operator selection, training), several automation-related problems have occurred. With the automation of a manual control task, the human has become a monitor of the system rather than an active member ("supervisory control", Sheridan, 1992). Automating higher-order cognitive processes (e.g. the calculation of fuel supply) also requires the operator to oversee the proper functioning of the automation. Effects similar to the vigilance decrement can be expected (Mackworth, 1948, 1950; Teichner, 1974; Parasuraman, 1979). Humans have difficulties sustaining attention over long periods of time to oversee the automation. The change from a manual controller to a supervisor of a system also has implications for the retention of the manual skill. More than likely the skill will decline if it is not used. Finally, Wiener et al. (1980) discuss the issues of alerting and warning systems such as frequent false alarms that lead to ignoring the warning.

In another seminal paper, Bainbridge (1983) points out the "ironies of automation" in process control. Oftentimes, the human is considered unreliable by the designer and therefore eliminated from the system. This leads to the first irony that the designer is also human and therefore can be unreliable; i.e. make mistakes in the design of the automated system. In fact, designer errors can be a major source of many operating problems. The second irony is that the designer who tries to eliminate the human operator still leaves the human in the system with an arbitrary collection of tasks that the designer cannot automate (yet). Indeed, the human seems to play a rather important role in highly automated systems. He or she is expected to (a) monitor the automation and (b) intervene in case it does not work as expected. It is incongruous that automation is put into a system because it is superior to the human operator, but that the human operator remains to oversee and diagnose the proper functioning of the automation. Problematic is also that after monitoring the system for a long time, the manual skills of the operator decline and intervention might be difficult. Still, human operators are given tasks that can only be performed effectively if the operators are manually controlling the system.

The following section will review some of the automation-related human performance consequences in more detail.

Excessive trust and misuse of automation. As increasingly more automation is introduced in the cockpit and other domains, the human remains to oversee and supervise the automation. However, human monitoring of automated systems is often poor (Parasuraman, Molloy, & Singh, 1993; Parasuraman, Mouloua, Molloy, & Hilburn, 1996). Human operators are able to detect system malfunctions fairly well when manually operating a system or when monitoring an automated system is the only task. However, when a system is automated and other tasks have to be accomplished, detection of system malfunctions deteriorates dramatically over time. This inefficiency in human operator monitoring of automation is referred to as complacency (Billings, Lauber, Funkhouser, Lyman, & Huff, 1976). It is interesting that even very unreliable automation (e.g. reliability of 25%) can cause reduced monitoring performance under automated compared to manual conditions (May, Molloy, & Parasuraman, 1993).

Several explanations for automation complacency have been put forward. Parasuraman et al. (1993) proposed that complacency is due to the sub-optimal sharing of attentional resources. This is reflected in reduced attention allocation to the automated system compared to manual performance due to overreliance and high trust in the automation. The view that automation-related complacency reflects a sub-optimal sharing of resources in a multi-task environment is consistent with the absence of complacency in a single task situation in a basic flight (Parasuraman et al., 1993) and an ATC (Thackray & Touchstone, 1989) task. Complacency also does not appear to be a result of purely visual factors or insufficient visual sampling of the automated task. Locating the monitoring task in the center of the monitor and in central as opposed to peripheral vision did not reduce complacency (Singh, Molloy, & Parasuraman, 1997). Moreover, spatial superimposition of the automated and primary manual tasks did also not reduce complacency (Duley, Westerman, Molloy, & Parasuraman, 1997). When eye fixations were forced on the automation monitoring task by superimposing it on the primary tracking task in a simulation of multiple flight tasks, primary task performance was preserved (indicating that the participants must have fixated in that area), but complacency was not reduced. Even though performance in the primary task indicates that participants fixated on the monitoring (and tracking) task, they might not have allocated any attentional resources to the monitoring task. This raises the issue of the dissociation between eye movements and attention (Palmer, 1998). While eye movements require a shift of attention prior to their execution ("mandatory shift hypothesis), shifts in attention do not require eye movements (Hoffman, 1998; Pashler, 1998). Humans can shift their attention while maintaining fixation.

Nevertheless, Moray (2000) proposed that the optimal monitoring or sampling (i.e. eye fixation) of a system depends on the frequency of the occurrence of signals in the system. According to Moray, even if the visual sampling of the automated system is optimal or "eutactic" (i.e. calibrated to the frequency of the occurrence of signals in the system), system malfunctions will inevitably be missed because of the unpredictability of system failures and the presumed single-channel nature of human attention (a view that contrasts sharply with other theories that maintain that attention can be divided (Parasuraman, 1998; Wickens, 1984)). Moray (2000) postulated that an observer could only be called complacent if a source is sampled less frequently than would be necessary by the occurrence of signals in the system (i.e. based on a model of optimal sampling). Complacency can also not be determined by detection, but only by sampling. According to Moray (2000), an operator should not be called complacent (which he associates with "blaming" the operator) if he or she samples according to an optimal model, but nevertheless misses a signal because of the unpredictability of the occurrence of the signal. An observer would be called "skeptical" if he or she sampled more often than necessary according to the frequency of signal occurrences. A problem with this theory arises from the difficulty in establishing an optimal sampling rate in complex human-automation environments. Therefore, it might not be possible to empirically validate Moray's (2000) model.

Finally, Farrell and Lewandowsky (2000) proposed that complacency reflects a weakening of the memory trace of the automated function over time. They explained this in terms of the well established generation effect in the memory literature. Stronger memory traces are induced by cognitive processes that are actively generated than by processes that are simply observed. The advantage of adaptive over static automation is also consistent with the hypothesis that complacency reflects a weakening of the memory trace of the automated function over time.

Automation is typically introduced into systems to reduce biases in decision-making, for example the bias of an ATCo to attend to only a limited number of cues with the potential consequence to miss a conflict. However, while the introduction of automation reduces one type of bias in decision-making, it introduces another, the "automation bias" (Mosier, Skitka, & Korte, 1994; Mosier & Skitka, 1996; Mosier, Skitka, Heers, & Burdick, 1998; Skitka, Mosier, & Burdick, 1999). The automation bias refers to errors resulting from the use of automation cues as a replacement for continuous information seeking and processing (Mosier et al., 1998). Decision aids do not present just another cue for decision-making. Often, the automation cues are more salient and considered superior to conventional information. Sometimes, the cues originally used for diagnosis are fully replaced by the automation cue. As trust in an automation aid increases, humans rely on the automation without checking it. Sometimes, the "raw" data on which the automated decision is based might not even be available for cross-checking of the automation anymore. This heuristic of relying on the automation saves cognitive capacities and is successful most of the time. However, when the automation fails, decision-making breaks down. The automation bias is very similar to the complacency concept, particularly when omission errors occur. Omission errors arise when decision-makers do not take appropriate action (e.g. fail to detect a conflict) because the automated decision aid does not inform them of an imminent problem or situation. Commission errors occur when decision makers inappropriately follow automated information or recommendations even though there is information in the environment that is inconsistent with the automation cue. Mosier et al. (1998) found that experience does not make operators less prone to automation bias. In fact, in one of her studies the more experienced pilots were more likely to rely on automated cues only.

Reduced trust and automation disuse. While complacency is a problem of excessive trust in the automation, problems can also arise when operators trust the automation too little. After a train accident near Baltimore in 1987, for example, it was found that the alarm in the train cab had been taped over. Even after an inspection had been announced, investigators found other trains in which the alarm had been taped over (Parasuraman & Riley, 1997). Disabling alarms can be a consequence of frequent exposure to false alarms. Operators tend to ignore or even turn off alarms that have "cried wolf" too often (Sorkin, 1988). In the case of a true emergency, the alarm either is ignored or remains silent because the operator has learned not to take it seriously.

Ideally, alarms should be designed to maximize the likelihood of detection and minimize the likelihood of false alarms. However, based on Bayesian analysis Parasuraman, Hancock, and Olofinboba (1997) showed that this might not be enough. Even though systems have high detection rates and low false alarm rates, the posterior probability for a true critical event (e.g. a midair collision between aircraft or rear-end collision of cars) can be very low if the base rate for the critical event is very low. Consequently, only a small proportion of alarms represents true critical events. In fact, good operators (e.g. experts) are less likely to create situations in which true critical events occur and thereby can reduce the base rate of a critical event even further. Therefore, good operators could further increase the likelihood of false alarms by reducing the base rate of a target event such as a collision (Meyer and Bitan, in press). Consequently, good operators might distrust the automation even more than less experienced ones and not take advantage of it in the rare occasion of a true problem. The concept of likelihood alarms (Sorkin, Kantowitz, & Kantowitz, 1988) might be a solution to the problem. Instead of providing two alarm states (i.e. collision versus no collision), likelihood alarms indicate the level of probability that a given alarm represents in fact a dangerous condition (e.g. from very unlikely to highly likely).

Manual skill degradation. That knowledge or skills deteriorate when they are not used for extended periods of time is well established in the literature (Arthur, Bennett, Stanush, & McNelly, 1998). In human-interaction with automated systems, skill degradation can result from the infrequent opportunity to practice or perform a learned skill (e.g. because the automation is carrying out the function that requires a particular skill). Typically, the longer the period of nonuse, the greater the decay. The degradation of skill only becomes apparent when the automation fails or becomes unavailable. In case of a sudden failure of the automated system operators have to rely on manual skills that they have not had to use in a long time. Time pressure, stress, and surprise might further aggravate the situation.

A decline in the ability to manually control aircraft was observed in pilots transitioning from co-pilot positions on modern automated aircraft to pilot-in-command positions on less automated aircraft (Wiener & Curry, 1980). As a consequence, some airlines suggested that pilots should frequently resume manual control as they are approaching this transition in order to regain their skill in manually controlling the aircraft (Wiener & Curry, 1980; Bainbridge, 1983;

Billings, 1997). It is typically assumed that higher degrees of overlearning (i.e. repeated use of a skill) are associated with lower degrees of skill degradation (Arthur et al., 1998). However, airline policies regarding the use of automation differ. Some air carriers require their pilots to always make full use of the automation.

Skill degradation is not restricted to psychomotor skills, but can also be found in more complex cognitive processes such as problem-solving or decision-making (e.g. the navigation based on charts that is frequently conducted by the flight management system now). In fact, as Arthur et al. (1998) concluded from their meta-analysis on the moderators of skill decay and retention, cognitive tasks are much more susceptible to skill decay than physical tasks. Comparing standardized units, the decay of cognitive skills was about twice the size of the decay of physical skills. This will become of particular importance when increasingly more automation of higher-order cognitive skills is introduced into many systems. High-level decision automation could result in a degradation of cognitive skills because of their disuse due to automation.

In the ATC environment, ATCos are almost exclusively trained in full radar environments, but expected to revert to procedural control (i.e. ATC based on their mental picture of air traffic, communication, and flight strips) in case of a radar failure. Fortunately, there is back-up equipment and full radar failures have become rare. The introduction of decision-making automation could degrade skills such as decision-making in the detection and resolution of conflicts. In the future, the problem of skill degradation will most likely be aggravated by the fact that younger operators of human-machine systems transition to automated systems much sooner than their older colleagues did and therefore lack the level of skill and long-time experience with manual operations that their senior colleagues can fall back on (Bainbridge, 1983). This applies both to manual control and higher-order cognitive skills (e.g. decision-making).

To counteract manual skill degradation, manual skills are regularly trained in simulators in aviation or process control systems. For the future, the concept of adaptive automation has shown promise to reduce the problem. In contrast to conventional automation that statically allocates a function either to the human or the machine, adaptive automation allows for the flexible allocation of functions to humans or machines depending on the environmental situation, operator state, or models of these (Parasuraman, Bahri, Deaton, Morrison, & Barnes, 1992; Rouse, 1988).

Further, the disuse and the associated degradation of skills could lead to a decrease in operator self-confidence to manually carry out that skill. Therefore, it is likely that trust in automation will be greater than self-confidence and as a consequence, operators will use automation more frequently, perhaps even in situation that do not warrant the use of automation (Mosier et al., 1994).

Out-of-the-loop phenomenon. Wickens (1992; 1994) describes a complex of symptoms induced by poorly designed automation and calls it the "out-of-the-loop unfamiliarity (OOTLUF)" phenomenon. First, operators have difficulties to detect automation failures. A complacent operator is less likely to monitor the automation therefore loosing awareness of the elements and dynamics of the system and its current state. If a failure is detected, the human operator needs a rather long time to intervene because he or she has to first regain awareness of the system state. Operators have a better mental model or awareness of the system state when they are actively involved in creating the state of the system than when they are passively monitoring the actions of another agent or automation (Endsley, 1996; Endsley & Kiris, 1995). Situation awareness (SA) refers to the operator's awareness of (1) the elements in a system, (2) their relationship to each other, and (3) the projection of their future state. All three elements are necessary for effective decision-making in dynamic environments (Endsley, 1996). Mode errors are an expression of reduced situation awareness (Sarter & Woods, 1994, 1995a). Automation on modern flight decks has reached such a level of autonomy that modes of the flight management system can change without the pilot's awareness. In an ATC simulation of FF conditions in which passive monitoring was compared to active control it took controllers longer to detect conflicts when they were passively monitoring pilot self-separations than when they were actively controlling traffic similar to current conditions (Metzger & Parasuraman, in press). The problem of manual skill degradation discussed in the previous section can also contribute to the fact that it takes longer to intervene from a monitoring than a passive role.

Mental workload. While many of the costs associated with automation have been on performance, the following paragraph focuses on the effects of automation on mental workload. One of the problems associated with mental workload in automated systems is the unbalanced distribution of mental workload. Automation can reduce workload in phases of work that already require little workload and increase workload even further in phases that already impose a high demand on the operator ("clumsy automation", Wiener, 1989). A typical example is automation in modern cockpits. Through the autopilot and flight management system, pilot workload has been reduced considerably. However, while workload is reduced significantly during cruise flight - a phase in flight that already imposes relatively little demand - workload can be significantly increased during take-off or landing. For example, if the crew is informed of a last-minute runway change during the final approach, the FMS has to be reprogrammed in a relatively short amount of time causing considerable workload for the crew during a phase of flight that already imposes a relatively high demand. In this case, an automation aid implemented with the goal to reduce workload becomes a burden and actually increases workload in an unforeseen situation.

As mentioned before, automation also leads to the situation that instead of manually performing a task, the operator is left to monitor or supervise the automation over extended periods of time ("supervisory control"; Sheridan, 1992). This requires considerable sustained attention or vigilance. For a long time, vigilance tasks were associated with under-arousal and very low mental workload. The vigilance decrement typically observed in these tasks (e.g. Parasuraman, 1979) was explained by the lack of stimulation that is necessary to support alertness (arousal or activation model of the vigilance decrement; Frankmann & Adams, 1962). Recent studies (Warm, Dember, & Hancock, 1996), however, have shown that vigilance tasks impose a rather high level of mental workload characterized by high subjective ratings on the frustration and mental demand sub-scales on the National Aeronautics and Space Administration Task Load Index (NASA-TLX; NASA Ames Research Center, 1986; Hart & Staveland, 1988). These findings are incompatible with the arousal model of the vigilance decrement. Rather, it was suggested that the vigilance decrement could be explained with a resource model. The depletion of information-processing resources during the course of a vigilance task is due to the constant need for the operator to make a decision regarding the presence of a signal or non-signal in the environment. This can be associated with considerable mental workload. Decision-making can be facilitated and mental workload can be reduced if careful consideration is given to system design (e.g. high signal salience, low background event rate, avoidance of noise, reduced spatial uncertainty).

Most of the research on the costs and benefits addressed the automation of relatively low-level cognitive functions (e.g. monitoring or tracking) in the cockpit. It remains to be studied how mental workload is affected by the automation of complex decision-making processes and other higher-order functions. One speculation is that operator mental workload would not be reduced as much in higher-order functions as in lower-order functions, if it is reduced at all. The operator's evaluation of the output of the automated decision-making process might require similar levels of mental workload as if the operator made the decision by him- or herself. The present work will help to gain an understanding of the effects of the automation of higher-order cognitive processes on mental workload in ATC. Eventually, this will help in the early identification and avoidance of problems that were encountered in other domains such as the cockpit or maritime automation (Lee & Sanquist, 1996).

As noted previously, human factors research on cockpit automation has shown that automation can have subtle and sometimes unanticipated effects on human performance (Parasuraman & Riley, 1997; Wiener, 1989). A recent FAA-sponsored report on crew-flight deck system interfaces has documented several incidents and accidents that have resulted from difficulties flight crews have interacting with cockpit automation (FAA, 1996). The report makes a number of recommendations in the areas of design, research, training, and regulatory standards. Similar effects of automation on human performance have been noted in other domains where advanced automation has been introduced, including medical systems, ground transportation, process control, and maritime systems (Parasuraman & Mouloua, 1996).

3.4 Automated systems in ATC

ATC automation has not been of the scale and complexity of cockpit automation. Controllers still only have few automation tools available and the tools available provide assistance with mostly lower-order cognitive functions. Automated data integration on the radar display is one example for the automation of a lower-order cognitive function (Hopkin, 1999). While primary radar only provides the lateral and longitudinal position of aircraft, secondary radar associates a label or data block to each aircraft target including aircraft identity, altitude, speed, and aircraft type. In addition, routine actions such as handing-off aircraft from one controller to the next have been facilitated by automation. This reduces the requirement for coordination between ATCos and frees ATCo resources for other, more important tasks or to accommodate user requests. Short-term conflict alerts (STCA) warn controllers of impending conflicts within the next two minutes based on current aircraft altitude, speed, and heading information. They do not take intended flight paths as indicated on the flight strips into account for conflict prediction. Whenever a set threshold is crossed (e.g. two minutes to collision), the ATCo is alerted. Even if one of the aircraft is expected to change its flight path (e.g. based on the flight plan) or one of the two aircraft involved is flying under VFR the controller is alerted resulting in frequent false alarms. Another type of alert is the minimum safe altitude warning (MSAW) that alerts the controller of aircraft flying dangerously low in order to avoid controlled flights into terrain. Most of these automation tools support or replace relatively low-level cognitive functions (e.g. monitoring for low altitude flights). Whenever a set threshold is crossed, an alarm goes off. Pilot intentions are not taken into account or projections into the future are not made. Aids such as the STCA or MSAW support the operator's information-processing in the first stage of information acquisition (see figure 3.1) by capturing and guiding the ATCo's attention to the relevant information. Nevertheless, these automation tools have yielded several benefits (e.g. increased safety) and freed up controller resources and time to concentrate on other important task such as conflict detection or to respond to user requests. In the future, a new generation of automation will be able to provide assistance with higher-order cognitive processes such as decision-making (Parasuraman, Duley, & Smoker, 1998; Wickens et al., 1998a; Billings, 1997). A few such tools have been studied and are already implemented. These tools and their effects on ATCo performance and mental workload will be described below.

As part of the FAA Free Flight Phase (FFP) 1 and 2 programs (Human Solutions, 1999), ATCos will be provided with several automated decision aids to make FF feasible. En route ATCos will be given access to tools that assists them in making decisions on where and when in the future aircraft will be in conflict and how to resolve the conflicts. These tools are already being field tested and scheduled for deployment to en route centers. The implementation of the User Request Evaluation Tool (URET) is among the FAA's top priorities. URET is a conflict detection and resolution aid that assists controllers in detecting potential conflicts between aircraft or between aircraft and restricted airspace and suggests conflict resolutions. URET continuously checks current flight plan trajectories for strategic conflicts up to 20 minutes into the future. Tools like URET include highly sophisticated algorithms that analyze and integrate data from different sources (e.g. radar data, flight plans) considering numerous additional parameters (e.g. climb rates for different aircraft types, wind and weather models, etc.). They go well beyond the capability of simple alerts such as the STCA.

Such decision aids are expected to be especially useful in the unstructured airspace under FF conditions. URET also allows controllers to evaluate pilot requests or potential conflict resolutions for conflicts in the form of a "what if" function before actually giving a clearance. It monitors conformance of flight trajectories and provides access to electronic flight data eventually replacing paper flight progress strips (Brudnicki & McFarland, 1997; Human Solutions, 1999). Similar tools such as Direct-to (Erzberger, McNally, Foster, Chiu, & Stassart, 1999) or the conflict prediction and trial planning (CPTP) tool (McNally, Bach, & Chan, 1998) are also being discussed and considered for implementation.

Conflict detection aids like URET, CPTP, or Direct-to provide decision aiding at the stage of information analysis and integration or decision selection (to the extent that they recommend a course of action). Conflict detection aids integrate a subset of information from several different sources (e.g. flight plans, radar track, weather information), project aircraft status into the future, and assess if a conflict is to be expected within a specific period of time. This goes beyond the stage of information acquisition in which specific information is highlighted or attention is cued, for example when an alarm goes off if a specific threshold is crossed such as in the STCA or MSAW. In those cases, there is no projection into the future or inference from the observed information. Conflict detection aids make a decision based on an inference on the current state of the world (Wickens, 2000). It is expected that conflict detection aids will guide selective attention and reduce biases in controller decision-making by assisting controllers in attending to the appropriate information. However, this needs to be evaluated empirically.

As the ATC system matures, increasingly higher-order cognitive functions are automated. This process ranges from the host system of the 1980s that provided data acquisition for the ATCo to the more sophisticated systems that detect and resolve conflicts. While none of the tools under development implement actions automatically (yet), it is conceivable that in the future actions might be implemented automatically by a decision aid (e.g., an automated conflict resolution could be automatically uplinked into the cockpit).

3.5 Conclusion

While automation has provided many benefits, it has not always come without a cost. Often, the introduction of automation into a system was associated with unanticipated human performance consequences. Therefore, it is important to assess the effects of a proposed system on human performance before the system is built and implemented in high-risk environments. A new system should at least be safety-neutral, preferably safety-enhancing, and never compromise safety. The modernization of the ATC system cannot occur at the expense of safety. On the contrary, to neutralize the increase in traffic, accident rates have to be reduced and safety increased within the next few years. One of the most important aspects of system safety is the human operator in the system. Operators typically perform many system functions and even as increasingly more functions can be performed by highly reliable automation, an additional function of the human operator is to oversee the automation and assure safety. Therefore, it is essential to understand how the proposed changes affect operator performance and mental workload in order not to compromise system safety.

The impending introduction of automation into the ATC system provides a unique opportunity to further our understanding of human interaction with automation and take into account the lessons learned from other domains (e.g. cockpit automation) to design a safe system. Problems encountered with previous attempts to automate other systems can be foreseen and avoided while automation benefits can be exploited. The early involvement of human factors researchers is essential to have an impact on system design.

The purpose of this chapter was to review some of the costs and benefits of automation encountered in the ATC and other domains. The next chapter will focus on the concept of mental workload and performance in the ATC environment.

4. Mental workload and performance

Mental workload and performance in the ATC environment are determined by many factors. The number of aircraft under control is one of the most obvious ones. With increasing air traffic, the workload of the ATCo increases up to a point where the controller can no longer handle traffic safely or efficiently. Until recently, controller workload could be reduced by dividing larger sectors into smaller ones and assigning additional controllers to the newly created smaller sectors. However, sectors cannot be divided perpetually. While increasing the number of sectors reduces the number of aircraft a controller is responsible for, it also increases the need for inter-controller coordination and communication. The reduction in workload due to the smaller number of aircraft is neutralized by the greater need for coordination between controllers. In addition, the smaller the sector size, the less time the controller spends with an aircraft giving him or her less chances to “learn” about an aircraft (e.g. characteristics such as heavy or slow) and to build a picture of the situation. Smaller sector sizes also cause proportionally more work per aircraft because of the shorter time in the sector. A more recent approach is to reduce controller mental workload by reducing the amount of time and effort an ATCo spends per aircraft. This might be achieved with the introduction of FF and automation. However, it needs to be assured that these approaches will not reduce safety.

Mental workload is one of the factors that determines performance and therefore is important to assess. In addition, mental workload assessments provide an index of the operator's spare capacity to perform other tasks. While performance assessment determines the effects of a new design on performance under certain operating conditions, workload assessment allows the designer to determine the operator's spare capacity and predict performance in responding to and recovering from unusual situations (e.g. bad weather) or emergencies. While controllers might perform equally well under design options A and B, their mental workload might be moderate in option A leaving enough spare capacity and very high in option B leaving no spare capacity to respond to additional demands. Based on a workload assessment, design option A would be preferable. Therefore, performance is not a sufficient criterion for the design of a safe system. Operator mental workload needs to be taken into account equally, as it can be the limiting factor in an attempt to increase efficiency, capacity, and safety.

4.1 Theoretical foundations of mental workload

The concept of mental workload evolved from attention research. While the study of selective attention addresses why and when humans selectively attend to one versus other stimuli, the study of workload refers to the intensity of this process. Attention is not an "all-or-nothing" process. It is a matter of degree how intensive the level of attention is that is expended and how much information is processed, especially in a multi-task environment (Kahneman, 1973; Manzey, 1998).

Measuring human capacity and the amount of information humans can process has long been of interest in psychology. The application of information theory (Attneave, 1959; Garner, 1962) tried to provide measures of channel capacity in terms of how much information was processed in a certain time (bits/sec). However, variables such as stimulus-compatibility and stimulus discriminability proved to be more important determinants of performance than the amount of information that was processed (Kahneman, 1973).

Most human-machine systems require the division of attention among concurrent activities. Two types of models can be distinguished to explain the division of attention among concurrent activities: structural and capacity models. Structural models assume that interference between concurrent activities occurs when the same mechanism is required to carry out two incompatible activities at the same time. Broadbent’s (1958) filter theory assumed that the structural mechanism (i.e. the filter) where parallel processing is impossible is located between the stages of sensory registration or storage and perceptual analysis (“early selection”). Deutsch and Deutsch (1963) on the other hand proposed that the filter is located before response selection takes place so that only one action can be executed at a time (“late selection”). Structural models imply that interference between concurrent activities is specific and takes place to the extent that activities call for the same mechanism. In a capacity theory of attention, Moray (1967) suggested that there is a general limit on capacity to perform concurrent tasks and that this limited capacity can be freely allocated among concurrent activities. When an activity demands more capacity than can be supplied, performance degrades. Performance can fail if there is not enough capacity to meet the demands or if the allocation of capacity is sub-optimal or allocation is not allocated to relevant information at all.

Kahneman (1973) introduced a theory of mental effort in which one source of resources is assumed to meet all demands imposed by the processing of information. Models based on the concept of attentional capacity or resources describe mental workload in terms of how much capacity a particular task requires in order to complete it. Mental workload is the ratio of capacity available to capacity required to complete a task. Resource models assume that certain tasks can be performed concurrently and information is processed in parallel. Models of mental workload differ in the number of resource pools they assume. Kahneman (1973) assumed a single pool of resources. All tasks, (e.g. visual or auditory, psychomotor or memory tasks) compete for the same resources and physiological measures of activation can be used to assess the use of resources or mental effort.

Wickens (1980; 1984) expanded the capacity model by assuming separate pools of resources for different stages and modalities of information processing. His model divides information processing into three dimensions: (1) stages of information processing (perceptual/cognitive and response), (2) codes of processing (verbal and spatial), and (3) input and output modalities (visual and auditory for input, speech and manual for output). Tasks interfere with each other to the extent that they share or compete for the same resources. E.g. a controller could communicate and search the radar for a conflict without interference as one task uses auditory, the other visual resources.

While some empirical evidence supports the validity of resource theory (e.g. Isreal, Wickens, Chesney, & Donchin, 1980), the theory has also been criticized (e.g. Navon, 1984; Neumann, 1985, 1996). It has been criticized that the number of resource pools could be further divided until they match any empirical data. Others have said that empirical data does not require the assumption of resources, but that interference can be explained by an outcome conflict.

Although there is no single agreed upon definition of mental workload, O'Donnell and Eggemeier (1986) define mental workload as

"*the portion of the operator's limited capacity actually required to perform a particular task. The objective of workload measurement is to specify the amount of expended capacity.*"

Therefore, operator workload reflects the level of demand for resources imposed by a certain task. Workload is an intervening construct that reflects the relationship between the demands of the environment imposed on the human operator and the capability of the operator to meet those demands (Parasuraman & Hancock, 2001). However, the definition makes it clear that there are individual differences in workload because operators can have different capacities or a task might require different amounts of resources depending on the operator. Novices need more attentional resources to perform a task than experts do. While task performance is automatic for experts, novices rely on effortful rather than automatic information processing (Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977). Effortful processing is more susceptible to interference than automatic processing.

In addition to the resource-limited information processing, information can be data-limited (Norman & Bobrow, 1975). While under resource-limited information processing an increase in effort can lead to better performance, this is not the case for data-limited processing. The allocation of additional resources does not improve performance when processing is data-limited. For example, if an operator is required to detect a very dim signal on a noisy radarscope, the limits of the sensory system and the quality of the data prevent the operator from improving his or her performance. No matter how hard the operator tries, performance will not improve. The only way to improve performance is to improve the quality of the data or the operator's sensory system, for example after resting (Kramer, 1991).

4.2 Mental workload and performance in ATC

4.2.1 Evidence from accidents and incidents

It is a common belief that ATC is a very busy, stressful job with constant high ATCo workload and that the higher the workload the higher the likelihood for incidents or accidents. This might not be true. While some researchers have found an increase in operational errors under high traffic load (Morrison and Wright, 1989), others have also found an increase under low to moderate traffic loads (Redding, 1992; Stager, Hameluck, & Jubis, 1989). Fowler (1980) noted that most controllers perform well under high traffic, but that errors tend to occur once traffic slows down. This suggests that the change in workload might be related to the occurrence of errors.

In an analysis of incidents in US air route traffic control centers, Schroeder and Nye (1993) studied the relationship between severity (i.e. aircraft proximity in the horizontal and vertical dimension) of operational errors and mental workload as indexed by the number of aircraft and ratings of sector complexity. Neither the number of aircraft in a sector nor sector complexity were related to the severity of operational errors. Different levels of error severity were distributed equally across all levels of complexity.

The authors also studied the contributing factors to fifteen major operational errors, seven of them classified as near midair collisions. They found major operational errors under all levels of workload. In another analysis of incident reports, Rodgers, Mogford, and Strauch (2000) found more frequent and more severe operational errors (i.e. a smaller separation remained, especially in the horizontal dimension) when controllers were unaware of the developing situation than when they were aware, but did not resolve the situation appropriately.

4.2.2 Model of mental workload in air traffic control

These inconclusive findings indicate that the relationship between ATCo performance and workload is not a simple one. Figure 4.1 displays a model on the relationship between taskload or workload drivers and performance (Wickens, Mavor, & McGee, 1997) that could elucidate the relationship between workload and operational errors. Central to the model is the distinction between workload drivers or taskload and workload. In addition, strategies is included to explain operator and system performance. The relationship between workload drivers and controller workload is mediated by the strategies that the controller chooses. High traffic load in a sector leads to high workload, but also to the choice of strategies (e.g. task shedding) that keep workload at an acceptable level. Examples for strategies include prioritizing of important tasks or shedding of less important tasks. Inappropriate levels of workload (i.e. excessive overload and underload) can degrade controller performance and lead to suboptimal system performance. The following sections discuss workload drivers and strategies in more detail.

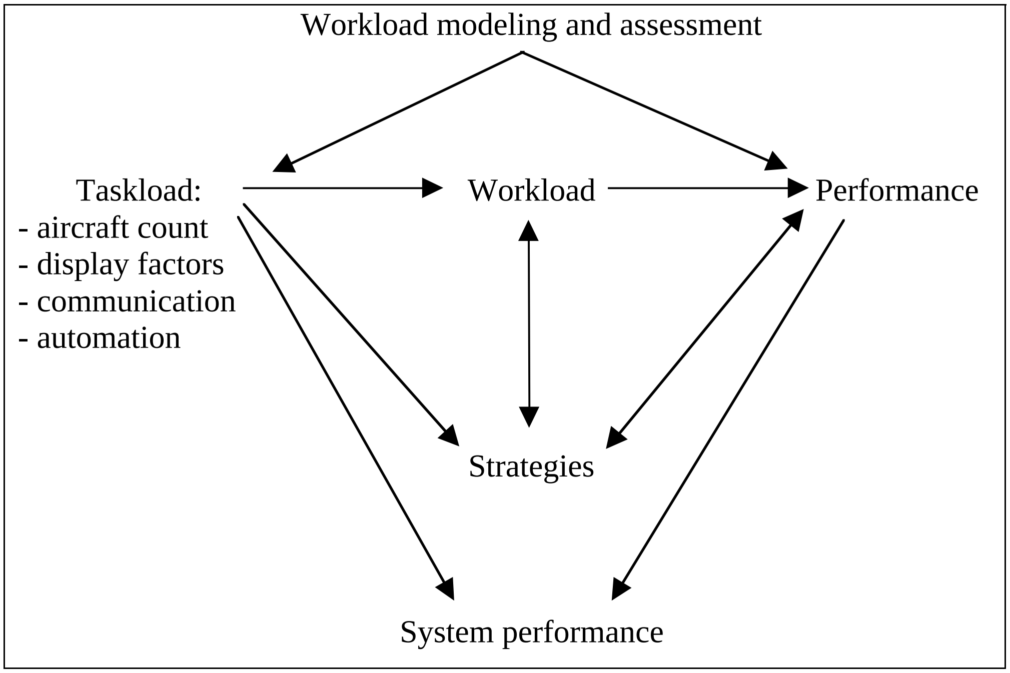


Figure 4.1: Model of mental workload (from Wickens et al., 1997)

4.2.2.1 Workload drivers.

Taskload or workload drivers are factors in the ATC environment that affect controller workload. Among them are airspace characteristics, displays, communication, and automation. It should be noted that workload is not only influenced by the magnitude of workload drivers, but also by the rate or direction of change (Huey & Wickens, 1993). A situation of high workload may be experienced differently by controllers when it presents itself suddenly than when it develops slowly. It may also be experienced differently when high workload is proceeded by low workload than when low workload is proceeded by high workload.

Airspace characteristics. For a long time, the relationship between airspace characteristics and mental workload has been investigated with the goal to predict controller mental workload from taskload. The simplest models study how the number of aircraft affects controller workload. Even though the number of aircraft captures a big portion of the variance in controller workload, other factors contribute to controller mental workload.

One of the first studies on workload in ATC was conducted by Arad (1964). He studied the effects of airspace characteristics and workload in order to determine sector design and staffing and distinguished between three different types of factors that affect controller workload:

(1) routine load (e.g. the number of aircraft under control, the number of terminal area hand-offs that have to be scheduled and sequenced over a certain fix, or the time an aircraft spends in a sector), (2) airspace load (e.g. average airspeed in a sector, average aircraft separation, or size of airspace), and (3) background load.

Kalsbeek (1971) attempted to quantify controller workload in order to establish limits of human capacity and determine the requirements for current and future ATC systems. He assumed that controller workload is determined by the number of elements under control and the complexity of the control to be exercised. Other early studies were done by Barrer (1982), Swedish (1982), Swedish and Niedrighaus (1983), and Stein (1985).

Mental workload in ATC is also determined by the relationship of the aircraft to each other, that is, the proximity of aircraft to each other and the angle of their vectors. Lamoureux (1999) recently investigated the impact of different aircraft-to-aircraft relationships on ATCo mental workload indicated by subjective ratings. The greatest driver for mental workload was a relationship where one aircraft was level while the other was climbing or descending and the aircraft were on converging tracks. The least significant contributors to mental workload were relationships where aircraft were head-to-head to each other. This can be attributed to the fact that the former situation is much more difficult to resolve than the later (turn both aircraft right). In general, aircraft in one-dimensional flight (flying straight and level) contributed less to mental workload than aircraft in two-dimensional (changing altitude *or* heading) or three-dimensional flight (changing altitude *and* heading). These experimental findings correspond to the findings of Rodgers et al. (2000) based on incident analysis.

Stager, Ho, and Garbutt (2000) showed that the single variable of total flight minutes, that is the number of minutes an aircraft spends in a controller's sector summed across all aircraft in the sector for a 10-minute period accounted for up to 70% of observed controller workload as indexed by over-the-shoulder expert ratings. Stager et al. (2000) demonstrated the feasibility to automatically and continuously measure controller workload for a specific sector with a regression equation that is based on one-time ratings of observed workload and continuously recorded flight minutes. This equation can serve as a criterion to assess the impact of system changes on controller workload and performance or to decide on appropriate staffing.

As the aviation community moves towards FF, there has been an renewed interest in understanding the contribution of various sector characteristics to sector complexity and controller mental workload and efficiency with the goal to determine sector design, controller training and staffing, display coding, and understand controller decision making (Mogford, Murphy, & Guttman, 1994; Mogford, Guttman, Morrow, & Kopardekar, 1995). Under FF, the structure of the traditional ATC system will be replaced by a more unstructured and complex system. Dynamic Density (DD) is a measure to predict controller efficiency and workload by airspace factors relevant to the FF concept (Mogford et al., 1995; Wyndemere, 1996). Different equations to predict mental workload have been proposed by different researchers (Wyndemere, 1996; Laudeman, Shelden, Branstrom, & Brasil, 1998; Mogford et al., 1994; Stein, 1985; Smith, Scallen, Knecht, & Hancock, 1998). Beside aircraft count, a common contributor to controller workload in most equations is the number of aircraft that are changing their heading, speed, or altitude as well as the angle of convergence. In an equation by Wyndemere (1996), level of ATCo knowledge about aircraft intent and aircraft density were the strongest predictors of sector complexity. Dynamic Resectorization is a concept closely related to DD. Depending on the DD determined for a particular sector, the sector design or size could be changed and adjusted so that the controller workload remains within an acceptable level. However, Pawlak, Bowles, Goel, and Brinton (1997) found that a fixed set of sector designs would be superior to an unlimited set so that controllers can be trained on different designs and know what to expect. Besides, it was concluded that sector boundaries should not change as dynamically as originally proposed. The amount of coordination that is required for a sector boundary change (e.g. when aircraft belong to a different sector before versus after the boundary change) would outweigh the benefits of the new sector design. It was suggested that sector boundary changes could follow a daily schedule based on known traffic flows and jet streams. Besides, sector boundary changes should only occur when workload is low and should be modifiable by managers or supervisors. Hadley, Sollenberger, D'Arcy, and Bassett (2000) came to a different conclusion. Dynamic resectorization did not interfere with controller performance in a simulation study with twelve ATCos. In fact, controllers experienced fewer losses of separation in the dynamic resectorization condition, rated mental workload on the NASA-TLX lower, and had higher situation awareness than in the baseline condition. Clearly, more research is needed regarding the feasibility of this concept.

Display factors. Controllers depend largely on radar displays to receive information such as aircraft callsigns, reported and assigned altitudes, and speed. Therefore, displays play an important role. They can either significantly reduce workload if they are well designed or significantly increase workload if they are poorly designed. A poorly designed display (e.g. clutter, poor luminance, contrast, and font size) can disrupt the controllers selective attention process and therefore increase workload. The need to project aircraft poses a high workload on the controller (e.g. when merging two streams of traffic approaching an airport). New displays that aid the controller in the projection and prediction of aircraft paths have become available (e.g. the computer-assisted approach sequencing/ghosting; Mundra, 1989). Three-dimensional displays could help to facilitate the visualization of the vertical dimension.

Communication. Voice is still the primary means of communication between controllers and pilots through radiotelephony in order to keep aircraft separated and avoid that they enter weather, restricted airspace, or other hazards (e.g. on or around the runway). Voice communication is also necessary between controllers for taking hand-offs and handing aircraft off to the next controller. Several studies have focused on the role of voice communication on workload. High levels of communication might not only increase workload, but also compromise situation awareness and building a mental model of the situation. Other issues are misunderstandings and confusions (e.g. callsign confusion), "hearback" problem (Morrow, Lee & Rodvold, 1994), and incorrect or partial readbacks from pilots that could increase workload. Voice communication has also been used as a dependent variable for workload measurement. Sperandio (1971; 1978) found that controllers reduced the time they spent communicating with aircraft as workload increased. In the future, voice communication will be replaced, at least for routine communications, by a digital datalink. It remains to be studied how the use of a digital datalink affects controller performance and mental workload. The digital transmission of data could support memory functions (e.g. controllers could save messages and look them up at a later point in time). However, the transmission of data via datalink might interfere with the visual scanning of the radar because processing of information from both sources requires visual attention.

Automation. Automation can moderate taskload. For example, it is expected that automation will reduce the negative effects of high traffic density on workload and ATCo performance. How automation can affect mental workload has already been discussed in the chapter on the costs and benefits of automation. Even though automation is usually introduced with the goal to reduce mental workload, this has not always been successful. Automation can reduce or increase mental workload or leave it unchanged. Therefore, the effects of automation as a moderator of taskload are less predictable than other drivers (e.g. traffic density). The unbalanced distribution of workload as well as the supervisory or monitoring role of the operator are among the issues that need to be taken into consideration when automation is introduced into a system. As advanced decision-making automation is being introduced into the ATC system, this issue should receive special consideration.

4.2.2.2 Strategies and workload management

It is difficult to specify the relationship between taskload, workload, and performance because human operators do not passively respond to their environment. Operators use strategies to cope with the load imposed by tasks and to balance their workload. They respond adaptively to their environment and by doing so can manipulate the environment. In his seminal papers, Sperandio (1971, 1978) first emphasized the role of strategies in the relationship between taskload and controller workload. In an experiment with French tower controllers, he found that controller workload increased with traffic, but that controllers significantly shortened their communication, became more proactive in controlling traffic, and increased the amount of information per unit of time to cope with the taskload. Several different types of strategies can be distinguished (Parasuraman & Hancock, 2001). Workload can be distributed over time such that controllers prepare for high-priority tasks when workload is low or shed low-priority tasks when workload is high. Workload can also be distributed over available resources. If the demands exceed a controller's resources, a second controller can be called for help or the sector can be divided. However, as sectors are divided into smaller sectors, the need for coordination and communication between controllers increases and diminishes the expected reduction in workload. Controllers can also change the nature of their task by postponing or aborting tasks, or choosing a different standard of performance. Not accepting any more aircraft into the sector by putting aircraft into a holding pattern or increasing the spacing between aircraft (which both can reduce the efficiency of the system significantly) represent the most common strategies in ATC to reduce both taskload and workload. If controller strategies are not successful in coping with the demands of the environment or controllers do not have adequate strategies (e.g.

inexperienced controllers), performance breaks down. Most of the time, however, controllers are successful in adapting to the demands of the situation with strategies.

The ATCo's adaptation to the demands of the situation is the reason why we do not necessarily observe an association between taskload, workload, and performance. A dissociation is found when taskload is high, but workload is low. This could occur when the load gets so high that the operator gets overwhelmed, disengages and reduces his or her workload. Figure 4.2 displays potential relationships between workload and performance (Parasuraman & Hancock, 2001). Workload insensitivity is found when workload remains constant, but performance changes. Performance insensitivity is present when operator performance remains constant, but workload changes. Association is found when performance and workload increase together, dissociation when one increases as the other decreases. An understanding of this relationship is helpful to interpret performance and workload data.

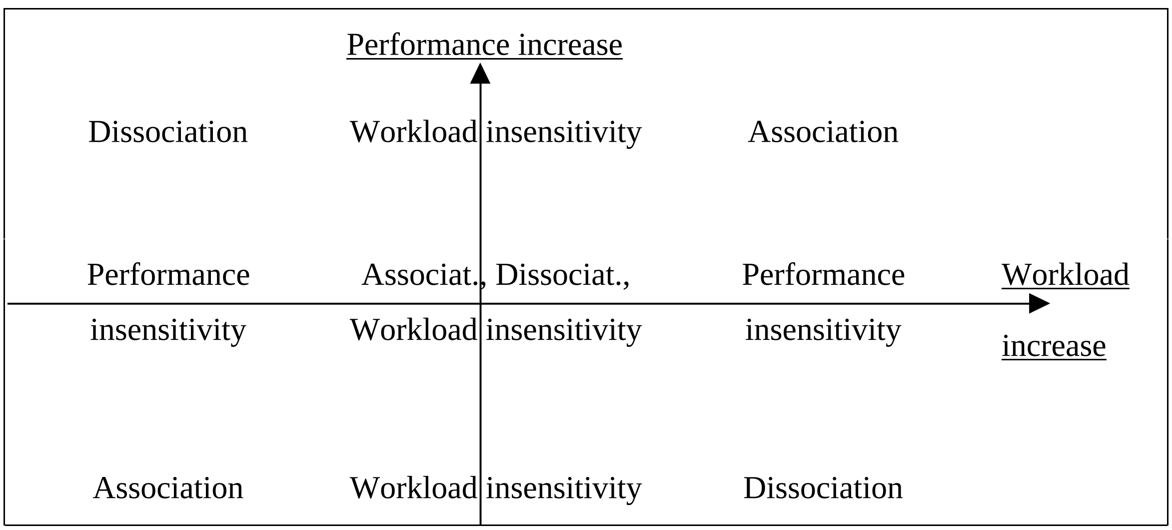


Figure 4.2: Relationship between performance and workload measures (Parasuraman & Hancock, 2001)

4.3 The need for operator-in-the-loop studies

The complicated association between taskload, mental workload, and performance supports the need for controlled operator-in-the-loop studies in the laboratory to investigate their relationship. Incident reports can only provide evidence for correlation, but not cause. While the level of workload must be inferred from recorded traffic or reports in incident analysis, it can be easily determined and manipulated in operator-in-the-loop studies.

While modeling (e.g. Performance and usability modeling in ATM - PUMA; Rose, Kilner, & Hook, 1997) provides an inexpensive means to determine mental workload before the system is implemented (e.g. during design and prototyping) the prediction will only be as good as the underlying model. Even though the influence of workload drivers can be modeled, the prediction of system performance has to be complemented by operator-in-the-loop simulations in order to take operator strategies into account. Taskload is mediated by strategies and together with workload determines controller performance. The same amount of workload drivers can result in a considerably different performance between controllers.

While laboratory experiments often lack the ecological validity and complexity of the real world, field studies usually do not allow for experimental control. Simulator experiments with subject matter experts allow researchers to incorporate the real world complexities while maintaining experimental control. Operator-in-the-loop simulations allow for a relatively easy manipulation of the variables that influence performance and mental workload (e.g. number of aircraft, presence or absence of a decision aid) and for the measurement of operator performance as well as strategies. By manipulating taskload, different strategies can be observed (Brookings, Wilson, & Swain, 1996). These features together make operator-in-the-loop simulations advantageous over accident or incident analysis, field observations and modeling approaches. The following sections describe how mental workload can be measured in operator-in-the-loop experiments.

4.4 Measuring mental workload

Research on mental workload that is based on capacity or resource-theory approaches typically assesses mental workload in operator-in-the-loop simulations using a battery of four measures: (1) primary task performance, (2) secondary task performance, (3) subjective ratings of mental workload, and (4) physiological measures. A combination of all four measures provides greater sensitivity to workload variations than each measure individually (Eggemeier & Wilson, 1991) and the assessment has greater stability than any measure by itself (Parasuraman et al.; 1992). Especially, when workload is not high enough to degrade performance in the primary task because the operator can compensate for increased task demand, secondary task, subjective, or physiological measures can discriminate higher from lower levels of operator workload.

4.4.1 Primary task performance

Primary task measures assess the operator's capability to perform a particular task of interest. The task of interest is typically an operator function within the human-machine system of investigation (e.g. driving a car, flying an aircraft, or controlling air traffic). Therefore, primary tasks are very domain-specific and must be chosen for the respective application. Measures of primary task performance assume that an increase in information-processing demands is associated with an increase in resource expenditure. If the task demands exceed the available resources, task performance degrades (Eggemeier & Wilson, 1991). Speed and accuracy in the task of interest are typical measured.

In an ATC system, a primary task of interest is the detection of aircraft on a conflict course. It is important to investigate detection rate as well as timeliness of detection. If conflicts are detected too late, there might not be enough time to resolve a detected conflict. Examples of ATC studies will be presented in a review of empirical studies in ATC in chapter 5.

An additional approach to mental workload is the assessment of operator strategies. It is not only of interest what the *level* of operator performance is, but also *how* it was obtained. Modifications in the way an operator performs the primary task of interest could be an indicator for mental workload. This approach is highly sensitive since it allows to observe variations in workload before performance degrades (Welford, 1978). ATCos, for example, treat aircraft individually if they have enough resources available. However, as soon as demand exceeds capacity, ATCos treat aircraft as a group rather than individually thereby reducing demand (Sperandio, 1971).

4.4.2 Secondary task performance

Based on a resource or capacity view of mental workload, performance in a secondary task is measured to assess spare capacity (Kahneman, 1973). The assumption is that as the demand in the primary task increases, performance in the secondary task declines. Subsidiary task or loading task paradigms have been used to evaluate mental workload. In a subsidiary task paradigm, the operator is instructed to maintain primary task performance at a single-task performance level and perform the secondary task as much as possible. The difference in the secondary task performance should reflect differences in the resource expenditure in the primary task. In loading task paradigms, the emphasis lies on the secondary task. Variations of resource expenditure on the secondary task are reflected in the primary task performance.

Secondary tasks can be artificial or embedded. An embedded task is a task that is usually part of a job, but of lower priority such as the updating of flight strips in an ATC task. Artificial secondary tasks include visual or auditory choice reaction times tasks (Kantowitz, Hart, & Bortolussi, 1983; Kantowitz, Bortolussi & Hart, 1987; Kantowitz, Hart, Bortolussi, Shively, & Kantowitz, 1984) time estimation or time interval production tasks (Hart, 1975; Michon, 1966), mental arithmetic (Brown & Poulton, 1961; Wierwille & Connor, 1983), or memory search tasks (Sternberg, 1966; Wierwille & Connor, 1983; Wickens, Hyman, Dellinger, Taylor, & Meador, 1986).

Brown and Poulton (1961) conducted one of the first studies to measure mental workload in driving with an artificial secondary task. Two groups of drivers that differed in their level of driving experience were instructed to drive in a residential (moderate load) and a shopping area (high load) while performing a secondary task that required adding three-digit numbers. The experiment showed both the sensitivity of the secondary task to driving and rest conditions and to driving in different areas. Secondary tasks are more likely to be sensitive if participants have to rely on effortful processing and cannot automatically perform them, and if the secondary task relies on the same type of resources as the primary task (e.g. a visual secondary task in an ATC task which is highly visual). The problem with artificial secondary tasks is that they might face acceptance problems in operational settings. For an overview on secondary tasks, see O'Donnell and Eggemeier (1986) or Eggemeier and Wilson (1991).

4.4.3 Physiological measures

The use of physiological measures for the assessment of mental workload has several advantages (Kramer, 1991; Wilson & Eggemeier, 1991). One of the most important ones is the fact that physiological measure do not require overt behavior to assess mental workload.

Supervisory control tasks or the monitoring of automated systems typically require little overt operator behavior leaving the researcher with little behavior to observe and limited data to collect. Therefore, physiological measures are especially useful when assessing human monitoring of and interaction with automation. In addition, physiological measures can be obtained relatively unobtrusively and do not change the primary task of interest. They can provide different views of the multi-dimensional concept of mental workload. As different measures are sensitive of different aspects of mental workload, a battery of physiological measures allows for a diagnosis of the source of workload. While some physiological measures respond faster (e.g. event-related potentials, ERP; heart rate variability, HRV) than others (e.g. brain metabolism measured with Positron Emission Tomography, PET, or functional magnetic resonance imaging, fMRI), all respond relatively quickly to phasic shifts in workload. This makes them valuable for the approach to implement automation adaptively (adaptive automation, adaptive function allocation, or adaptive aiding, Parasuraman et al., 1992; Rouse, 1988). Rather than implementing automation statically in an all-or-none fashion, adaptive automation adjusts the level of automation based on events in the environment, models of optimal operator performance, or user states to make maximum use of the benefits of automation while reducing the disadvantages. Physiological measure could be used as indicators of operator overload or underload states. Disadvantages of physiological measures include the high cost, the lack of standardized scaling and interpretation, the difficulty to discriminate signal from noise, and the contamination of the signal by factors other than workload (e.g. physical workload or movement, emotions, environmental factors such as ambient lighting).

A multitude of physiological measures have been used for mental workload assessment such as the electro-encephalo-gram (EEG, e.g. alpha and theta activity), ERP (Parasuraman, 1990), in particular the P300, heart rate and heart rate derived measures, in particular the .10 Hz component of HRV, epinephrine levels in the blood, and ocular measures such as pupil diameter, eye blink rate, and saccadic eye movements (Backs & Boucsein, 2000).

Measures of cardiovascular activity. Aasman, Mulder & Mulder (1987) showed that the .10 Hz band was sensitive to manipulations of memory load and concluded that changes in the amplitude of the .10 Hz band "reflect the use of resource-limited, effortful, mental operations" that rely on working memory. The .10 Hz amplitude is associated with the regulation of blood pressure. It is suppressed with increased load on working memory, but only resource-limited, and not data-limited processes lead to a change in the .10 Hz amplitude. Vicente, Thornton, and Moray (1987) showed the sensitivity of the .10 Hz band of HRV to difficulty manipulations in a psychomotor task. In a study on the detection, diagnosis and correction of faults and incidents in flight engineer trainees in a flight simulation, the .10 Hz band of HRV was reduced during a high workload problem-solving phase during level flight (Tattersall and Hockey, 1995). The .10 Hz band has shown sensitivity to detect fatigue in driving (Egelund, 1982). However, not all researchers have found HRV to be sensitive to different levels of mental demand (Wilson, 1992). Byrne, Chun, and Parasuraman (1995) found that the .10 Hz band of HRV was sensitive to rest-task manipulations, but not to manipulations of tracking difficulty in flight simulator tracking task. Similarly, Jorna (1992) concluded in a review paper on HRV that the .10 Hz band can reliably distinguish between rest and load conditions, but is not as sensitive to distinguish between levels of difficulty of a task. Therefore, HRV has great potential to detect underload conditions in the context of automated systems (Byrne & Parasuraman, 1996). Meshkati (1988) concluded that heart rate variability is considered one of the most used and most promising physiological measures of mental workload.

ATC has a long tradition in the use of physiological measures to assess workload (Kalsbeek, 1971). Several studies have shown HRV to be useful for the assessment of mental workload in ATC. In a study with eight military ATCos, Brookings et al. (1996) assessed the differential sensitivity of different physiological measures of workload in an ATC simulation. Workload was manipulated by varying traffic volume and traffic complexity. Complexity was manipulated by varying the mixture of aircraft types and the ratio of departing and arriving traffic. Brookings et al. (1996) showed the sensitivity of HRV to workload manipulations for several physiological measures. HRV was sensitive to the complexity manipulation, but not as expected in the .10 Hz band, but the .15-.4 Hz band.

Visual attention. Perhaps the most directly related to the attentional resource concept of mental workload, at least in the visual domain, are the measures of saccadic eye movements and eye fixations. How long the eye rests at a given coordinate is an indicator for the amount of information that is gathered or the effort expended to gather the information. That eye movement patterns can describe the objects of attention in the environment was first described in the classic work by Yarbus (1965/1967). Recent advances in technology have made saccadic eye movement recording devices more affordable and data collection in dynamic environments more feasible than in the past allowing for a unique insight into visual attention processes of operators of human-machine systems (Velichkovsky & Hansen, 1996). The primarily visual nature of tasks in the flight deck or the ATC environment make eye movement recording a prime candidate to the understanding of mental workload in these systems. The recording of saccadic eye movements in the context of automation is relatively new.

Saccadic eye movements and visual attention are closely related, even though not fully. While a shift in attention preceding a saccade is mandatory to determine where the next fixation will occur ("mandatory shift hypothesis"), a saccade to or a fixation of a location does not guarantee a shift in attention to that same location. In other words, attention can move independent of the eyes (Pashler, 1998; Hoffman, 1998). This can be shown in a simple demonstration in which a participant is asked to maintain eye fixation on a particular point in the environment and name the color of an object in the periphery. Even though the participant maintains eye fixation on a point, he or she can shift his or her attention to an object in the periphery and name the color. Nevertheless, saccadic eye movements and attention are related to a great extent. A functional tie between the two is given due the fact that visual acuity is greater in the center of the fovea than in the periphery. If an object in the environment is of special importance, it becomes necessary to move the eyes and foveate or fixate the object in order to improve the quality of the information and perceive details (Pashler, 1998). Therefore, eye movements and fixations can serve as a measure of the allocation of attentional resources to a particular point in the environment or the information-processing demand of a particular task (Wickens & Hollands, 2000). Humans make about 3-4 saccades during a second (Becker, 1991 as cited in Hoffman, 1998) during which information processing is suppressed. Information is processed only during fixations, the time between saccades as a person looks at a stationary target in the visual field. Saccades are extremely fast and can reach speeds of up to 900° of visual angle per second (Goldberg, 2000).

Visual sampling in a supervisory control task can be distinguished from a target search task. In a supervisory control task the location of a target is known. The frequency and timing of the sampling is of interest. In a target search like the search for conflicting aircraft in ATC, the existence and location of targets is unknown.

Van Orden, Limbert, Makeig, & Jung (in press) found systematic changes in several eye measures as a function of target density in a visuospatial memory task. Blink frequency, fixation frequency, and the extent of saccades in degrees were associated with greater visual information processing load (early stages) while pupil diameter as associated with greater cognitive processing (later stages of information processing).

Wierwille, Rahimi, and Casali (1985) found an effect for the total time spent fixating on the navigation display in their flight simulation with a navigational task that required trigonometric calculations. The time fixating on the display increased with task difficulty. Callan (1998) on the other hand found that the frequency of fixations longer than 500 ms was related to the number of flight rule errors committed in a flight simulation.

In a study on visual scanning and pilot expertise Bellenkes, Wickens, and Kramer (1997) found that experts fixated on most instruments more frequently and had shorter dwell times (i.e. their gaze remained in an area for shorter periods of time) than novices. The most information-rich instruments were fixated more often than others and experts extracted information more efficiently (i.e. in a shorter amount of time) than novices, especially from the instruments that conveyed the most information. Experts also showed a pattern that guarded them from tunneling in on displays by checking primary flight indicators even when they performed maneuvers that were not expected to change the indicator. Bellenkes et al. (1997) proposed that visual scanning is a good indicator of the underlying mental model of the operator by showing that experts demonstrated the cross-coupling of instruments during a maneuver while novices did not show this cross-coupling pattern. That experts (as indicated by flight hours) had more frequent fixations and shorter dwell times than novices was also found by Kasarskis, Stehwien, Hickox, Arentz, and Wickens (2001) in a study of scanning behavior during VFR landings. Better landing performance was associated with the same pattern of more frequent fixations, but shorter dwell times. This pattern is consistent with other studies in simulated instrument flight (Fitts, Jones, Milton, 1950; Kramer, Tham, Konrad, Wickens, Lintern, Marsh, Fox, & Merwin, 1994; Tole, Stephens, Harris, & Ephrath, 1982) and ATC (Stein, 1992). Tole et al. (1982) found an increase in fixations on the attitude directional indicator, one of the most information-rich displays in the cockpit, for novices, but not in experts. Experts had shorter dwell times indicating higher automaticity of information-processing. Tole et al. also found that dwell duration increased with mental workload in a simulated communication task. Increased dwell duration under high workload was also found by Harris, Tole, Stephens, and Ephrath (1982).

An FAA task force in 1987 found that operational errors in ATC were associated with the ATCos' failure to see critical information and initiated a research program on controller information scanning to understand why controllers fail to see critical information so that errors could eventually be reduced. Stein (1989) defined scanning as "a systematic and continuous effort to acquire all necessary information in order to maintain complete awareness of activities and situations which may affect the controller's area of responsibility."

In Stein's (1992) study on the effects of ATCo experience and traffic load on ocular measures such as saccade duration and extent, fixation frequency and duration, he found that experienced controllers searched their environment more frequently than less experienced controllers. An impact of taskload on performance or eye movements was not found. However, activity level was related to saccade duration. The busier the controller became, the shorter and more frequent were his or her saccades. Stein (1992) also found that scanning behavior changes significantly in the first five minutes on the radar. Saccade extent and duration became shorter and then stabilized. Average fixation duration increased during the same period. This correlates with controller reports that most operational errors happen in the beginning of a shift or after controllers return to the radar after a break. Stein (1992) also investigated if the eye tracker had an impact on controller perception in the study. Controllers reported wearing the eye tracker was most annoying when traffic was low, but tended to forget about it when traffic load was high. However, none of the controllers reported that it influenced their operational strategy. In fact, ATCos made fewer operational errors when they were wearing the eye tracker than without it, perhaps due to the fact that the eye tracker and visor that the participants look through help to focus on the task.

In a study on the effects of active versus passive control and traffic load in sixteen air traffic controllers, Willems and Truitt (1999) found that the level of control (active or passive) or traffic load did not affect the number or duration of fixations, but changed the scan pattern. Controllers showed a less structured or more random scanning pattern as indicated by a conditional information index (Ellis & Stark, 1986) under high traffic and when controllers were actively controlling under high traffic.

Willems, Allen, and Stein (1999) studied the effects of task load, visual noise on the radar, and intrusions of VFR or IFR aircraft into controlled airspace on eye movements and other variables of twelve controllers. They found that the number of fixations on the radar decreased with increasing traffic load. The increase in traffic load diverted the attention of the controller to other areas and tasks in the ATC environment (e.g. the keyboard to update flight strips). Controllers also focussed on areas of high traffic density. This could be the reason why controllers missed to detect airspace intruders in some cases and detected them late in others. A problem with the measure of saccade duration in these studies is the fact that eye movements were recorded at a speed of 60 Hz (i.e. every 17 ms). Assuming that saccades typically take only about 30 ms, this measure is not very reliable.

Another difficulty with ocular measures such as fixation or dwell frequency and duration is the lack of definition of these terms. Oftentimes, the studies do not describe their criteria for fixations or dwells. Sometimes, these terms are used synonymously, sometimes dwells are defined as a series of fixations. In addition, each eye tracking system gives a different output with different criteria for fixations or dwells and most systems are flexible to allow researchers to set their own criteria. Standardization in the use of terms and criteria would allow for a better understanding and comparison between the different studies. Nevertheless, the studies show promise for fixation frequency and duration as new measures of mental workload. Compared to other measures, eye parameters allow researchers to capture attentional strategies as a response to task demands that are otherwise difficult to obtain.

4.4.4 Subjective measures

The easiest way to measure mental workload is to ask the person performing a task how much workload he or she experienced. Several standardized scales have been developed for this purpose among them the NASA-TLX (NASA-Ames Research Center, 1986; Hart & Staveland, 1988; Byers, Bittner, & Hill. 1989; Nygren, 1991), the subjective workload assessment technique (SWAT; Reid & Nygren, 1988; Reid & Colle, 1988; Biers & McInerney, 1988; Reid, Potter & Bressler, 1989), the subjective workload dominance technique (SWORD, Vidulich & Tsang, 1987; Vidulich, Ward, & Schueren, 1991; Tsang & Vidulich, 1994), the Cooper-Harper Scale (Cooper, 1957; Cooper & Harper, 1969; Wierwille & Casali, 1983), or the Bedford Scale (Roscoe, 1987; Wainwright, 1987). Most of them have multiple dimensions (e.g. mental demand, temporal demand, physical demand, frustration) corresponding to the findings that mental workload is affected by factors independent of each other. Research has not shown major advantages of one of the scales over the others (Eggemeier & Wilson, 1991). However, they all rely on the participants' ability to accurately recall their level of resource expenditure retrospectively. There has been some concern regarding the reliability of such information (Eggemeier & Wilson, 1991). The Air Traffic Workload Input Technique (ATWIT; Stein, 1985) is a unidimensional subjective rating scale specifically designed to measure workload in air traffic control. However, the unidimensionality of the scale does not lend the scale much diagnostic value (i.e. does not help to determine if workload is caused by frustration or mental demand, e.g.).

The NASA-TLX consists of six subscales three of which characterize the demand a task places on the operator (mental, physical, temporal demand) and three that results from the interaction between operator and task (performance, effort, frustration). The NASA-TLX is considered to be one of the most effective measures of subjective mental workload (Nygren, 1991; Hill, Iavecchia, Byers, Zakland, & Christ, 1992). It is convenient to use and has good (test-retest) reliability (Warm et al., 1996).

Subjective measures of mental workload might also reveal information on future user acceptance of the tool or procedure under investigation. If operators subjectively experience increased workload when using a tool, they might be hesitant to accept and use it. Conversely, when operators experience a reduction in workload, they might be very interested in implementing and using a tool. In the worst case, this could contribute to an overreliance on the tool.

4.4.5 Relationship between measures

Although the use of all four types of measures allows for a comprehensive evaluation of performance and mental workload consequences of design alternatives in human-machine systems, results from the four types of measures do not always lead to the same conclusion. Sometimes dissociation between the different measures of workload can be observed (Yeh & Wickens, 1988). Physiological and subjective measures might indicate higher workload, but primary performance might improve. Such a dissociation of measures provides a unique insight into operator strategies and could reflect increased effort to keep up with the primary task which is reflected in improved or constant performance, higher subjective ratings of mental workload, and physiological measures indicating higher workload. Therefore, a dissociation of different workload measures provides valuable information about the strategies operators employ to cope with the situation (see 4.2.2). While dissociations between performance and workload measures indicate strategies, dissociations between workload measures could increase the diagnosticity of the assessment. For example, the .10 Hz band of HRV is only sensitive within the resource-limited region of information-processing (Aasman et al., 1987). If subjective ratings of mental workload are very high, but the .10 Hz band of HRV shows no effects, operators could have reached the data-limited region of information-processing.

5. Review of empirical studies on the impact of automated decision aids and Free Flight

The following sections provide a review of studies on the effects of automated decision aids and FF on ATCo mental workload and performance. It is essential to review the literature on both, FF and ATC automation. First, automation is essential for FF and therefore, the two concepts go hand in hand. In fact, future ATC automation has to be designed for use in a FF environment. In addition, FF and automation are similar in terms of their effects on the controllers. Both can lead to a transfer of some aspects of decision-making away from the controller. Humans are less aware of changes in the environmental or system state when those changes are under the control of another agent, either automation or another human (i.e. the pilots). The operator may not be able to sustain a good picture of the situation when not actively engaged. Therefore, the effect of airborne separation is similar to the effect of automation in that it could lead to a loss of controller situation awareness.

5.1 Free Flight

The move towards FF (RTCA, 1995) and the projected increase in air traffic over the next decade (Wickens et al., 1998a; Eurocontrol, 1998) will change the airspace structure drastically. An increase in the number of flight paths and flight path variability has been shown with computer simulations. Traffic patterns became less uniform and predictable under FF (Ball, DeArmon & Pyburn, 1995). This change will most likely increase the difficulty of detecting conflicts. While under current conditions potential conflict points are limited to the intersecting airways, FF conditions will create more potential intersections. Figure 5.1 demonstrates the structure of the airspace under current and FF conditions. With the same number of aircraft it is much more difficult to control traffic under FF than under current conditions. In addition, pilots will be allowed to change their flight plan at any time making aircraft movements unpredictable for the ATCo.

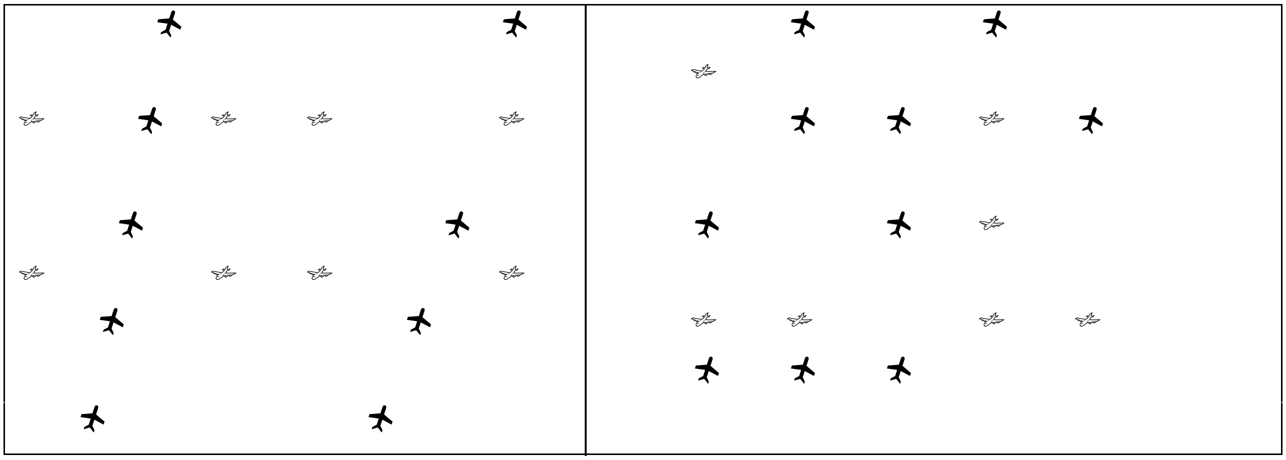


Figure 5.1: Airspace structure under current and free flight conditions

While there have been plenty of speculations and concerns about the consequences of FF for the ATCo, mostly among ATCos and researchers (Wickens et al., 1998a), empirical evidence has been scarce until recently. Several empirical studies have demonstrated the feasibility of FF from the perspective of the flight deck (e.g. van Gent, Hoekstra, & Ruigrok, 1998; Morphew & Wickens, 1998; Lozito, McGann, Mackintosh, & Cashion, 1997; Dunbar, Cashion, McGann, Macintosh, Dulchinos, Jara, & Jordan, 1999), but empirical studies testing the impact of FF on the ATCo have been neglected. There were questions if controllers would be able to serve as a back-up in case of a problem (e.g. failure of airborne separation) when a shift in separation authority to the pilots would leave the ATCo out of the control loop. More recently, several studies examining controller performance and workload under FF conditions have become available and provide first answers to this question.

In a simple ATC game, Rowe, Sibert, and Irwin (1998) studied the impact of airspace complexity on mental workload in participants familiar and unfamiliar with ATC. The game was an abstraction of FF in which some aircraft followed fixed routes on the screen while others maneuvered freely. Complexity was determined by the number of aircraft maneuvering freely (4, 8, 12, or 16 aircraft). HRV was sensitive to the complexity manipulation, especially in participants familiar with ATC. Rowe et al. (1998) also found that as the complexity reached its maximum in the game (i.e. 16 aircraft), HRV of participants familiar with ATC increased indicating decreased mental workload. This could be an indicator for the point when participants were loosing the picture and disengaged in the task. This phenomenon has also been shown by

Aasman et al. (1987) and could be an indication of a switch from resource-limited to data-limited information processing (Norman & Bobrow, 1975). Subjective ratings of mental workload measured with the NASA-TLX increased with the number of free flyers even when the number of free flyers was increased from 12 to 16.

Endsley, Mogford, Allendoerfer, Snyder, and Stein (1997) tested ten full performance level (FPL) civilian controllers in a high-fidelity ATC simulation under four conditions: a baseline corresponding to current ATC procedures, direct routing with intended flight path information, direct routing with deviations from intended flight path after sharing intent with the controller, and direct routing with deviations from intended flight path without sharing intent with the controller. Measures of performance, mental workload, and situation awareness served as dependent variables. Situation awareness was assessed using subjective measures and the Situation Awareness Global Assessment Technique (SAGAT; Endsley & Kiris, 1995). SAGAT stopped the simulation at random intervals and controllers were probed about their awareness of the current and future traffic situation (e.g. aircraft location, callsign, separation, hand-offs, etc.). While operational errors were significantly increased only in the condition in which pilots deviated from their flightplan without sharing their intent, subjective mental workload increased and situation awareness decreased in all FF conditions. Higher levels of FF were associated with higher levels of workload and lower levels of situation awareness. Endsley et al. (1997) noted that direct routing increases the controllers need to communicate and query the pilot's intent suggesting that the increased communication was the major contributor to the increase in mental workload under FF. The knowledge of pilot intent seems to be a critical determinant of controller performance.

Galster, Duley, Masalonis, and Parasuraman (2001) investigated ATCo conflict-detection performance and mental workload in a medium-fidelity ATC simulation. Ten active en route ATCos were required to monitor air traffic under moderate and high traffic density, but were not provided with pilot intent information. Results indicate that ATCos had difficulties in detecting conflicts or self-separating events in a timely manner. In the moderate traffic condition, 10% of the conflicts were not detected prior to the loss of separation. In the high traffic condition 50% of the conflicts were missed. Self-separating events remained unreported even more frequently. 70% in the moderate and 85% in the high traffic load condition were missed. Under high traffic, notification of impending conflicts was reduced and mental workload increased as indexed by subjective ratings and secondary task performance. Galster et al. (2001) concluded that FF will create a highly efficient and dense airspace leaving the ATCo with little time to respond to emergencies.

In an experiment by Endsley and Rodgers (1998), twenty controllers passively monitored recorded traffic scenarios that each included an operational error. The scenarios froze two minutes prior and at the time of the operational error and controllers were asked a series of questions that addressed their awareness of the system state (e.g. where on a blank sector map particular aircraft were at the point of freezing and in the next two minutes, aircraft callsign, altitude, speed, etc.). Controllers had difficulties recalling many system parameters (e.g. the location of aircraft or speed). Reporting of dynamics (e.g. recalling which aircraft were in a turn) was especially poor as was their awareness if aircraft had complied with a clearance or if the execution of the clearance was finished or still impending. Lower accuracy was associated with a higher number of aircraft under control and, to a lesser extent, higher reported mental workload. While the accuracy for most aircraft details decreased significantly with the number of aircraft, accuracy in reporting which aircraft were in conflict, both currently and in the near future, was unaffected. This probably indicates a prioritizing strategy. Since attending to all aspects of the situation would exceed controller capacity, controllers focus on important over unimportant aspects. While this heuristic is efficient most of the time, there may be instances in which it will lead to a failure (e.g. when a pilot does not follow the controllers' clearance or when an aircraft reaches the assigned altitude later than expected).

The authors concluded that the low awareness of aircraft parameters was at least partially due to the passive monitoring as opposed to active controlling condition. In a similar experiment, Mogford and Tansley (1991; as cited in Endsley & Rodgers, 1998) studied controller trainees under active controlling conditions. Although they found a similar distribution of attention to each type of information (e.g. aircraft location or callsign), controllers achieved a much higher accuracy in their awareness of current and future system states. This has implications both for FF conditions and the automation of higher-order cognitive functions. Since both can put controllers in a monitoring role, reductions in situation awareness can be expected.

These studies provided the first empirical evidence that ATCo performance under FF might be compromised. They also indicated that the passive monitoring role of the ATCo might be one of the reasons for reduced ATCo performance under FF conditions. Metzger and Parasuraman (in press) directly compared the effects of active control versus passive monitoring and moderate and high traffic density on controller mental workload and performance in an ATC simulation. Eighteen ATCos participated in an ATC simulation under active control and passive monitoring of traffic and under moderate and high traffic density. Dependent variables included accuracy and timeliness in detecting potential conflicts, accepting and handing-off aircraft. Mental workload was assessed with a secondary task, heart rate variability and NASA-TLX ratings. Results showed detrimental effects of high traffic and passive control on performance. Even though there was no difference in the number of potential conflicts detected, it took controllers under high traffic density and monitoring conditions significantly longer to detect potential conflicts. This is an important finding considering that FF will create a highly efficient and dense airspace leaving the ATCo with little time available to resolve conflicts or other emergencies. If less time is available, but ATCos require more time under FF conditions as shown in this study, performance and safety could be severely compromised.

Willemsen and Truitt (1999) conducted a similar study on the effects of reduced involvement in en route ATC on eye movements, workload, and situation awareness. Mental workload was rated lower under monitoring than active control conditions. Workload correlated well with traffic load. Response times to questions related to SA were unaffected by traffic load under active control. However, SA was significantly decreased under monitoring conditions in the high traffic condition. ATCos were able to recall more datablocks correctly under active than monitoring conditions. However, controllers did not seem to be aware of their reduced SA. Responses in a questionnaire revealed that they found the active control condition more difficult and felt that their SA had not suffered from reduced involvement. The unawareness of reduced situation awareness could be potentially dangerous. If the ATCo is not aware of it, he or she might not choose appropriate strategies (e.g. putting aircraft in holding patterns until they are capable to safely handle the aircraft) in order to cope with the situation safely. The control condition or traffic load did not affect the number or duration or eye fixations or blinks. However, the scan pattern changed as a function of traffic load and level of control. Controllers showed a less structured or more random scanning pattern under high traffic and when they were actively controlling under high traffic.

These experiments clearly support the notion that the ATCo's passive monitoring role is one contributor to the reduced performance under FF. Another contributor, the lack of information on intended flight paths, has already been mentioned by Endsley et al. (1997). Under FF, the airspace will be less structured and pilot intentions that are now inferred from flightplans and airspace structure will be uncertain. Castaño and Parasuraman (1999) studied the impact of different levels of intent information, traffic density, and conflict geometries (i.e. angles of convergence in a conflict) on controller performance and mental workload in an ATC simulation. Intent level was manipulated through the presence or absence of flight strips, airspace structure components, and route displays. High intent was equivalent to current ATC conditions with the addition of a route display. While in the low intent condition, only the sector boundaries and callsigns of aircraft were available, the medium intent condition included waypoints and a route display. Controllers had to detect and resolve conflicts. Performance measures included the number of operational errors (OEs) and clearances issued. Mental workload was assessed using the NASA-TLX as a subjective measure. ATCos had more difficulties detecting conflicts with obtuse conflict geometries (e.g. head-on collisions) than conflicts with acute angles. As predicted, more operational errors were committed under low than under medium intent conditions in the high traffic condition. However, the most OEs were committed under high intent information. This was probably due to display clutter associated with high intent information. Under low intent conditions, significantly more conflicts were predicted by the controllers than were scripted in the scenarios compared to the medium intent information. This could be interpreted as a controller tendency to err on the side of caution and might have implications for efficiency in the airspace. If controllers are more cautious than necessary, they might adopt strategies to increase safety (e.g. spacing aircraft further apart or issuing clearances that are not necessary) and at the same time reduce efficiency. However, in the high intent condition, controllers predicted more conflicts than in the medium intent condition. Again, this might be due to clutter on the display, which is confounded with the level of intent information available. Subjective mental workload was higher under high than under moderate traffic conditions. Highest workload was reported in the medium intent condition. The lowest workload was rated in the low intent condition possibly due to the lack of display clutter. This could indicate that clutter had a greater effect than the intent manipulation for subjective mental workload.

Another potential contributor to reduced performance under FF is the lack of airspace structure. While altitude and route restrictions in the current ATC system might not make the system as efficient as it could be, they give the system the structure that ATCo have come to rely on. The goal of FF is to remove those restrictions in order to make flights more efficient. Remington, Johnston, Ruthruff, Gold, and Romera (2000) studied the effects of the presence or absence of route and altitude restrictions, traffic load, and conflict geometries on ATCo conflict detection in a series of short scenarios. The absence of route and altitude restrictions corresponded to proposed FF conditions. It was found that both traffic load and conflict geometry had strong effects on the detection of conflicts. The higher traffic load, the longer it took ATCo to detect conflicts. The shorter the time to conflict and the smaller the angle of closure, the earlier the detection of conflicts. The removal of altitude restrictions had a (small) negative effect, the removal of route restrictions had very little effect. The authors suggested that controller strategies such as a clockwise visual search path might have mitigated any potential negative effects of the removal of restrictions. The lack of an effect of the removal of route restrictions could also be due to the fact that display clutter is reduced when the traffic is spread out more evenly over the display. The authors conclude that the lack of large effects of the removal of restrictions does not justify the introduction of FF. They note that in their experiments, controllers performed only one (i.e. conflict detection) out of several tasks that ATCo usually perform in a sequence of independent very short scenarios that is uncharacteristic for real-world ATC tasks. In addition, all aircraft flew straight lines at constant speeds. The removal of restrictions in the real world might have much stronger effects.

Another issue with FF is the accommodation of mixed equipage by ATCos. While some aircraft will be sufficiently equipped to participate in FF (e.g. with GPS, ADS-B) and will only need monitoring, others will not have sufficient equipage and require ATC similar to current procedures. Corker, Fleming, and Lane (1999) studied the effects of different proportions of mixed equipage on ATCo detection of airborne self-separation and workload under FF conditions. Eight controllers were each tested under the following conditions: traditional ground-based control (baseline); traditional control, but with all aircraft flying direct routes; all aircraft flying direct routes with 20% aircraft self-separating; and all aircraft flying direct routes with 80% aircraft self-separating.

Controllers rated that conflict resolution and separation assurance increased in difficulty with increasing proportions of aircraft that were self-separating. A regression analysis revealed that communication time between pilots and controllers was the greatest contributor to ATCo subjective mental workload. Aircraft mix (e.g. slow versus fast moving aircraft) and the number of aircraft waiting to enter the sector also were greater contributors than the number of aircraft alone. Under baseline conditions, communication time increased with the number of aircraft. In the direct routing condition, communication time decreased compared to the baseline probably because there was no need to communicate after the direct route was approved and pilot intent was clear. In the 20% self-separating condition, communication time for the exchange of intent information increased significantly, but was not accompanied by an increase in reported workload. Apparently, the exchange of intent information does not pose a significant workload burden on the controller. Communication time was further analyzed. Under direct routing with 80% aircraft self-separating, communication time was significantly decreased compared to all other conditions. Workload, however, was markedly increased probably due to the constant high monitoring requirement which is even higher without the knowledge of pilot intent. It was concluded that automation is needed to provide controllers with intent information and to monitor pilot conformance with their stated intent in order to reduce the workload burden on controllers when monitoring aircraft under mature FF conditions. It was difficult for controllers to decide without intent information if aircraft will self-separate in time or not. In most cases, controllers took over control to preclude a separation violation. Not only can this lead to an increase in controller workload, but also to sub-optimal controller decisions in terms of system efficiency. In fact, controllers might feel so uncomfortable with this situation that they impose tighter control and cancel the expected benefits of FF.

With the exception of the study by Remington et al. (2000) that did not find any adverse effects of FF, these experiments have provided the first empirical evidence that FF might be associated with reduced ATCo performance and increased mental workload. Factors, leading to the performance decrement were identified. The passive monitoring role, lack of intent information, and mixed equipage could all contribute to a reduction in ATCo performance and an increase in mental workload.

A study with ten United Kingdom Royal Air Force military controllers (Hilburn, Bakker, Pekela, and Parasuraman, 1997), however, found performance benefits of FF. ATCos performed in conditions of controlled flight, FF with intent sharing, and FF without intent sharing under high and low traffic density. Pupil diameter indicated that under low traffic, workload was lowest in the FF condition with intent sharing, but highest under high traffic and controlled flight conditions. Blink rate measures suggested an interaction between traffic and control condition. Under low traffic load, workload was lowest for the controlled flight condition, but under high traffic load, workload was lowest in the FF condition with intent sharing. Although those results are trends only, measures of subjective workload point towards the same direction. Similar to the results of Endsley et al. (1997), more flightplan information queries were made by the controllers under FF conditions than under controlled flight conditions.

This study showed much less detrimental effects of FF than the studies described before, perhaps due to the different controller populations that the different studies tested. Hilburn et al. (1997) tested military, all others civilian ATCos. Differences between civilian and military controllers have been noted (Hilburn & Parasuraman, 1997). Since military controllers do not file flight plans and therefore are used to work without flight strips and with little intent information, they might represent a more appropriate population for FF studies. Perhaps they are used to the higher uncertainty under FF conditions. This also points to the possibility that some of the negative problems associated with FF could be reduced once ATCo have been trained appropriately and have gained some experience with it.

Conclusion. Except for Remington et al. (2000) who found neutral effects and Hilburn et al. (1997) who found beneficial effects, most studies found a rather negative impact of FF on ATCo performance and workload. ATCos were moved from strategic management and the availability of aircraft intent information to a system in which they were reactive to the environment. Still, the operational concept expected the controller to make decisions based on a strategic management paradigm. ATCos experienced great difficulties when tactical information became less available. If ATCo are still expected to be responsible for the separation of aircraft in future ATC automated decision aids need to be provided to the ATCo. Especially tactical and dynamic, not strategic decision aids have to be developed because controllers will no longer be able to make decisions based on flightplans (Corker et al., 1999). Although flightplans will still be filed under FF, pilots may change their intent at any time. This creates a need for information on short-term tactical intent to make FF feasible from the perspective of the ATCo.

5.2 Automation

Currently, very little decision-making automation is implemented in the ATC system. As a consequence, only few studies were conducted examining the impact of automated decision aids on ATCo performance and mental workload. However, recently a few automated decision aids for ATCos have become available and research on those will be discussed in this section. Although the automation aids will be described briefly, the focus is on examining the effects of the tools on the ATCo.

The Computer Oriented Metering, Planning and Advisory System (COMPAS) is an automated planning aid assisting ATCos in the planning and control of traffic approaching an airport. It has been implemented at the Regional ATC Center in Frankfurt, Germany since September 1989 (Völckers, 1991). The goal of COMPAS is to make optimal use of the runways, recognize and reduce congestion of incoming traffic in a timely manner, reduce delay times and ATCo workload while maintaining a high level of safety. COMPAS uses information from radar data and flight plans and integrates it with information on weather, airspace, aircraft performance and separation standards to propose a plan to the ATCo. The recommendation is advisory and leaves controllers in the loop to make and execute decisions. System performance and acceptance, and controller workload were evaluated in a series of simulator experiments in which ATCos worked traffic with and without COMPAS (Schick, 1991a). Dependent performance measures were the observed and planned time distribution of aircraft over certain waypoints, approach sequences, and tracks of horizontal vectoring. Frequency and duration of controller communications to aircraft, frequency and duration of phone calls to other controllers as a measure of coordination, and the actuation of keys on the COMPAS keyboard served as measures of communication load and manual input load. Subjective ratings of controller acceptance of the system were obtained. Workload ratings were obtained using the SWAT. Two types of control units are involved in handling the approach traffic, namely terminal area control and sector (en route) control. For approach control, the average flight time of aircraft as well as radio communication between controllers and pilots was significantly reduced in the terminal area. In addition, controllers issued less clearances for heading changes and more clearances for direct vectoring increasing efficiency in the airspace. Subjective ratings showed a high degree of acceptance of COMPAS. On the other hand, the average flight time and subjective ratings of mental workload in the en route sectors were increased. However, controller time on the radio and the number of heading changes were not affected by the use of COMPAS. Overall, it was found that the approach sequences were fairer, i.e. the first-come-first-serve rule was not violated as often when COMPAS was used versus when it was not used. Coordination between en route and terminal area radar control (TRACON) controllers as indicated by phone calls between the two facilities was significantly reduced.

A field evaluation of COMPAS (Schick, 1991b) found similar results. COMPAS contributes to a steady traffic flow and greater fairness in the approach sequence facilitating planning and executive work in the approach area. In en route or area control, evidence was found for an increased control load. Approach control can take advantage of the en route controllers' prior effort to establish a sequence. It was concluded that COMPAS could contribute to a better distribution of workload across control units or facilities.

Similar to COMPAS, the center TRACON automation system (CTAS) is a decision aid that supports the controller in the sequencing and scheduling of traffic in or transitioning to the terminal area. The software tools assist ATCos in planning and controlling by means of advisories presented on ATC displays. The design philosophy of CTAS is to provide automation tools that augment rather than replace the human. One software component, the descent advisor calculates aircraft trajectories and estimated times of arrival for each aircraft within 200 miles of the airport, and dynamically develops a plan to sequence and schedule each aircraft. Advisories are displayed to the controller in the form of four-dimensional trajectories with the goal to maximize total efficiency and accuracy of arrival time for the arrival stream. The descent advisor detects planning or separation conflicts and provides the controller with advisories on how to resolve them.

Hilburn (1996) studied how the level of automation and traffic load affected mental workload, operator and system performance in two experiments using the descent advisor. The level of automation was either manual control, automated conflict detection, or automated conflict resolution. Traffic density was either low or high. Performance measures included monitoring performance for failures in the datalink as well as arrival accuracy and number of arrival sequence changes, and number and severity of separation violations as measures of ATC system performance. Pupil diameter, frequency and duration of eye fixations and dwells, scanning randomness, and HRV served as physiological measures, ratings on the NASA-TLX and the Subjective Mental Effort Questionnaire (SMEQ; Zijlstra & van Doorn, 1985) as subjective measures of mental workload. High traffic load was associated with higher mental workload than low traffic load. This was reflected in measures of pupil diameter, dwell time, fixation frequency, scanning entropy, and HRV. Automation demonstrated benefits on mental workload and performance. A trend indicated an automation benefit in pupil diameter, however, this was found in experienced ATCos only. Dwell duration as an indicator for the amount of information that is extracted from a display or the effort expended, did not find a strong automation effect. However, fixation frequency was increased with automation indicating higher workload. HRV showed a workload reduction with automation, especially under high traffic. While HRV and pupil diameter suggested reduced workload under both automated conditions, for most measures, workload reduction was greater for conflict detection than for conflict resolution automation. Subjective ratings indicated higher workload with high traffic. In the high traffic condition, workload was rated higher under automated than manual conditions suggesting that ATCos experienced increased workload under automation, especially with resolution automation.

Monitoring performance as indicated by response times to simulated failures in the datalink was significantly better under resolution automation compared to the manual condition across both traffic loads. A trend suggested that the benefit of automation was greater under high than under low traffic conditions. This is contrary to findings that automation of monitoring and control tasks has a negative effect on monitoring performance in case of an automation failure (Parasuraman et al., 1993).

System performance was studied using the measures of arrival accuracy, number of arrival sequence changes, and the number and severity of separation violations. Both automation levels resulted in a trend for better arrival accuracy than the manual condition and a lower number of arrival sequence changes under manual control than under the automation conditions. Fewer separation violations were seen under detection automation than under resolution automation or manual control. Looking at the duration of the violations reveals a slightly different picture. The average duration of separation violations was longest for detection automation and shortest for resolution automation.

While the first experiment suggested a benefit of static automation on mental workload and performance, a second experiment showed that the benefits of automation on mental workload and monitoring performance in an ATC decision-making task could be enhanced by implementing automation adaptively, for example only when traffic load is high. HRV indicated the highest workload under the static automation schedule and lowest under adaptive automation. Adaptive automation showed the greatest benefit on mental workload under high traffic as indicated by HRV. Under low traffic, HRV showed an automation cost of the static automation schedule over the manual or adaptive schedule. Pupil diameter indicated increased workload with increased traffic load and a trend for a benefit of adaptive over static automation. Fixation duration indicated a trend for higher workload under high than under low traffic load.

In both experiments, results from objective and subjective workload measures dissociated. While objective measures found a benefit, subjective measures found a cost of automation on workload. This could have consequences for ATCo acceptance of the automated tool. If ATCos do not subjectively experience a workload benefit, they might be resistant to accept the automation. However, the number of participants in the two experiments (Hilburn, 1996) was fairly low (n = 8) and many results were only marginally significant. Further research could clarify, if these findings can be replicated.

Harwood, Sanford, and Lee (1998) describde a field assessment of CTAS. While field assessments are typically conducted during the later stages of system production and deployment (i.e. when it is difficult to implement changes in the system design), the one by Harwood et al. (1998) was conducted very early in the development process and ATCo were involved throughout the development process. Field assessments of CTAS revealed benefits for all three software modules of CTAS. The assessment focussed on the effects of the descent advisor on ATCo workload and acceptance. Subjective ratings on a 10-point scale showed no effect of the use of the automated advisories on the quantity of decisions, planning, and calculations. Fewer clearances had to be issued and accuracy in estimating times of crossing certain fixes was increased. However, the use of the automated advisories increased workload for type and number of coordination. This could be an artifact since coordination and communication were increased during the assessment procedure. Harwood et al. (1998) reported that one of the biggest benefits of the CTAS assessment in an operational setting was the increased acceptance and trust that controllers had in CTAS. Even though some ATCos had experienced the performance and workload benefits of CTAS in the laboratory, their confidence in the system was increased after experiencing the same benefits in the field.

A few other automated decision aids are available in ATC. The Precision Runway Monitor and Final Monitor Aid System (Lind, 1993) or the converging runway display aid (Mundra, 1989; Mundra & Levin, 1990) assist ATCos in the terminal and tower area to merge traffic without conflicts. Their main goal is to increase runway capacity. They will not be discussed here because this work focuses on the en route environment and no human performance study is available on the converging runway display aid.

Surprisingly little research has been conducted on conflict detection and resolution aids like URET, CPTP, or Direct-to. Initial analyses of URET revealed that false alarm rates might be quite high (Cale, Paglione, Ryan, Timotea, & Oaks, 1998). However, although URET is already being field tested, there is no data on its effects on ATCo performance and workload. Results of a field trial at the Indianapolis Air route traffic control center revealed that the controllers unanimously supported the tool with respect to the presentation of information, computer interface, accuracy of the conflict prediction and trajectory modeling. It was believed to be suitable for clearance decision making as well as sector planning. It was expected that safety and productivity for the data controller were enhanced. Given the reduced requirements for flight strip manipulation and elimination of the need to scan flight strips for potential problems, workload could potentially be reduced. However, to date, no human-in-the-loop study has been reported with ATCos using URET (Brudnicki & McFarland, 1997).

Conclusion. While the purpose of the introduction of automation or new procedures in the ATC system is to increase capacity and efficiency, this goal should not be achieved at the expense of safety. Automation or new procedures implemented with a view to increasing capacity and efficiency must at least be safety neutral and preferably should enhance safety. The automation tools discussed above had mostly beneficial effects on controller performance and mental workload. Both, COMPAS and CTAS, find reductions in workload and no negative consequences on performance. In fact, CTAS is already in commission in several facilities in the US. The studies by Schick (1991a, 1991b) point toward an important issue. The introduction of automation tools does not only have an effect on the immediate user, but also on other members in the system. In their case, COMPAS reduced workload in the terminal area, but increased workload in the en route areas leading to a better distribution of load across the facilities.

With the introduction of FF, it becomes necessary to also examine the impact of these tools under FF conditions. It may also be necessary to assess new tools in the context that they will be used in (e.g. FF conditions, digital datalink). Simply adding new tools to the old system is not sufficient. Automation tools should be integrated into the system in which they will be used in a way that they do not interfere with each other, with other tasks, or the operational concept.

5.3 Automation and FF

The literature on the consequences of FF for the ATCo, with the exception of two studies (Hilburn et al., 1997; Remington et al., 2000), demonstrates the negative effects of FF on ATCo performance and mental workload. A review of the (scarce) literature on the effects of ATC automation suggests benefits of automation on ATCo performance and mental workload under current ATC conditions. It remains to be studied if automation tools such as conflict detection aids have beneficial effects on ATCo performance and mental workload under FF and if they could compensate for some of the negative effects associated with FF.

Conflict detection requires the reliable projection of aircraft status and conflicts into the future. However, such projections are based on expected flight paths and factors such as wind, weather, or turbulence. Under current conditions expected flight paths could be predicted relatively reliably from filed flight plans because pilots have to stay on the agreed upon routes and ask for ATCo permission if they wish to deviate. Under FF, however, pilots may change their intended flight path at any time, thereby reducing the predictability and limiting the utility of conflict detection aids. By changing their flight path, pilots could resolve their own conflicts or even create new ones.

Only two studies so far have investigated the effects of automation and FF jointly. The emphasis of these studies was on ATCo trust in conflict detection automation under FF conditions. Trust and self-confidence determine, among other factors (cf. Riley, 1996), the use of automation. Lee and Moray (1992) and Tan and Lewandowsky (1996) found that the difference between ratings of trust and self-confidence predicted the use of automation. If trust in the automation was greater than self-confidence to perform without the automation, the automation was used. If self-confidence to perform without the automation was greater than trust in the automation, the automation remained unused. Even though trust and self-confidence have some influence on operator performance and mental workload through the usage of automation, performance and workload were not addressed per se in these two studies.

In an experiment by Masalonis, Duley, Galster, Castaño, Metzger, and Parasuraman (1998) current en-route ATCos viewed 45 brief ATC on a PC-based ATC simulator. Aircraft predicted to be in conflict were highlighted. In some trials the prediction became inaccurate because pilots self-separated, i.e. resolved an existing conflict themselves, but the aid still indicated a conflict (error of commission or false alarm). In other trials, pilots maneuvered freely creating conflicts which went undetected by the conflict detection aid (error of omission or miss). There was no significant difference in trust ratings following the detection of a conflict that was resolved by the pilot (false alarm) or a correct assessment. However, when the aid did not show a pilot-created conflict (miss), trust declined. Apparently, trust was more affected by misses than by false alarms. It was concluded that conflict detection aids would be more accepted if they were programmed to predict unexpected maneuvers, perhaps through intelligent modeling of pilot behavior in FF. In addition, training is needed to calibrate trust in a conflict detection aid and trust in pilots to successfully self-separate. Controllers tended to intervene less often in self-separations as time passed. Objective measures of trust were unaffected. The agreement with correct automation decisions was high even when the automation had just failed on the previous trial. Therefore, controllers may perform well with conflict detection aids even under FF.

In another experiment (Masalonis, 1999), trust and usage of a conflict detection aid were studied under FF and current ATC conditions. The conflict detection aid was either reliable or unreliable and the participants were either informed about the weaknesses of a conflict detection aid under FF conditions or received no information on this issue. Masalonis (1999) found that ATCo detected about 90% of all conflicts. However, they missed almost half of the conflicts that were missed by the automation suggesting that they might have overly relied on the automation. Trust was lower in FF for participants who were informed about the weakness of the aid under FF before they started the experiment. The difference between FF and non-FF scenarios was not reflected in the non-informed participants' trust ratings, not even toward the end of the experiment. Only the uninformed showed a relationship between trust ratings and the tendency to accept the decision of the automation without verifying it.

Conclusion. These experiments elucidated some of the issues associated with the use and utility of conflict detection automation under FF conditions. The finding that ATCos missed a large number of conflicts that remained undetected by the aid points toward a potential for automation-related complacency. This is an important issue that requires further investigation. Clearly, more research is needed studying the effects of automation and FF jointly. While the focus of these experiments was ATCo trust in automation, it is of particular interest how ATCo performance and mental workload are affected under both reliable automation and in cases when automation reliability might be reduced due to uncertainty in the FF environment.

5.4 Statement of problem and overview of research

Research has shown mostly negative effects of FF conditions on ATCo performance and mental workload. In addition, the goal of FF is to increase airspace capacity. Therefore, traffic density and complexity will be much higher under FF. The combination of increased traffic density and the negative impact of the authority shift from the ground to the flight deck could have a dramatic impact on ATCo performance and workload and therefore system safety. Automation could be a remedy to the negative impact of FF on the ATCo. However, while the effects of automation on the ATCo have been studied under current ATC conditions, they have not been investigated under FF and high traffic density conditions. Due to the high uncertainty of pilot intent in the FF environment, the reliability and utility of automated decision aids might be limited. It is still an open question whether supporting ATCo with decision-aiding automation could compensate for the negative effects of FF conditions and high traffic density. Hence, there is a need for research investigating the effects of automated decision aids on ATCo performance and mental workload under FF conditions.

Overview of the research. The present research investigated whether a conflict detection aid can neutralize the negative effects associated with FF and high traffic density. Therefore, ATCo performance and workload under automated conditions was compared to a baseline in which ATCos operate under FF conditions without a conflict detection aid. In addition to traditional automation that heavily relies on the visual system, a fairly new approach to the design of automation that attempts to distribute information-processing across modalities was studied. The utility of multimodal feedback in guiding ATCo attention in an increasingly visual environment was examined. While the first two experiments assumed that the automated decision aid functions 100% reliably, a third experiment examined the effects of automation that is highly reliable, but could fail occasionally due to the high uncertainty in the FF environment. Studying ATCo performance and mental workload under conditions of FF, high traffic density and unreliable automation conditions is important in order to anticipate if ATCos would be able to detect automation failures and intervene in time to recover from the situation. A timely recovery from emergency situations is a critical issue if the introduction of automation and FF is not to compromise safety.

6. Methodology

6.1 Overview

Three operator-in-the-loop experiments were conducted to examine the effects of a conflict detection aid and traffic density under reliable and unreliable automation conditions on ATCo performance and mental workload. The choice of the independent variables was guided by the imminent introduction of conflict detection automation into the ATC system, rapidly increasing air traffic, and the lack of research literature on the effects of these changes on the ATCo and ultimately system safety. The experiments were conducted on a mid-fidelity ATC simulation (Masalonis, Le, Klinge, Galster, Duley, Hancock, Hilburn, Parasuraman, 1997) using professional FAA ATCos from the Washington area en route and TRACON facilities as participants. Although recruiting professional ATCo was problematic due to the shortage of personnel at the FAA facilities and incurred a high cost, it was deemed necessary. A pilot study (Galster, 1998) revealed that college students performed poorly at the ATC tasks even after extensive training. Besides, they would not use the same strategies that professional ATCos use.

To account for the multi-task environment in which ATCos operate and based on the resource view of mental workload, a battery of tasks was chosen to obtain primary and secondary task performance. This was supplemented by subjective ratings and physiological measures to obtain a comprehensive picture of ATCo performance and mental workload. Besides, ratings of trust in the aid and self-confidence to perform without the aid were obtained.

The simulation of air traffic in all scenarios was created with the input of a subject matter expert, an ATCo with Human Factors training and experience from the London area traffic control center.

6.2 ATC simulation

A PC-based medium-fidelity ATC simulator (Masalonis et al., 1997) was used to simulate an en route airspace. The simulation ran on a Pentium-I processor on an X-windows platform and a Linux operating system with two 21-inch monitors attached (15- and 21-inch monitor in Experiment 1). The simulation consisted of the primary visual display (PVD) or radar display and a combined datalink and electronic flight strip display (15-inch monitor in

Experiment 1). At a distance of about 55 centimeter between the participant's eye and the monitor, the displays on the 21-inch monitors covered approximately 36° (horizontal) and 29° (vertical) of visual angle (15-inch monitor: about 33° (horizontal) and 28° (vertical) of visual angle). The two displays were set up at an angle of about 160° and together covered about 58° (15-inch monitor: about 55°) of visual angle (horizontal). A trackball was used as input device for both monitors.

Figure 6.1 shows the primary visual or radar display. The polygon indicates the sector boundaries. Controllers were responsible for all aircraft within their sector. A real sector was chosen (Harrisburg, PA), but was modified in order to avoid benefits for controllers who might have experience with this particular sector. Waypoints (e.g. CMH or RAJAP) and jet routes (i.e. the lines connecting the waypoints) are shown in picture 6.1. The aircraft in the sector were represented by aircraft targets and datablocks. The datablocks could be moved around the targets to avoid overlapping datablocks. The datablocks contained the most important information associated with a flight such as the callsign of the aircraft (e.g. UAL 529 for United Airlines flight number 529), the flight level (i.e. altitude of the flight in hundreds of feet, e.g. 350 for 35000 feet) and if altitude is constant, climbing or descending (indicated by "C", "+", or "-"), a computer identification number (e.g. 758), and groundspeed in knots (e.g. 480). In the upper right hand corner, the picture shows several tools that the controllers had available such as the vector, J-ring, and history displays. The vector display showed the position of aircraft in a specified amount of time into the future based on current speed and heading. The J-ring display drew a circle around a selected aircraft with a specified radius up to 7 miles. The function of the J-ring was to help controllers determine if an aircraft will violate the given separation standards. In the field, controllers also use the J-ring as a memory aid, i.e. in order to flag a flight as one that needs attention. The history display shows a trail behind an aircraft indicating the direction and speed of flight. The faster the aircraft travels the longer the trail. The radar display updated every five seconds. Also shown in the picture is the conflict detection aid. It consisted of two red circles drawn around the two aircraft involved in a conflict. The prediction was based on flight plan information and turned on five (Experiment 1) or six (Experiment 2 and 3) minutes before a potential loss of separation occurred or would have occurred if none of the aircraft involved self-separated. Based on the RTCA (1995) report, separation standards of 5nm horizontally and 1000 feet vertically at all altitudes were adopted in this experiment.

The circle within the sector designated the hand-off circle. Controllers were instructed to hand-off aircraft as soon as possible *after* the aircraft passed the circle. Controllers under current procedures hand-off aircraft and responsibility much earlier. Since aircraft are under positive control at all times, the controllers know the intentions of the aircraft. Under FF conditions, however, pilot intentions might change on short notice. Therefore, controllers cannot give up responsibility as early as currently. The buttons on the bottom of the monitor allowed the controllers to adjust the brightness of foreground and background and to change the display range. The use of this functionality was not allowed in the experiments in which eye movements were recorded.

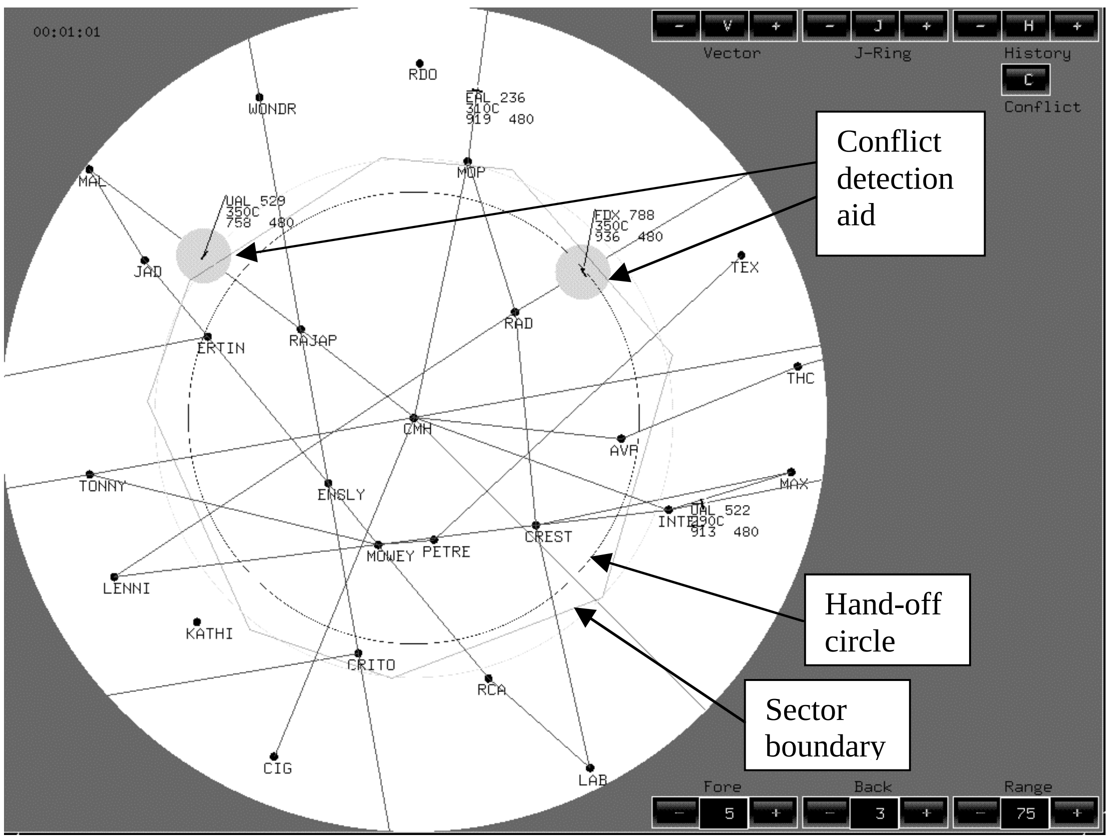


Figure 6.1: Primary visual display (PVD)

Figure 6.2 shows the datalink and electronic flight strip display. The datalink was chosen as the means of communication between ATCos and aircraft because it allowed for maximum experimental control and did not require any confederate experimenters as pseudo-pilots. More importantly, however, the use of datalink is envisaged in future ATC systems for routine communications and information that is not important to other pilots in the sector in order to reduce frequency congestion. The datalink consisted of a list of flights, an area for incoming messages from the aircraft, as well as several buttons for accepting aircraft into the sector or handing off to the next sector. As soon as an aircraft came close to entering the sector boundaries on the PVD, it sent a message to the area where incoming messages appeared on the datalink display. It was marked "Incoming message" and could be opened by clicking on it. After clicking, it said "Entering sector". To accept the aircraft into the sector, the controllers clicked the "Accept"-button and the aircraft sent a message "Roger" back to confirm that they received the controller acceptance. To hand-off aircraft, the controller had to select the aircraft in the list of flights and click "Auto Hand" in the lower right corner. The aircraft acknowledged the instruction by returning a message "Wilco". The electronic flight strips for each flight that were displayed on the same monitor contained the most important information of a flight such as the callsign, computer identification number, the waypoints the flight passed on its way through the sector and the flightlevels.

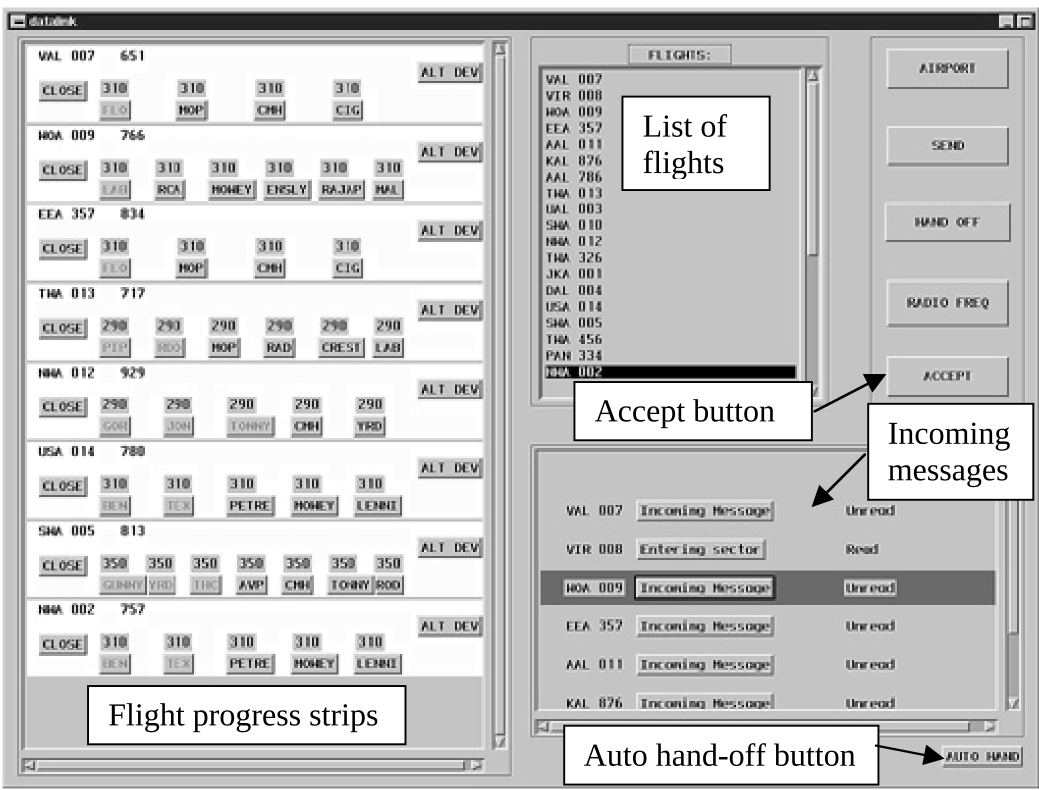


Figure 6.2: Electronic flight strip (left half) and datalink display (right half)

Figure 6.3 displays the full simulation set-up with a participant wearing an eye-head tracking system.

Figure 6.3: Experimental set-up with eye-head tracking system

The simulation contained the tasks described in the next section from which the dependent variables of performance were obtained.

Primary task performance: Conflict detection. The detection and resolution of potential conflicts between aircraft is the most important task of the ATCo in order to assure safety in the air and on the ground. Therefore, it was chosen as the primary task of interest.

In a FF environment, potential conflicts can result in an actual conflict or a self-separation of the aircraft involved. A self-separation exists when one of two aircraft on a conflict course makes an evasive maneuver to avoid the loss of separation either by changing heading, speed, or altitude. A conflict occurs when two aircraft on a conflict course fail to self-separate and loose separation (i.e. come within 1000 feet vertically and 5nm horizontally of each other, RTCA, 1995).

While self-separations represent instances of successful airborne separation and would not require ATCo intervention in the real world, conflicts are instances in which airborne separation fails and the controller would have to step in to resolve the conflict in order to avoid a disaster. Therefore, conflict detection performance serves as an estimate of safety and the likelihood that controllers will be able to act as a back-up in the case that airborne separation fails. The detection of self-separation serves as a measure of situation awareness and indicates how aware controllers are of the elements and dynamics in the airspace they are responsible for, a prerequisite for successful decision-making.

ATCos were instructed that their most important task was to detect potential conflicts that could result in either actual conflicts or self-separations. ATCos were asked to report potential conflicts as soon as possible either by calling out the callsigns of the two aircraft involved (Experiment 1) or by clicking on a "conflict"-button on the radar display (Experiments 2 and 3) that became available after a software update. The callsigns as well as the time of the report were recorded.

Accuracy and timeliness in the detection of conflicts and self-separations served as dependent variables. The percentage of correctly reported conflicts and self-separations were obtained as well as advance notification times for both events. The advance notification time was defined as the interval between the time when the loss of separation occurred (for conflicts) or would have occurred had the aircraft not self-separated (for self-separations) minus the time when the controller indicated that he or she detected a potential conflict. The greater the time, the earlier the detection took place and the better was the conflict detection performance. If ATCos did not indicate that they detected a conflict before the loss of separation occurred or after the evasive maneuver started, a miss was recorded.

Primary task: Accepting and handing-off aircraft. To facilitate the control of air traffic and, ultimately, the detection of conflicts, it is important that ATCo and pilots communicate with each other, especially as aircraft are accepted into a sector or handed-off to the next sector. This highly proceduralized communication task establishes the transfer of responsibility between ATCos in different sectors. In the simulation, it yielded additional performance measures such as the accuracy and timeliness in accepting and handing-off of aircraft.

Aircraft approaching the sector boundaries sent messages (“incoming message”) to the ATCos that appeared in the communication interface on the lower right hand side of the datalink display. Controllers were instructed to open all incoming messages by clicking on them with the cursor and accept the aircraft as soon as possible by clicking on the “accept”-button.

The percentage of aircraft successfully accepted before the end of a scenario and the time it took controllers to accept aircraft into the sector were obtained. The response times was obtained by calculating the interval between the time the controller received the message "entering sector" on the datalink and the time the controller took the hand-off by clicking the "accept"-button on the datalink.

Controllers were instructed to hand-off all aircraft as soon as they passed the designated hand-off circle on their way to the next sector. They were specifically instructed not to hand-off aircraft before they passed the circle. Handing-off a particular aircraft was achieved by selecting that aircraft from the list of flights on the datalink display and clicking the “hand-off” button.

The percentage of aircraft handed-off successfully was obtained as well as the percentage of aircraft handed-off early. Aircraft handed-off successfully were aircraft that were handed off after the aircraft had passed the hand-off circle. Early hand-offs were aircraft that were handed off before they crossed the hand-off circle. Response times for handing-off aircraft to the next sector were obtained by calculating the interval between the time when the aircraft crossed the hand-off circle and the time the controller actually handed the aircraft off to the next sector controller by clicking the "hand-off"-button on the datalink.

Secondary task performance: Updating flightstrips. Consistent with the attentional resource view of mental workload a subsidiary task paradigm was used. Participants were instructed to maintain primary task performance allocating their attention to the secondary task as much as they could. Flight progress strips contain all the information a controller needs to control traffic such as intended route of travel, waypoints to cross, altitudes, etc. In case of a radar failure, flight strips (in addition to the ATCos’ mental picture of the traffic and communication) serve as a back-up that the controller can rely on. Flight strips are generated by the main ATC computer system and distributed to the ATCo prior to the arrival of the aircraft in the ATCo’s sector. ATCo manually update the information on the flight strips as the aircraft progresses through the sector or if changes are made to the flightplan. However, this is not their main priority. Therefore, the updating of flight progress strips was chosen as an embedded secondary task in the simulation.

ATCo were instructed to check off waypoints on the electronic flightstrip as soon as aircraft passed the corresponding waypoints on the PVD. E.g. as soon as a particular aircraft passed the waypoint CMH on the PVD, the controller was supposed to click on the CMH waypoint on the flightstrip for that aircraft.

Accuracy and timeliness in updating the waypoints on the flightstrip served as a dependent measure of secondary task performance. The percentage of missed waypoint updates as well as the percentage of early updates were obtained. Missed waypoints were waypoints that the aircraft had passed on the radar display, but were not updated on the flightstip before the flight was handed off. If a controller clicked on a waypoint button before an aircraft actually passed the waypoint on the radar, an early update was registered. For successfully updated waypoints, response times were obtained by calculating the interval between the time when an aircraft crossed one of the waypoints on the PVD and the time the controller acknowledged that an aircraft passed the waypoint by clicking on the corresponding waypoint button on the electronic flight progress strip.

6.3 Additional apparatus

Beside the objective performance measures obtained from the ATC simulation, additional dependent variables were obtained from a heart rate monitor, an eye-head tracking system, as well as subjective ratings scales to measure subjective mental workload and trust.

Physiological measures. Measures of cardiovascular and ocular activity were obtained as physiological measures of mental workload and visual attention (ocular measures). The .10 Hz band of HRV served as a measure of mental workload in experiment 1. The number and duration of fixations, the number and duration of dwells on different areas of interest in the simulation as well as gaze transitions between the areas of interest served as physiological measures of mental workload and visual attention in Experiments 2 and 3. Detailed descriptions of the apparatus (i.e. heart rate monitor and eye-head tracking system) are provided in the respective chapters.

Subjective ratings of mental workload. ATCos were asked to fill out the NASA-TLX after each scenario. The ratings on the NASA-TLX were chosen as a measure of subjective mental workload. Scores were obtained by averaging the ratings of the six NASA-TLX subscales, a method found to be psychometrically equivalent (Nygren, 1991) to the weighted subscore averaging originally suggested by the authors of the NASA-TLX.

Trust. Because the use of automation depends to a large part on the operator's trust in the system and self-confidence to perform a task without the aid of automation (Riley, 1996; Lee & Moray, 1992, 1994), subjective rating scales were used to obtain ratings of trust and self-confidence from ATCos. The scales were similar to the ones used by Lee & Moray (1992; 1994), i.e. Likert-rating scale ranging from 0-100 with endpoints labeled from "not at all" to "extremely". The scales can be found in the appendix. Table 6.1 gives on overview of all dependent variables investigated in the three experiments.

Table 6.1: List of dependent variables

Primary task performance: Detection of conflicts and self-separations

- Percentage of detected conflicts and self-separations
- Advance notification time

Primary task performance: Accepting and handing-off aircraft

- Percentage of successfully accepted aircraft
- Response times to request for acceptance
- Percentage of aircraft handed-off successfully
- Percentage of aircraft handed-off early
- Response times to hand-off

Secondary task performance

- Percentage of missed waypoint updates
- Percentage of early waypoint updates
- Response times

Physiological measures

Exp. 1:

- .10-Hz band of HRV

Exp. 2 and 3:

- Entropy
- Number and duration of fixations on different areas of interest
- Number and duration of dwells on different areas of interest
- Dwell time (= number x duration of dwells)

Subjective ratings of mental workload

- NASA-TLX scores

Trust and self-confidence ratings

- Trust

- Self-confidence (Exp. 2 and 3)

7. Experiment 1: Effects of a decision aid and traffic density

7.1 Introduction

A review of the literature found mostly negative effects of FF on ATCo performance and mental workload. FF will allow the ATCo to accommodate more aircraft than before and create a highly efficient and dense airspace leaving the ATCo with less time to respond to emergencies (Galster et al., 2001). Metzger and Parasuraman (in press), however, found that ATCos need more time to detect conflicts under these conditions. This raises the question if automation could improve ATCo performance and reduce mental workload under FF conditions and the associated high traffic density. In fact, the concept of FF has always assumed the availability of automation support for pilots and ATCos and automation has repeatedly been suggested in the literature as a means to support ATCo performance (e.g. Galster, 1998; Galster et al., 2001; Wickens et al., 1998a).

While previous studies have shown promising results for automated decision aids under current ATC conditions (e.g. Schick, 1991a, 1991b; Hilburn, 1996), no empirical data is available studying the effects of advanced decision aids on ATCo performance and mental workload under FF conditions. This is surprising given that decision aids such as URET are already scheduled for implementation. Because automation can sometimes have unanticipated consequences it should be carefully evaluated regarding the expected benefit and potential cost before being implemented. This is especially important given the requirement for improved safety and the envisioned reduction of accident rates by 80% (FAA, 2000).

Therefore, the purpose of the first experiment was to study the impact of a conflict detection aid on mental workload and controller performance in an ATC task simulating FF under moderate and high traffic density and to investigate the potential of a conflict detection aid to compensate for the reduced performance and increased mental workload associated with increased traffic density and FF conditions.

FF comes in many varieties and the specific way it will be implemented is still to be determined. FF could range from full separation authority on the flight deck to keeping authority on the ground with controller decision aids that free up controller resources that can be used to respond to more user requests. Most likely, the implementation will be gradually, from moderate to mature levels of FF. For the following simulations, a rather mature level of FF was chosen in anticipation of a worst-case scenario for the future. Even though pilots stayed on routes and filed a flight plan, they could deviate from the flight plan and routes at any time without notifying the controller. Authority for separation was on the flight deck. Controllers monitored traffic and were expected to act as a back-up in case self-separations failed. Conditions of moderate and high traffic as well as conditions of automation support and manual performance were investigated.

7.1.1 Hypotheses and Research questions

Consistent with findings in other studies it was expected that conflict detection performance would be reduced under high compared to moderate levels of traffic when ATCos had no automation support available. With the support of a decision aid, however, performance should be improved under both moderate and high traffic density.

Likewise, it was expected that mental workload would be reduced under high compared to moderate levels of traffic when ATCos had no automation support available. With the support of a decision aid, however, mental workload should be reduced under both moderate and high traffic density.

To make automation beneficial, performance and mental workload under high traffic in the presence of the conflict detection aid should be at least at the same level as performance and mental workload under moderate traffic in the absence of the aid.

It was also expected that the performance of routine ATC tasks (e.g. communication) would be reduced under high compared to moderate traffic conditions without the aid and that the conflict detection aid would free resources and improve performance in routine ATC tasks compared to unaided performance.

Because the use of automation, and eventually operator performance, is determined, among other factors, by operator trust in the automation, ATCo ratings of trust were investigated.

7.2 Methods

7.2.1 Participants

Twelve active full performance level en-route ATCos from the Washington Center air route traffic control center (ARTCC) between the ages of 32 and 51 years (M = 37.17, SD = 4.84) served as paid volunteers. Their average overall ATC experience including all military and civilian positions ranged from 11 to 19.5 years (M = 13.46, SD = 3.24). All were male.

7.2.2 Apparatus

For a description of the ATC simulation refer to Chapter 6. In addition to the ATC simulation, a heart rate monitor was used in order to obtain the .10 Hz band of HRV as a measure of mental workload. To obtain the data, three electrodes were placed on the forearms of the ATCos in a Lead I configuration, that is, two electrodes were placed on the right arm and one, the ground, on the left arm. As Kramer (1991) pointed out, the heartbeat has a fairly large signal-to-noise ratio and does not require a very precise placement of electrodes to successfully detect the R-wave of the Electro-cardiogram (ECG) signal. The ECG was amplified using a Scope Service ECG preamplifier. A bandpass filter (Krohn-Hite 3550) was applied to filter out noise below 5 Hz (high pass) to attenuate movement artifacts and anything above 50 Hz (low pass) to eliminate 60 Hz line noise. In addition, a UFI Impedance Pneumograph Resp I and UFI Pneumotrace (Amplifier for Respiration with respiration belt) were used. The ECG was digitized at 1 KHz using PC-based software. Interbeat intervals were measured using a software-based Schmitt trigger algorithm (CSLacq, Byrne, 1994a). After removing and editing artifacts in the heartrate data, a power spectral analysis was applied to the heart rate variability data (HRV) in order to obtain the 0.10 Hz band of the HRV. The calculation was done using CSLstat 1.07 (Byrne, 1994b). The program ran on a PC-DOS system with a 386 processor.

7.2.3 Design

A two-factorial repeated measures design with two treatment levels on each factor was chosen. Independent variables were (1) traffic density with (a) moderate or (b) high levels of traffic in the ATC sector and (2) the availability of a detection aid with (a) aid absent and (b) aid present as treatment levels. All ATCos performed in all resulting four conditions. The order of conditions was presented according to a complete double cross-over design with the availability of the detection aid as the first, and traffic density as the second cross-over. Hence, half of the participants performed the two traffic conditions (one moderate, one high traffic) with the aid first, the other half performed the two traffic conditions without the aid first. The two different traffic density conditions were always performed in (varying) sequence before switching to the other automation condition. The order of traffic density was balanced so that half of the participants that first performed with the aid present were presented with the moderate, the other half with the high traffic density first. In the same way, half of the participants that first performed with the aid absent were presented with the moderate, the other half with the high traffic density first. This resulted in the equal distribution of all conditions across all four positions in the order of presentation. The participants were randomly assigned to an order. Dependent variables are listed in table 6.1.

For each condition, one scenario was created. ATCos were presented with four 30-minute scenarios that were created to combine high (on average about sixteen aircraft after a 10-minute ramp-up period) and moderate (about ten aircraft after a 10-minute ramp-up period) traffic load with the absence and presence of a conflict detection aid in a sector with a 50-mile radius. Each scenario contained two conflicts and four self-separations.

In scenarios with a conflict detection aid, five minutes before a potential conflict occurred, a red circle appeared around the two aircraft involved. As soon as one aircraft made an evasive maneuver (e.g. descended 1000 feet), the circle disappeared. In scenarios without detection aid, the circle only appeared when aircraft had already lost separation in order to give the controller a feedback similar to their real work environments.

7.2.4 Procedure

After signing the informed consent form, the controllers were connected to the heart rate monitor. Three electrodes were attached to their forearms, one on the left side, two on the right side. A respiration belt was put around their lower ribcage. The controllers then were given a demonstration of the simulation, completed a fourteen-minute practice trial, and were familiarized with the NASA-TLX. After that, a five-minute baseline of their heart rate was obtained during which controllers were instructed to relax. Then, controllers each completed four 30-minute scenarios and filled out the NASA-TLX after each scenario. Two more five-minute baselines of their heart rate were obtained, one after the second scenario, the other one after the last scenario.

7.3 Results

All twelve participants were entered into the statistical analyses. For all dependent variables, 2 (presence or absence of aid) x 2 (high or moderate traffic load) repeated measures ANOVAs were calculated. Both independent variables were within-subject factors. An alpha level of .05 was used for all statistical tests.

7.3.1 Primary task performance: Detection of conflicts and self-separations

Averaged across all condition, ATCos detected 78.13% (*SE* = 4.44%) of all conflicts. Controllers detected a higher percentage of conflicts when traffic density was moderate (*M* = 89.58%; *SE* = 4.23%) than when traffic was high (*M* = 66.67%; *SE* = 7.16%), $F(1, 11) = 8.59$, $p < .05$. Neither the presence or absence of the aid, $F(1, 11) = .06$, $p > .05$, nor the interaction between the presence or absence of the aid and traffic density had a significant effect on the detection of conflicts, $F(1, 11) = 1.32$, $p > .05$.

Overall, ATCos detected 53.13% (*SE* = 4.80%) of all self-separations. More self-separations were detected under moderate (*M* = 68.75%; *SE* = 6.60%) than under high traffic density (*M* = 37.50%; *SE* = 5.43%), $F(1, 11) = 25.00$, $p < .001$. More self-separations were detected when the decision aid was present (*M* = 69.79%; *SE* = 6.73%) than when it was absent (*M* = 36.46%; *SE* = 4.99%), $F(1, 11) = 30.61$, $p = .001$. The trend for an interaction between the presence or absence of the aid and traffic density, $F(1, 11) = 3.00$, $p = .11$, is shown in figure 7.1. The detection of self-separations had a greater benefit from the presence of the aid under moderate than under high traffic density.

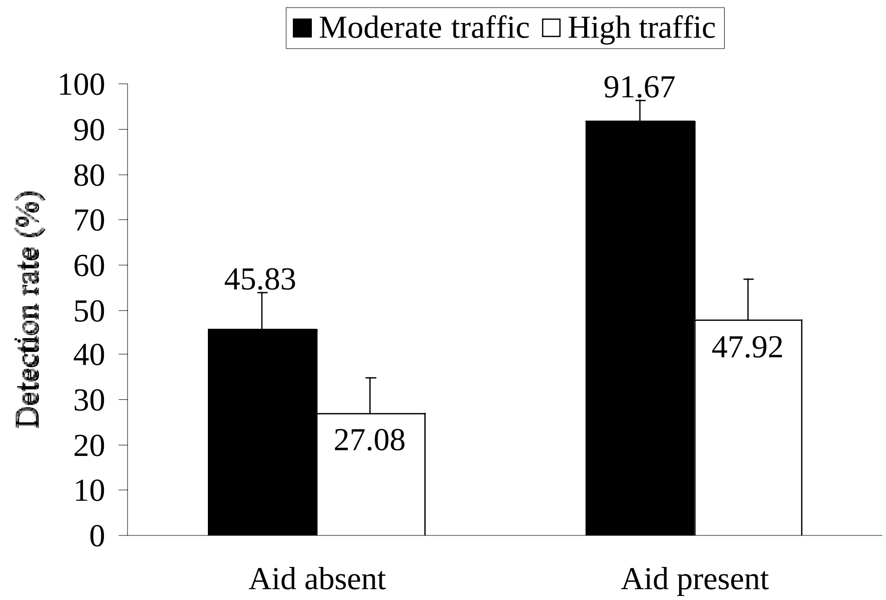


Figure 7.1: Detection rate for self-separations as a function of traffic density and the availability of a conflict detection aid

Advance notification times were averaged across the two conflicts and four self-separations in each scenario. Due to undetected potential conflicts, eight out of 96 cells (= 8.33%) were empty. In these cases controllers did not detect any of the conflicts or self-separations in a scenario. Since this would only leave six subjects in the analysis, the eight empty cells were replaced by the respective means of the conditions in which the cell was missing (e.g. mean of the condition aid present/high traffic).

Conflicts were detected earlier under moderate (M = 221.65 s; SE = 16.23 s) than under high traffic density (M = 199.41 s; SE = 20.92 s), but the effect failed to reach significance, $F(1, 11) = 1.52$, $p > .05$. Conflicts were detected earlier when the aid was present (M = 256.99 s; SE = 10.12 s) than when it was absent (M = 164.06 s; SE = 20.53 s), $F(1, 11) = 24.39$, $p < .001$. A trend for the interaction between the presence or absence of the aid and traffic density is displayed in figure 7.2, $F(1, 11) = 2.10$, $p = .18$. The presence of the aid achieved a greater performance benefit under high than under moderate traffic density.

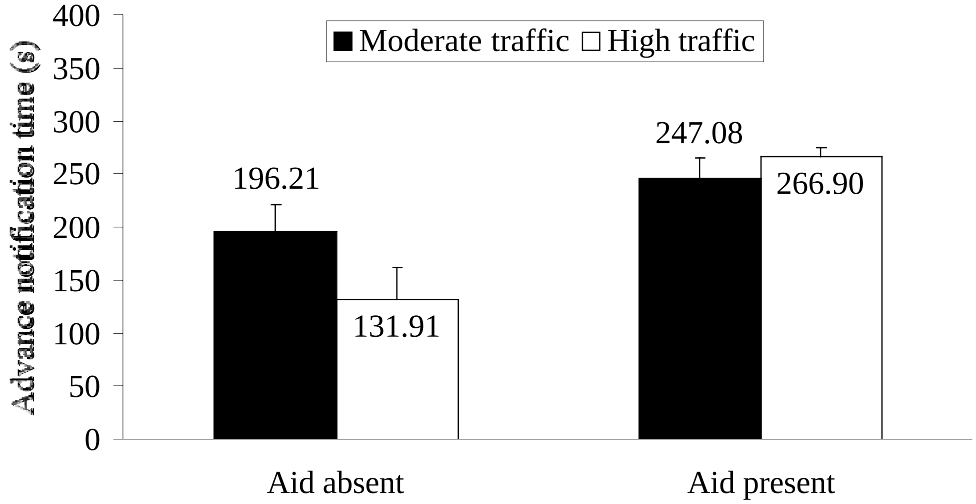


Figure 7.2: Advance notification time for conflicts as a function of traffic density and the availability of a conflict detection aid

Self-separations were detected earlier under moderate (M = 347.03 s; SE = 18.01 s) than under high traffic density (M = 251.20 s; SE = 11.39 s), $F(1, 11) = 17.23$, $p < .01$. A trend was found for an earlier detection of self-separations when the aid was present (M = 314.12 s; SE = 13.52 s) than when it was absent (M = 284.12 s; SE = 21.24 s), $F(1, 11) = 2.17$, $p = .17$. A trend for an interaction between the presence or absence of the aid and traffic density, $F(1, 11) = 2.03$, $p = .18$, is shown in figure 7.3. Similar to the detection of conflicts, a greater benefit was achieved under high than under moderate traffic density by the presence of the aid. There was no effect of the aid under moderate traffic because ATCos detected self-separations before the aid did.

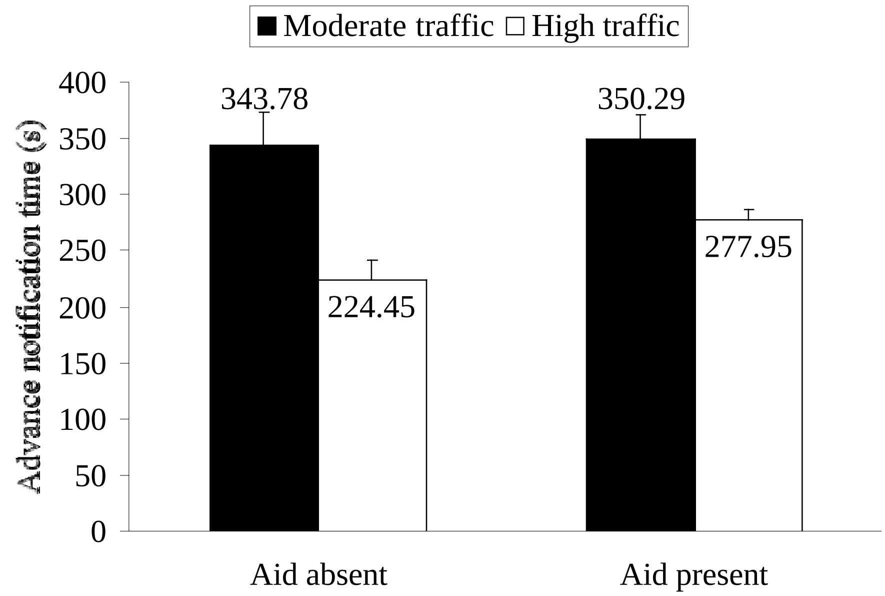


Figure 7.3: Advance notification time for self-separations as a function of traffic density and the availability of a conflict detection aid

7.3.2 Primary task performance: Accepting and handing-off aircraft

Controllers accepted more than 98% of the aircraft (*M* = 98.43%; *SE* = 0.42%) into their sector with an average response time of 41.91 seconds (*SE* = 2.48 s). Due to the small number of misses, no inferential statistics were calculated for the percentage of successfully accepted aircraft. There were no effects of the presence or absence of the aid, $F(1, 11) = .01$, $p > .05$, or the interaction, $F(1, 11) = .49$, $p > .05$, on response times. A trend was found for longer response times to accept aircraft under high (*M* = 46.01 s; *SE* = 4.20 s) than under moderate (*M* = 37.82 s; *SE* = 2.46 s) traffic conditions, $F(1, 11) = 2.63$, $p = .13$.

Controllers handed-off more aircraft successfully when the aid was present (*M* = 81.71%; *SE* = 3.19%) than when it was absent (*M* = 70.00%; *SE* = 4.91%), $F(1, 11) = 8.22$, $p < .05$. There were no effects of traffic density, $F(1, 11) = .06$, $p > .05$, or the interaction, $F(1, 11) = 1.44$, $p > .05$, on the percentage of aircraft handed-off successfully.

Controllers also handed off more aircraft prematurely when the aid was absent (*M* = 24.40%; *SE* = 5.08%) than when it was present (*M* = 13.80%; *SE* = 3.23%), $F(1, 11) = 6.78$, $p < .05$. Under high traffic density, ATCos handed-off significantly more aircraft early when the aid was absent (M = 25.95%; SE = 7.22%) than when it was present (M = 9.78%; SE = 3.35%). Under moderate traffic density, the effect of the absence (M = 22.86%; SE = 7.44%) or presence of the aid (M = 17.82%; SE = 5.43%) was smaller. This interaction was marginally significant, $F(1, 11) = 3.39$, $p = .09$. No main effect for traffic density was found, $F(1, 11) = .55$, $p > .05$.

Controllers handed-off aircraft significantly later under high (M = 44.41 s; SE = 5.98 s) than under moderate traffic conditions (M = 27.51 s; SE = 5.46 s), $F(1, 11) = 24.76$, $p < .001$. No significant effects for the presence or absence of the aid, $F(1, 11) = 1.58$, $p > .05$, or the interaction between traffic load and the presence or absence of the aid, $F(1, 11) = 1.06$, $p > .05$, on response times were found.

7.3.3 Secondary task performance

Performance in the secondary task was mostly affected by traffic density, but not by the presence or absence of the aid or the interaction between traffic density and the presence or absence of the aid. Controllers missed updating more waypoints under high (M = 63.41%; SE = 6.23%) than under moderate traffic density (M = 41.55%; SE = 6.73%), $F(1, 11) = 14.14$, $p < .01$. The presence or absence of the aid, $F(1, 11) = .00$, $p > .05$, or the interaction between the presence or absence of the aid and traffic density, $F(1, 11) = 1.25$, $p > .05$, had no significant effects. ATCos updated more waypoints early under moderate (M = 15.00%; SE = 3.62%;) than under high traffic density (M = 7.62%; SE = 2.39%), $F(1, 11) = 3.93$, $p = .07$. The presence or absence of the aid, $F(1, 11) = .02$, $p > .05$, or the interaction between the presence or absence of the aid and traffic density, $F(1, 11) = .03$, $p > .05$, had no significant effects on early updates.

Only ten ATCos entered the analysis of response times. One ATCo had no response times in the aid absent-moderate traffic condition, another participant missed updating all waypoints in all conditions. On average, controllers updated a waypoint 86.36 seconds (SE = 6.39) after the aircraft passed the corresponding waypoint on the radar display. No significant results were obtained for traffic density, $F(1, 9) = .29$, $p > .05$, presence or absence of the aid, $F(1, 9) = .21$, $p > .05$, or the interaction, $F(1, 9) = .83$, $p > .05$.

7.3.4 Physiological measures: HRV

The effect of traffic on the .10-Hz band of the HRV was significant, $F(1, 11) = 5.43$, $p < .05$, and indicated higher mental workload under high ($M = 4.63$; $SE = .19$) than under moderate traffic density ($M = 4.74$; $SE = .19$). The effect of the presence or absence of the aid, $F(1, 11) = .03$, $p > .05$, and the interaction, $F(1, 11) = .61$, $p > .05$, were non-significant. Other measures of cardiovascular activity (i.e. heart rate, heart rate variability, respiratory sinus arrhythmia) did not reveal effects of traffic density, the presence or absence of the aid, or the interaction between the two variables.

7.3.5 Subjective ratings of mental workload

Controllers rated their mental workload significantly higher under high ($M = 66.29$; $SE = 3.55$) than under moderate traffic conditions ($M = 52.57$; $SE = 3.47$), $F(1, 11) = 28.47$, $p < .001$. No significant effects were found for the presence or absence of the aid, $F(1, 11) = 1.27$, $p > .05$, or the interaction between the presence or absence of the aid and traffic density, $F(1, 11) = 1.01$, $p > .05$.

7.3.6 Trust

Controller ratings of trust in the conflict detection aid on a scale from 0 to 100 ranged from 30 to 90 with an average of 63.33 ($SE = 4.7$). Median and mode were both 70. This can be considered a moderate level of trust.

7.4 Discussion

The purpose of the experiment was to investigate if ATCos would perform better and experience lower workload under FF when they had a conflict detection aid available and if a conflict detection aid would be able to compensate for the reduced performance and increased workload associated with FF and the high traffic density expected for the future.

As expected, ATCos missed more potential conflicts and detected them later under high than under moderate traffic density. This validates the findings of adverse effects of high traffic density on controller performance and therefore system safety in earlier FF studies (Galster et al., 2001; Metzger & Parasuraman, in press). Especially the reduced timeliness of the detection of potential conflicts is of concern given that the highly dense and efficient airspace under FF conditions will leave the ATCos with less time to resolve conflicts. This could have serious implications for safety. However, the presence of a conflict detection aid significantly improved performance compared to manual conditions. ATCos detected conflicts and self-separations earlier and detected more self-separations with the support of a decision aid. Advance notification of conflicts and, to a smaller extent, the detection of self-separations in the presence of the aid and high traffic conditions (i.e. approximating future conditions) even exceeded performance levels in the absence of the aid and moderate traffic conditions (i.e. representing current conditions). Therefore, detection aids might be able (at a minimum) to compensate for the performance decrements typically induced by high traffic density and perhaps even exceed current levels of performance and safety. This is an encouraging result with respect to the FAA's goal to increase system safety and reduce accident rates drastically (FAA, 2000). Previous studies found that it took ATCos longer to detect potential conflicts under FF than under current conditions without decision aid (Metzger & Parasuraman, in press) even though FF will require ATCos to detect potential conflicts earlier due to the high density of traffic. The results of the present study suggest that the detection aid can reduce the time required to detect potential conflicts compensating for some of the adverse effects of FF conditions.

It should be pointed out, however, that the automation had a benefit on the percentage of detected self-separations, but not conflicts. Because conflicts represent failures of airborne separation, their detection is more important for system safety than the detection of self-separations. Therefore, an automation benefit would be more desirably for conflicts than for self-separations. Hence, the availability of a conflict detection aid might compensate partially, but not fully for the performance decrements induced by FF and high traffic. Further, the availability of a detection aid might not be an appropriate justification to expect controllers to manage an excessive amount of traffic because even with a detection aid they detected fewer conflicts under high than under moderate traffic density.

Performance in routine communication tasks showed similar adverse effects of high traffic density with and without a decision aid. Under moderate traffic conditions, aircraft were accepted earlier and response times to hand-offs were shorter than under high traffic conditions.

Beneficial effects were found for the decision aid. For example, ATCos handed off more aircraft successfully when the aid was present than when it was absent indicating that the conflict detection aid freed attentional resources that could be allocated to other tasks such as communication. Interestingly, more aircraft were handed off prematurely with than without the aid. This effect was particularly prominent under high traffic density. This could be interpreted as a controller strategy to manage workload. Perhaps controllers felt more time pressure when they were manually performing and under high traffic and were trying to hand off aircraft whenever they could, even if it was prematurely.

To summarize, the decision aid was successful in promoting ATCo performance in the detection of potential conflicts and routine tasks and could compensate for negative effects of FF and high traffic density. FF transfers separation authority from the ATCo to the pilots removing the ATCo from the decision-making process. Reduced performance (e.g. delayed conflict detection) under FF conditions (Metzger & Parasuraman, in press) is a reflection of the ATCo being out of the decision loop. Even though automation does not bring the ATCo back into the decision loop, it improves ATCo performance by performing the ATCo's decision-making function. Moreover, one could indeed argue that the automation removes ATCos further from the processes in the system because ATCos now become passive monitors not only of pilot actions, but also of the automation. This is acceptable as long as the ATCo is not required to intervene, but could pose problems once ATCo intervention is required.

Mental workload was increased under high compared to moderate traffic density irrespective of the presence or absence of the detection aid. In contrast to the hypothesis, the decision aid did not reduce mental workload. While performance increased tremendously with the aid, mental workload remained unchanged. In the terms of figure 4.2, this represents a workload insensitivity (Parasuraman & Hancock, 2001). According to the model by Wickens et al. (1997), it could be argued that decision aid freed resources that ATCos chose to allocate to other tasks (e.g. communication) leaving workload unchanged. That successful hand-offs benefited from the aid supports this view. However, alternative interpretations are conceivable. It could be argued that due to the high demand for ATCo monitoring of pilot actions and the automation workload was not reduced (Warm et al., 1996). An additional explanation is that traffic density might be a stronger workload driver than automation. Each aircraft requires the

ATCo to perform many routine and coordination tasks that are not supported by the decision aid. Hence, a conflict detection aid would not reduce these tasks and their associated workload.

The lack of a workload reduction could also be a consequence of the short look-ahead time of the aid. Controllers might have felt that a five-minute look-ahead time would not be enough to control the situation. Therefore, they relied on their own skills rather than fully depending on the aid and used the aid as a back-up in case they missed a potential conflict. That many self-separations under moderate traffic conditions were detected before the aid indicated a potential conflict and the moderately high ratings of trust support this view. Using the automation only as a back-up would be a good strategy because it keeps the operator involved and able to intervene in a timely manner should the need arise. However, if controllers rely on their own skill to detect conflicts, it is obvious that mental workload cannot be considerably reduced by the introduction of the aid. Therefore, a conflict detection aid might be helpful in increasing safety by helping controllers to detect conflicts earlier, but it might not be an appropriate means to increase the amount of traffic they can manage if they only use it as a back-up and workload is not reduced. Even though it seems surprising that controllers did not experience lower workload with the aid of a conflict detection aid, other studies found similar results (Skitka et al, 1999). For example, pilots did not rate their workload lower when they had a decision aid available than when they were unsupported. This creates the potential for an acceptance problem. If operators do not subjectively experience the benefit of a tool, they might be hesitant to accept and use it.

Based on discussions with the controllers, it is not surprising that trust ratings were not higher. Their comments were not very favorable of detection aids in general and the one used in the simulation. Currently, en route centers and TRACON have short term conflict alerts (STCA) that indicate, based on a simple threshold-crossing algorithm, if aircraft will be in conflict within the next two minutes based on current speed and heading. This algorithm leads to frequent false alarms, for example for aircraft flying under VFR that are not subject to the 5nm/1000 feet separation standards. The conflict detection aid used in the study analyzed and integrated data from different sources (e.g. radar data, flight plans) and projected aircraft status several minutes into the future. Real-world detection aids can include highly sophisticated algorithms that consider additional numerous parameters (e.g. climb rates for different aircraft types, wind and weather models, etc.). They have little in common with the simple threshold-crossing alerting mechanism of the STCA. Perhaps this difference between the aid in the experiment and the aid they use on the job was not made clear enough. Better instructions as well as training to improve the ATCos' understanding of the aid could help to increase their trust in and reliance on the aid and therefore reduce workload. As Masalonis (1999) found, ATCos vary their trust and are mostly affected by misses rather than false alarms. Perhaps ATCos perceived the aid as too conservative to be trustworthy because it did not give any false alarms. In addition, ATCos might have felt that the five-minute look-ahead time of the aid would not give them enough time to resolve a conflict. In fact, ATCos detected self-separations under moderate traffic before the aid indicated a potential conflict. This represents a ceiling effect and the look-ahead time of the aid should be increased in future studies. However, the earlier the warning the more likely it is that a controller will be notified of an impending conflict which later turns out not to be a conflict, for example because of changing winds or because pilots self-separated. In the real world, longer look-ahead times might lead to high false alarm rates and an underutilization of the aid as a long-term consequence. This illustrates the challenge of designing decision support tools for ATC systems. Unlike in other systems (e.g. power plants) where processes follow well understood principles of physics and are relatively easy to predict, processes in the ATC system are much more difficult to predict. Weather and temperature predictions are still not very accurate (e.g. the prediction of clear air turbulence) and the prediction of human actions presents an even greater challenge. In the current ATC system, rules and tight control of ATCos over pilots make the pilots quite predictable. But if rules and restrictions are lifted in favor of a greater level of freedom for the pilots in a FF environment, the prediction of pilot actions becomes much more difficult (cf. Corker, 2000).

Finally, it should be noted that although controller performance was significantly improved by the aid, it was not perfect. A significant number of potential conflicts was still missed. In the real world, this would not be acceptable. The high number of missed events can probably be attributed to the fact that traffic patterns were created by the experimenter and did not represent recorded or live traffic as in some higher-fidelity ATC simulations. Therefore, they lacked some of the structure that ATCos are used to. However, that would be the case under FF as well. Also, ATCos were not nearly as familiar with the sector as they would be in the real world. Therefore, the values obtained (e.g. detection rates) should be considered as a conservative estimate and not be directly compared to real world numbers, but rather to the different conditions created in the simulations. Another reason for the less than optimal controller performance in terms of conflict detection even with the detection aid might be the high visual demand of the separate, non-integrated datalink display. Accepting and handing off aircraft as well as the secondary task of updating the waypoints required a high level of searching for and monitoring of information leading to a potential attention diversion away from the radar display. ATCos might have missed conflicts because they did not see them due to their attention to the data link and flight strips. If attention is allocated to the datalink and flight strip displays, the onset of a conflict alert would have to be detected through peripheral vision. However, slow movements and color are not easily detected in peripheral vision (Palmer, 1998). Conflict detection aids with auditory feedback might be more salient and draw the attention of the controller back to the radar display. The use of eye tracking equipment would reveal ATCo attention allocation strategies and how they are affected by different levels of traffic density.

This leads to the conclusion that the provision of a conflict detection aid could serve to mitigate some of the performance problems that several studies have shown (Endsley et al., 1997; Galster et al., 2001) and even increase system safety under high traffic and FF conditions. In addition, the decision aid might free resources that can be allocated to the performance of other tasks.

8. Experiment 2: Effects of traffic density and automation feedback type

8.1 Introduction

The main driver of proposals such as FF and automation is the need to accommodate unprecedented amounts of traffic. Increasing airspace capacity is the ultimate goal of any attempt to modernize the ATC system. While it is possible to divide sectors into smaller sectors to reduce ATCo workload this strategy has its limits as pointed out previously (see chapter 4). Increased airspace capacity can be achieved by allowing more aircraft to occupy the same amount of airspace. As a consequence, traffic density will be considerably increased. Traffic density, however, is a major contributor to ATCo mental workload and ATCos are limited in the amount of traffic they can safely handle. Less space between aircraft translates into less time to detect and resolve potential conflicts and therefore into reduced safety margins. Several experiments found that ATCos required extra time under FF conditions to detect potential conflicts (Galster et al., 2001; Metzger & Parasuraman, in press). While ATCos in these studies were not assisted by decision support tools, the previous experiment indicated that decision aids could improve ATCo performance under FF conditions. Still, performance was reduced and workload increased under high compared to moderate traffic density. Not only will FF increase traffic density, it will also make traffic patterns less structured than they currently are (see figure 5.1; Ball et al., 1995). While under current conditions conflicts between aircraft can only occur at the intersections of jetroutes, under mature forms of FF conflicts could occur at any point in the airspace.

These factors have implications for the ATCos' visual scanning of the radar display and other information sources in the ATC environment. If controllers miss a conflict or commit an operational error, they often report that they failed to notice or see critical information (Stein, 1989, 1992). Clearly, the multitude of stimuli that competes for the controller's attention at one time is an important contributor to such failures to attend to critical information. The ATCo's job is composed of many tasks and mostly based on visual information - scanning the radar display to build "the picture" of the situation and detect conflicts or reading the flight strips to plan and avoid problems ahead of time. Only for voice communication with pilots and other ATCos, the ATCo uses the auditory channel. Selecting one of many sources of visual information can lead to a failure to perceive critical information especially when traffic density is high and many information sources compete for the controller's scarce resources.

Voice communication is a rather direct way of communicating and has the advantage that even prosodic information is transmitted that could alert ATCos of emergency situations (e.g. when an ATC can "sense" from the sound of the pilot's voice that he or she is distressed or in panic). However, controller-pilot digital datalink communicaton (CPDLC) has been proposed as a means to alleviate pressure on the often congested radio frequencies. It is envisioned that CPDLC will be used for the transmission of most routine messages and to individually address single aircraft instead of addressing all aircraft on a frequency. Only emergency transmissions or information that is useful for other pilots on the same frequency will be transmitted via radio-telephony. The introduction of datalink communication will considerably alter the ATCo's workplace. CPDLC will add a layer of technology between pilots and ATCos and distance them from each other. Pilots will loose party-line information (e.g. transmissions from pilots on the same frequency that might be of interest to other pilots) and prosodic aspects of human speech will no longer be available. While the use of voice communication allows ATCos to take advantage of different information-processing channels (i.e. visual and auditory), datalink will reduce the use of the auditory and pose a greater burden on the visual channel. As a consequence, the ATC environment will become even more visual in nature because ATCos will have to rely on the visual channel to compose and read datalink messages (unless synthetic speech is used) and to operate the interface. Together, increasing traffic density, unstructured traffic patterns, and datalink communication will create unprecedented demands for limited visual attentional resources. Moreover, it could be speculated that the datalink display diverts attention away from the radar. How this will affect ATCo performance and the distribution of visual attention especially under high traffic density remains to be studied. Hilburn (1996) found few effects of traffic density on the scanning of a datalink display. However, the datalink in his study was integrated on the radar and the aircraft datablocks. While this might be a preferred design option, it might not actually be implemented that way.

The increasingly visual nature of the ATCo environment parallels an earlier trend in the cockpit. In older aircraft, pilots received feedback from cues other than the visual modality. They were “flying by the seat of their pants”. Vibration or sound of the rather noisy engines provided the pilot with feedback on the state of the engines. Moving throttles gave feedback on the amount of thrust. Today, engines are less noisy and throttles do not move anymore. Technology added a layer between the human and the machine and the information that pilots used to be able to hear or feel now have to be conveyed through a large number of visual displays.

Sklar and Sarter (1999) attributed many break-downs in human-machine cooperation in the aviation domain to the almost exclusive use of visual feedback. Multi-modal feedback has recently been suggested as a means to improve human interaction with automation and to mitigate some automation costs (Parasuraman, 2000; Sarter, 2000). As systems become increasingly automated and the human element is further removed from the system, the user needs more feedback on the state of the system especially under high levels of automation (Norman, 1990; Sarter, 2000). To avoid overloading the visual modality, the use of input modalities other than the visual one has been discussed (Sklar & Sarter, 1999; Sarter, 2000; Brickman, Hettinger, & Haas, 2000). Focal visual attention might not be an appropriate resource for all information. Because humans cannot attend to all visual stimuli at the same time, it becomes necessary to guide and capture the attention of the operator with other types of feedback. Sarter (2000) suggested the use of cues in the operator's visual periphery as well as tactile and auditory feedback. Sklar and Sarter (1999) conducted a study in which pilots received feedback on unexpected changes in an automated cockpit system with either visual, tactile or a combination of visual and tactile feedback. Pilots detected the highest percentage of events in the tactile feedback condition and responded fastest in the multi-modal (i.e. visual and tactile) feedback condition.

Focal visual attention is an appropriate resource when the operator is aware of the need to attend to information. However, if the operator needs to be informed that important information is available (e.g. when a conflict between aircraft is present on the PVD), an omnidirectional modality could provide benefits. Auditory or tactile feedback can capture and guide the attention of the operator irrespective of where he or she might be looking.

In the highly visual environment of the flight deck and other systems (e.g. process control), the auditory modality is already being used to guide and capture attention. For example, the traffic collision and avoidance system (TCAS), now mandatory in all commercial aircraft in the US, uses visual and auditory feedback to notify the crew of aircraft in close proximity and to advise the pilot on an avoidance maneuver. While visual feedback provides the pilot with the spatial information (i.e. where the intruding aircraft is), traditional auditory feedback does not include such information. The function of most auditory feedback is to direct attention to the spatial information on the visual display (Begault & Pittman, 1996). In the future however, three-dimensional auditory displays will even allow information on the location of a stimulus to be provided to the operator (Brickman et al., 2000).

Brickman et al. (2000) discussed the use of multi-modal feedback in combat aircraft. While compared to older aircraft more visual information is available in modern aircraft, the pilot is expected to respond faster and is allowed increasingly less time to attend to the information. Brickman et al. suggested the use of haptic, tactile, three-dimensional auditory, and even olfactory feedback to support visual performance in such environments.

The advantage of tactile and auditory cues are their omnidirectionality and little space requirement. Further, they are difficult to suppress and allow for parallel processing. Disadvantages include their intrusiveness and clutter if used in excess (Sarter, 2000).

Currently, auditory channels are not utilized for automation feedback due to the heavy use of voice communication in ATC. However, auditory automation feedback could be an option for future ATM systems that will rely heavily on controller-pilot digital datalink communication. The use of auditory feedback is already being investigated by the FAA (Newman & Allendoerfer, 2000). While the current system makes use of visual and auditory information-processing channels, the introduction of datalink in future systems will emphasize the visual and de-emphasize the auditory channel. Hence, auditory feedback would be an option to direct attention to visual stimuli in an increasingly visual environment. The increasing traffic and the associated amount of information on the PVD will make it essential to find better ways to guide and capture controller attention. Multi-modal feedback could be one such way.

There has been a long debate on the basic mechanisms of dividing attention between modalities and selectively attending to different modalities. Researchers disagree whether there is one supramodal attention mechanism that limits the processing of information from different modalities (e.g. interference, time requirement when shifting from one modality to the other) or if there are different attentional mechanisms for different modalities that operate independently leading to performance benefits when two modalities are used.

Multiple resource theory (Wickens, 1984) suggests that task-sharing is improved if information is distributed across different resources. Sensory modalities define one dimension of resources. Each modality has its own pool of resources. If two or more sensory modalities instead of one are used, information can be processed in a parallel rather than serial manner because additional resources from another pool are available for allocation. Based on this theory, a performance benefit would be expected when different input modalities are addressed. Indeed, empirical evidence for performance benefits was found in dual-task studies. However, the benefit of distributed attention across modalities could be due to a lack of interference in the periphery.

Spence and Driver (1997a, 1997b, 1997c) proposed that auditory and visual resources do not operate independently. They found a significant performance cost when participants had to shift their attention from one modality to the other in a range of tasks such as simple detection or discrimination tasks. Further, shifts of attention in one modality were associated with shifts of attention in the other modality. They also found that is was difficult for participants to direct visual and auditory attention to different locations simultaneously and that this could only be achieved with a cost in performance. This was interpreted as evidence that the visual and auditory modalities do not operate independently. Spence and Driver (1997a) characterized the link between different modalities as a one-way cross-modal link. While an unpredictive (e.g. of location) auditory alert reduced response times to both, auditory and visual stimuli, a visual alert produced performance benefits for visual, but not for auditory stimuli (Spence & Driver, 1996). Auditory orienting leads to visual orienting, but visual orienting does not lead to auditory orienting.

Researchers seem to agree on the notion that auditory signals have greater alerting properties than visual warnings (Posner, Nissen, & Klein, 1976; Perrott, Sadralodabai, Saberi, & Strybel, 1991; Spence & Driver, 1997a). Posner et al. (1976) found that an auditory warning signal was more effective than a visual one in reducing response times to a visual target. While an auditory signal presented simultaneously with or after a visual target reduced response time to a visual target stimulus, the opposite was not true. Visual warning signals did not speed up response to visual targets. The reason for this asymmetry has not been fully explained yet.

While alerting based on visual stimuli usually requires effortful processing, auditory signals can often be processed automatically. However, if situations are created in which visual signals can also be processed automatically (e.g. when the subject is already expecting a visual signal), the benefit of auditory alerting is reduced.

Perrott et al. (1991) found an advantage of spatially correlated auditory cues on response latencies over no-sound cue conditions in a visual search task under different levels of visual load and different distances between the fixation point and search target (0-14.8 degrees, i.e. within the central visual field). After an initial fixation point was presented, participants had to search for a target in an array of distractors and press one of two buttons depending on the orientation of the target ("<" or ">"). The presence of spatially correlated auditory information improved visual search performance compared to no-sound conditions. Even when the target appeared at the initial fixation point (i.e. no search was necessary), performance was better with auditory cues. This is an important indicator of the greater alerting properties of auditory compared to visual cues. However, the benefits of spatially correlated auditory cues became even more evident when the target was located at greater distances from the initial fixation point (i.e. requiring a shift of gaze) and the display became more cluttered. Comparing a spatially correlated auditory cue to a visually enhanced target (i.e. white target on black background and black distractors on white background) revealed a similar advantage of the auditory over the enhanced visual cue. The utility of the auditory cue was small when the target was near the initial fixation point and few distractors were present, but became greater when the target was remote and more distractors were present. This indicates that sound is useful even in situation when a very distinct and easy to detect visual stimulus requires attention.

Consequently, the benefits of better conveying information with visual and auditory signals simultaneously (e.g. auditory information can be presented outside the current field of view) and the better alerting properties of auditory signals need to be weighted against performance decrements due to the division of attention between the visual and auditory modality when introducing multimodal feedback into systems.

The purpose of the next experiment was to twofold. First, the impact of different levels of traffic density on ATCo performance, mental workload, and eye movements were investigated when ATCos were supported by a decision aid. Of particular interest was the distribution of eye movements across different areas of interest (e.g. the datalink) under levels of moderate and high traffic density in an environment where ATCos were supported by a decision aid. Second, the effectiveness of different types of feedback to capture and guide ATCo attention in a highly visual environment was investigated. It was investigated if a conflict detection aid with visually enhanced and multi-modal feedback could improve conflict detection performance further and reduce mental workload.

Hence, the present study investigated the effect of different levels of traffic density and different types of feedback (single modality versus multi-modal) on controller performance, mental workload, and visual attention in an ATC task simulating FF conditions.

8.1.1 Hypotheses and research questions

The distribution of visual attention across the displays as indicated by eye fixations and dwells was examined under moderate and high traffic. This should indicate how a datalink display and the expected high levels of traffic expected for the future will impact (visual) attention processes of the ATCo. Due to its purely visual nature, the datalink has the potential to divert ATCo attention away from the PVD, especially under high traffic, when there is increased demand for communication. So far, very few studies have investigated visual attention in ATC using eye movements, especially when controllers were using a datalink for communication under FF conditions. This was an exploratory investigation without specific hypotheses.

It was expected that multi-modal feedback would result in better conflict detection performance (i.e. higher detection rates and earlier detection) than simple visual feedback, especially under high traffic density. Therefore, the hypothesized performance benefits of multi-modal feedback would be greater under high than under moderate traffic density. The same prediction was made for a visually enhanced form of feedback that provided information on the expected flight path and the resulting location of the predicted conflict. In the previous experiment it appeared that controllers were not always sure why they received a conflict feedback when aircraft were not on an immediate head-on conflict course (i.e. when one or both aircraft had to make a heading change as indicated on their flight plan before they got into conflict). It was expected that a visually enhanced feedback would make the decision of the aid more transparent leading to a reduced visual search requirement. Under FF conditions, it is essential that ATCos detect and respond to potential conflicts fast because traffic density is high and leaves little time before a loss of separation occurs. Therefore, benefits of visually enhanced and multi-modal feedback were expected especially for advance notification times. It was also expected that mental workload would be reduced under enhanced and multi-modal feedback compared to simple visual feedback because both provided an indication of where the conflict would occur and should reduce the need to search the display to find this point of conflict. In addition, it makes the decision of the aid more transparent and comprehensible to the ATCo by displaying the converging flight paths.

Among other factors, the use of automation and ultimately performance in a human-automation system is determined by the operator's trust in the aid and self-confidence to perform the task without the aid. It was anticipated that controllers would be less self-confident to detect conflicts without the aid under high than moderate traffic density and that controllers would trust the enhanced aid more than the simple visual aid because it makes the reason for the decision and the alert more comprehensible.

8.2 Method

8.2.1 Participants

Eight active ATCos from the Washington Center air route traffic control center (ARTCC; $n = 5$), Baltimore-Washington International (BWI; $n = 2$) and Dulles (IAD; $n = 1$) terminal radar control area (TRACON) facilities served as paid volunteers. Due to the introduction of new equipment as part of the modernization of the en route ATC system at the Washington Center ARTCC and scheduled training and overtime for most staff, it was difficult to recruit en route controllers at the time of the study. Therefore, TRACON controllers were included in the experiment. ATCos were between the ages of 33 and 45 years ($M = 37.38$; $SD = 3.82$). Their overall ATC experience in terms of years on-the-job ranged from 11 to 21 years ($M = 15.31$; $SD = 3.71$). En route and TRACON controllers did not differ in terms of age, $F(1, 6) = 1.47$, $p > .05$, or years on-the-job, $F(1, 6) = 0.56$, $p > .05$. All participants were male.

8.2.2 Apparatus

For a description of the ATC simulator see Experiment 1. The set-up was identical to the previous experiment with the exception that the PVD and the datalink display were both presented on 21-inch monitors. The 21-inch monitor was used to facilitate the search for information on the datalink and the flight strips and to allow for more accurate analysis of eye movements. A speaker was placed on the left and right side of the simulation set-up to present auditory warning signals at a frequency of 1000 Hz for 500 milliseconds. The warning signals were spatially unpredictive, that is, they provided no information on the location of the conflict.

Because ATCos detected potential conflicts in the previous experiment at around the time when the conflict detection aid appeared (ceiling effect), the look-ahead time of the detection aid was increased from 300 s (previous experiment) to 360 s in the present experiment.

Instead of verbally indicating when controllers detected a conflict, a "conflict button" was implemented in this version of the ATC simulation in order to obtain conflict detection performance parameters (e.g. detection times) as part of the computerized output. Controllers were instructed to select the aircraft that they decided were in conflict and then click the conflict button in the upper right corner of the PVD. The aircraft involved and the time of detection were included in the data output file. Figure 8.1 shows the conflict button as well as the detection aid with enhanced visual feedback.

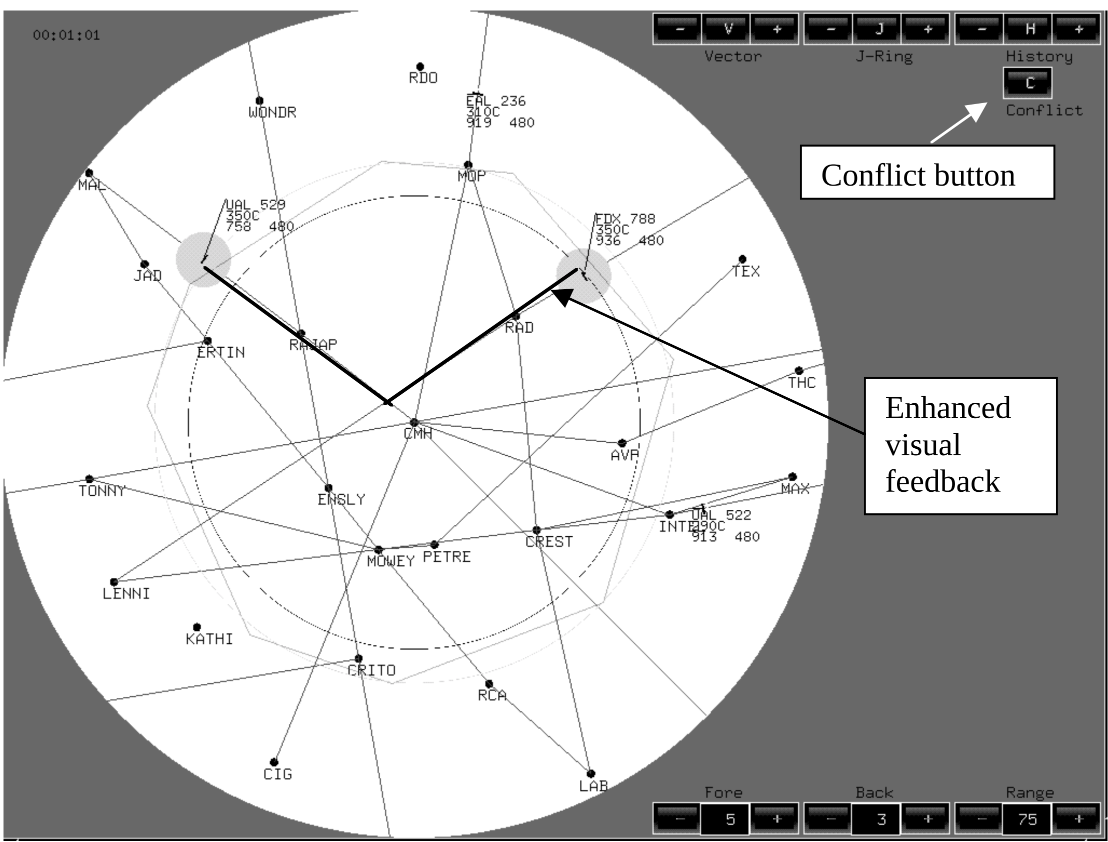


Figure 8.1: PVD with conflict button and enhanced visual feedback

Subjective ratings of trust in the detection aid and self-confidence to detect conflicts without the aid as well as NASA-TLX ratings were obtained.

The tasks and dependent variables were the same as in experiment 1 with the exception that cardiovascular activity was not recorded in this experiment. However, ocular activity (i.e. eye fixations and dwells) was recorded as a measure of visual attention.

Eye and head tracking system. An Applied Science Laboratory (ASL) Model 5000 eye tracker was used to record eye movements from the left eye. The head-mounted system determines eye movements based on the corneal reflection technique at a sampling rate of 60 Hz. A magnetic head-tracker (The Flock of Birds®, Ascension Technology Corporation) was used to allow and account for participants' head movements. The Flock of Birds is a six-degree-of-freedom measuring device that tracks the position and orientation of a receiver by a transmitter when the receiver is located within about 1.3 meters of the transmitter. Position and orientation of a receiver mounted on the headband are determined by the transmission of a pulsed magnetic field from the transmitter to the receiver. From the measured magnetic field characteristics, the receiver computes position and orientation of the head and sends the information to the host computer where the information is then merged with the eye position data. The computer system is then able to separate and "subtract" the head movements from the eye movements. Eye and head tracker together determine the participants' point-of-gaze with respect to a scene while accounting for head movements (e.g. from the flightstrips to the PVD).

The eye-head tracking system consisted of a PC with interface cards and the necessary software, control units for the eye tracking system and an adjustable headband including an optics system and a visor to mount the equipment on the participants' head. The optics system contained an eye camera and an illuminator that sends a near-infrared beam to a visor. The illumination beam is coaxial with the optical axis of the eye camera. The visor deflects the light beam into the participant's left eye to illuminate the cornea. At the same time, the eye camera continuously records images of the eye and the reflection of the beam off the cornea that are mirrored in the visor. This is transmitted to the eye camera control unit. The eye tracker control unit consists of three monitors (experimenter monitor, monitor for scene and eye image) and connects to the PC.

The ASL 5000 eye tracker uses the corneal reflection technique to compute the eye line of gaze. The distance between the reflection of the illuminator from the front surface of the cornea and the midpoint of the pupil is approximately proportional to the extent of the eye movement. The relationship between eye line of gaze and the distance between pupil and corneal reflection (PCR) is determined with equation 8.1.

$$PCR = K \sin(\theta) \qquad \text{(Equation 8.1)}$$

K is the distance between the iris and corneal center of curvature and θ is the eye line of gaze angle with respect to the light source and camera. The corneal reflection is detectable over about a 30-40°-diameter field of visual angle (without head movements).

A calibration process adjusts this relationship to interindividual differences such as cornea shape. Figure 8.2 explains how the distance between pupil center and corneal reflection is obtained. As the eye moves, the reflection off the cornea stays constant. Only the center of the pupil moves. The change in distance between the midpoint of the corneal reflection and the midpoint of the pupil is proportional to the change in point-of-gaze.

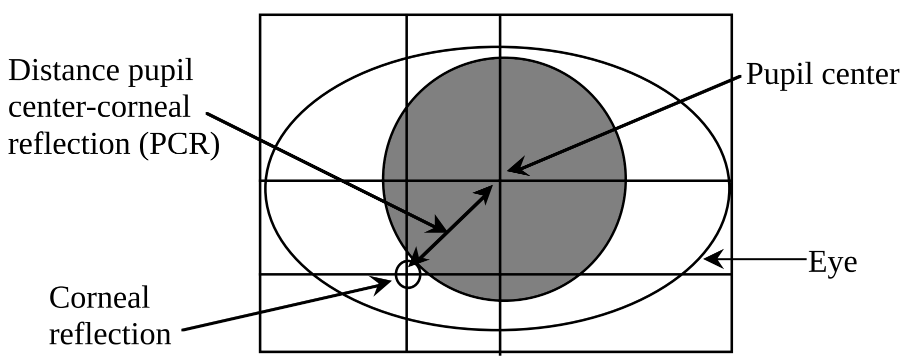


Figure 8.2: Determination of point-of-gaze and pupil diameter

There is no single agreed upon definition of a fixation other than that a fixation refers to the time between saccades when the eye is stationary. The analysis program provided by ASL defines a fixation as the mean x- and y-coordinates measured over a minimum of 100 milliseconds during which the eye does not move more than 1° visual angle vertically and horizontally. A dwell was defined as a series of contiguous fixations within a defined area of interest (e.g. the radar display). Dwell duration is the "sum of all the fixation durations that make up a dwell" (ASL, 1999).

In more detail, fixations are determined with a three-boundary approach with boundaries of 0.5°, 1.0°, and 1.5°. For data sampled at 60 Hz, the program starts by examining a window of six data points or samples (16.6 ms each) for their standard deviation (SD) of the horizontal (x) and vertical (y) eye position coordinates. If the SD are smaller than 0.5°, the mean x and y coordinates are used as the temporary fixation coordinates (x_t, y_t). If the SD is greater than 0.5°, the window is moved until a window of six data samples is found that has a SD of smaller than 0.5°. This is the fixation start point. Then the program calculates the horizontal and vertical distance (d_x, d_y) of the next data sample from x_t and y_t. If d_x and d_y is smaller than 1°, the sample is included in the fixation and the next sample is tested. If it is not smaller than 1°, the next sample is tested. This process is repeated until a data sample is found that is less than the 1° criterion or until three sequential samples have been tested. If one of these samples is less than 1°, previous samples that were greater than 1° are tested against a third criterion, namely 1.5°. All samples that are less than 1° or 1.5° are then included in the fixation and used for the determination of the final fixation position. If d_x and d_y from three sequential samples exceed 1°, the means of x and y are calculated. If the means do not differ from x_t and y_t by more than 1°, they are included in the fixation. If they differ more than 1°, the previous fixation is terminated at the last acceptable sample and the process reiterates with a new fixation. Blinks were defined as a pupil loss of 200 ms or less. However, a blink does not terminate a fixation. Pupil loss of more than 200 ms terminates a fixation at the last acceptable sample.

For the analysis of eye movements, three areas of interest were defined corresponding to the three ATC simulation tasks of conflict detection, communication to accept and hand-off traffic, and updating the flight strips: (1) the radar display, (2) the communication area, and (3) the flight strips. The ASL analysis program allows to match fixations and dwells to these areas and determine how often and how long the eye fixated or dwelled on each area. Figure 8.3 shows a schematic of these areas of interest. While the eight points in the figure represent eight fixations, the series of five contiguous fixations within the radar display constitutes one dwell.

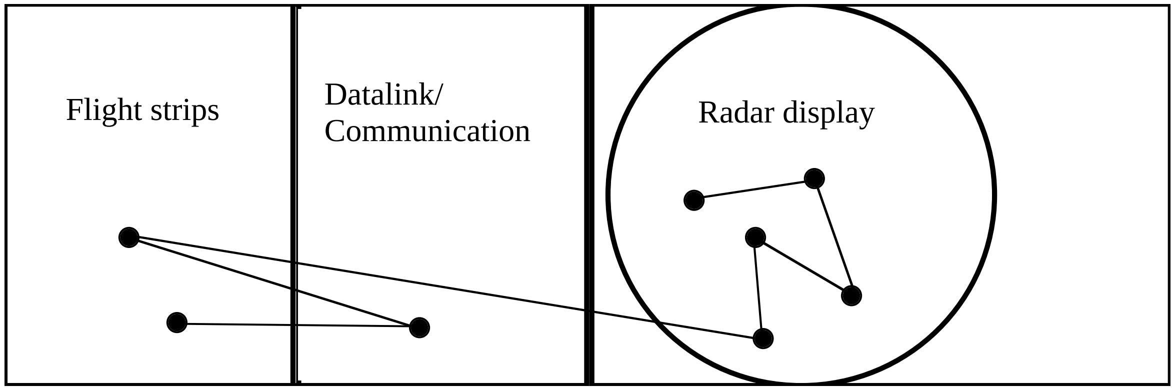


Figure 8.3: Areas of interest created for analyzing eye fixations and dwells on the simulation

Entropy, or scanning randomness, was calculated based on dwell transitions between these areas of interest using equations 8.2a or 8.2b (Harris, Glover, & Spady, 1986)

$$H = \sum_{i=1}^{D} H_i \qquad \text{(Equation 8.2a)}$$

$$H = -\sum_{i=1}^{D} p_i \log_2 p_i \qquad \text{(Equation 8.2b)}$$

where

H = observed average entropy

p_i = probability of transition between two areas of interest x_{ij} divided by the sum of the off-diagonal terms in the transition matrix

D = number of off-diagonal terms in transition matrix N(N-1)

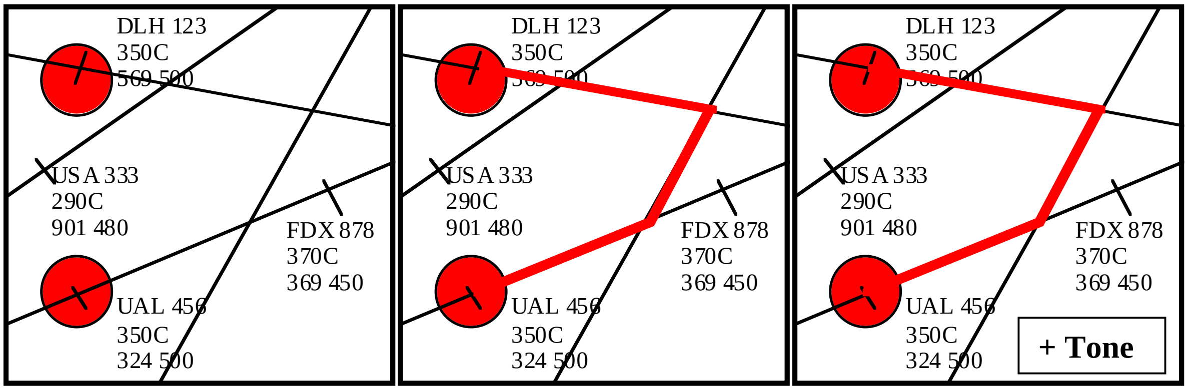
N = number of areas of interest.

8.2.3 Design

A two-factorial repeated measures design with two treatment levels on one and three treatment levels on the other factor was chosen. Independent variables were (1) traffic density with (a) moderate and (b) high levels of traffic in the ATC sector and (2) feedback type of the conflict detection aid with (a) simple visual, (b) enhanced visual, and (c) multi-modal feedback as treatment levels. All ATCos performed in all resulting six conditions. The order of feedback type was counterbalanced across participants. The order of traffic density was fixed. The low traffic conditions were always performed before the high traffic conditions in order to give

ATCos additional practice before performing under high traffic density. Both traffic density conditions per feedback were completed before performing in the next feedback condition. The dependent variables are listed in table 6.1.

For each condition, one scenario was created. Controllers were presented with six 25-minute scenarios that were created to combine high (on average about sixteen aircraft in the sector at one time after an initial 10-minute ramp-up period) and moderate (ten aircraft) traffic density with three different types of feedback in a 50-mile radius sector. The conflict detection aid alerted the controllers of an impending conflict six minutes before the loss of separation. Because in the previous experiment ATCos sometimes reported potential conflicts before the aid appeared, the look ahead time was increased from five (previous experiment) to six minutes. The three different types of feedback presented in figure 8.4 were used: (1) a simple visual aid indicating with a red filled circle which aircraft were predicted to be in conflict, (2) an enhanced visual aid indicating with a red filled circle which aircraft were predicted to be in conflict and indicating with two red heading lines why and where they were predicted to be in conflict, and (3) an enhanced visual aid with an auditory component (multi-modal feedback condition). The enhanced visual aid was provided in order to make the decision of the aid more transparent. The auditory feedback produced two short tones (approximately 500 ms) at 1000 Hz as soon as the visual aid appeared on the screen. In fact, only two different scenarios (one for moderate and one for high traffic) were used. In order to create a second set of scenarios, the sector and traffic patterns were rotated to simulate a different flow of traffic. Therefore, the scenarios for the three feedback type conditions were essentially the same and differences in controller performance and mental workload should be due to the feedback manipulation and not other variables specific to a particular scenario (e.g. conflict geometries). Each scenario contained five potential conflicts that were to be detected - three self-separations and two conflicts.



(1) Simple visual feedback (2) Enhanced visual feedback (3) Multi-modal feedback

Figure 8.4: Feedback conditions

8.2.4 Procedure

After providing biographical information, controllers were given a demonstration of the simulation, completed a fourteen-minute practice trial, and were familiarized with the NASA-TLX. Training was more extensive than in the previous study. ATCos received more information on the functionality of the aid with a specific emphasis on the differences between the STCA controllers currently use in their facilities and the more advanced functions of the aid in the study. ATCos were told that the aid used in this experiment detected conflicts not just based on current location, speed, and heading, but also based on the flightplans of aircraft and six minutes in advance. They were given several examples.

Then, controllers completed the six 25-minute scenarios and rated their mental workload on the NASA-TLX and the trust rating scales after each scenario. Two controllers wore the eye-tracker in all three high traffic conditions. Due to the weight of the eye tracker and the pressure from the headband, this proved to be too long a time for the participants to wear the eye tracker comfortably. Therefore, the remaining six ATCos wore the eye tracker in two (one high and one moderate traffic condition) out of six scenarios.

8.3 Results

All eight participants could be entered into the analyses. The following measures of performance and mental workload were analyzed with 3 (feedback type) x 2 (traffic density) repeated measures ANOVAs. Both variables were within-subject factors. An alpha level of .05 was used for all statistical tests.

8.3.1 Primary task performance: Detection of conflicts and self-separations

Controllers detected almost all events except for five potential conflicts out of 240 events to be detected. This corresponds to a near-perfect detection rate of 97.92% (SE = 0.93%). Due to the small number of missed events no inferential statistics were calculated. The missed potential conflicts were in five different scenarios (two under high, three under moderate traffic; three self-separations and two conflicts). Only in the high traffic and simple visual feedback condition did all ATCos detect all events.

Advanced notification times for conflicts and self-separations were calculated by averaging notification times across the two conflicts and three self-separations, respectively. For the five missing events, the advance notification time was based on the available datapoints only (e.g. data was averaged across two instead of three advance notification of self-separations in a condition). Note that the advance notification of the decision aid was 360 seconds.

Neither traffic density, (1, 7) = .06, p > .06, feedback type, F(2, 14) = .08, p > .05, nor the interaction between traffic density and feedback type, F(2, 14) = .96, p > .05, had significant effects on the advanced notification time for conflicts (M = 388.06 s; SE = 15.81 s).

Self-separations were detected significantly earlier under moderate (M = 447.95 s; SE = 8.06 s) than under high traffic density (M = 362.29 s; SE = 3.99 s), F(1, 7) = 73.00, p < .0001. Neither feedback type, F(2, 14) - .32, p > .05, nor the interaction between traffic density and feedback type, F(2, 14) = .35, p > .05, had significant effects.

8.3.2 Primary task performance: Accepting and handing-off aircraft

Controllers accepted more than 98% of the aircraft (M = 98.91%; SE = 0.30%) into their sector with an average response time of 26.20 seconds (SE = 1.17 s). The number of misses was too low to calculate meaningful inferential statistics. There were no effects of traffic, $F(1, 14) = .59$, p . .05, feedback, $F(2, 14) = .08$, $p > .05$, or the interaction, $F(2, 14) = 1.39$, $p > .05$, on response times to requests for acceptance.

There were no effects on the percentage of successful handoffs for traffic, $F(1, 14) = 1.97$, $p > .05$, feedback type, $F(2, 14) = .30$, $p > .05$, or the interaction between traffic and feedback type, $F(2, 14) = 1.44$, $p > .05$.

More aircraft were handed-off early under moderate (M = 31.60 %; SE = 3.92 %) than under high traffic load (M = 25.99 %; SE = 3.10 %), $F(1, 7) = 3.66$, $p = .10$. Effects of feedback type, $F(2, 14) = .45$, $p > .05$ and the interaction, $F(2, 14) = 1.11$, $p > .05$, were non-significant.

It took controllers longer to hand-off aircraft under high (M = 25.19 s; SE = 2.47 s) than under moderate traffic density (M = 22.25 s; SE = 2.10 s), $F(1, 14) = 3.50$, $p = .10$. A trend was found for feedback type, $F(2, 14) = 2.32$, $p = .14$. It took ATCos longest to hand-off aircraft with the multi-modal feedback (M = 26.22 s; SE = 3.16 s) followed by the enhanced feedback (M = 25.33 s; SE = 2.78 s). Fastest response times were obtained with the simple visual feedback (M = 19.61 s; SE = 2.26 s). No significant effect of the interaction between feedback type and traffic was found for response times, $F(2, 14) = .96$, $p > .05$.

8.3.3 Secondary task performance

Performance in the secondary task was mostly affected by traffic density. Controllers missed to update more than three times as many waypoints under high (M = 34.72%; SE = 2.32%) than under moderate traffic load (M = 10.00%; SE = 1.43%), $F(1,14) = 146.72$, $p < .001$. Controllers updated a higher percentage of waypoints early when traffic was moderate (M = 27.08%; SE = 3.70%) than when traffic was high (M = 15.12%; SE = 2.33%), $F(1,14) = 26.61$, $p = .001$. Response times to the secondary task were more than twice as long for high (M = 138.27 s, SE = 10.21 s) than for moderate traffic load (M = 62.73 s; SE = 4.26 s), $F(1, 14) = 35.11$, $p < .001$.

There was no effect of feedback type on the percentage of missed updates, $F(2, 14) = 1.22$, $p > .05$, early updates, $F(2, 14) = .05$, $p > .05$, or response times, $F(2, 14) = .32$, $p > .05$.

A marginally significant effect was found for the interaction between feedback type and traffic, $F(2, 14) = 2.89$, $p = .09$ on the percentage of missed updates. While there was no significant difference between simple (*M* = 9.58%; *SE* = 3.3%), enhanced (*M* = 11.25%; *SE* = 1.88%), and multi-modal feedback (*M* = 9.17%; *SE* = 2.34%) under moderate traffic density, more updates were missed in the multi-modal feedback condition (*M* = 40.28%; *SE* = 4.55%) than in the simple (*M* = 33.10%; *SE* = 3.40%) or enhanced feedback condition (*M* = 30.78%; *SE* = 3.74%) under high traffic. No interaction effect was found on response times, $F(2, 14) = .51$, $p > .05$. However, a trend was also found for the interaction between feedback type and traffic density on early updates, $F(2, 14) = 2.24$, $p = .14$. Under high traffic density, the fewest early updates were made in the multi-modal feedback condition (*M* = 11.11%; *SE* = 2.95%) followed by the simple visual (*M* = 15.28%; *SE* = 4.14%) and the enhanced visual (*M* = 18.98%; *SE* = 4.83%). Under moderate traffic density, the most early updates were made in the multi-modal feedback condition (*M* = 30.00%; *SE* = 7.07%), followed by the simple visual (*M* = 26.25%; *SE* = 6.41%), and the enhanced visual condition (*M* = 25.00%; *SE* = 6.46%).

8.3.4 Physiological measures: Eye movements

Two participants were excluded from the analyses of eye movements because they performed in the high traffic density conditions only. This left six participants for the analyses of eye movements under moderate and high traffic conditions. One additional participant requested to take the eye tracker off due to discomfort and pain about 18 minutes and 40 seconds into a high traffic scenario (i.e. he completed about 75% of the scenario). In order to make his results comparable to other participants' results, the number of fixations and dwells was adjusted by adding 25% to the number of fixations and dwells on each area of interest in the scenario that he cut short.

Entropy. Entropy was higher under moderate (*M* = 2.50; *SE* = .03) than under high traffic density (*M* = 2.33; *SE* = .07), even though the effect did not reach significance, $F(1, 5) = 3.91$, $p = .11$. Higher values under moderate traffic reflect a more random scan than under high traffic, an indicator for lower workload under moderate traffic (e.g. Hilburn, 1996). The effects of feedback type on scanning randomness were not investigated due to the low number of participants and the fact that ATCos could wear the eye tracking equipment for a limited amount of time only due to discomfort.

<u>Number of fixations.</u> The number of fixations was significantly different for the different areas of interest, $F(2, 10) = 154.98$, $p < .0001$. The radar display had the highest number of fixations ($M = 2337.18$; $SE = 69.17$) followed by the communication area ($M = 691.10$; $SE = 40.37$), and the flight strips ($M = 497.94$; $SE = 72.76$). This corresponds to about 66% of all fixations on the radar, 19% on the communication and 14% on the flight strips. Figure 8.5 shows the significant interaction between traffic and area of interest, $F(2, 10) = 5.03$, $p < .05$. While there was no significant difference in the number of fixations between moderate and high traffic on the flight strips, $F(1, 5) = .49$, $p > .05$, a higher number of fixations on the communication areas was found under high than under moderate traffic, $F(1, 5) = 36.91$, $p < .01$, and a lower number of fixations on the radar was found under high than under moderate traffic density, but failed to reach significance, $F(1, 5) = 1.21$, $p > .05$. This indicates a trade-off of fixations between the communication and conflict detection tasks under high traffic conditions. The main effect for traffic density was non-significant, $F(1, 5) = .41$, $p > .05$.

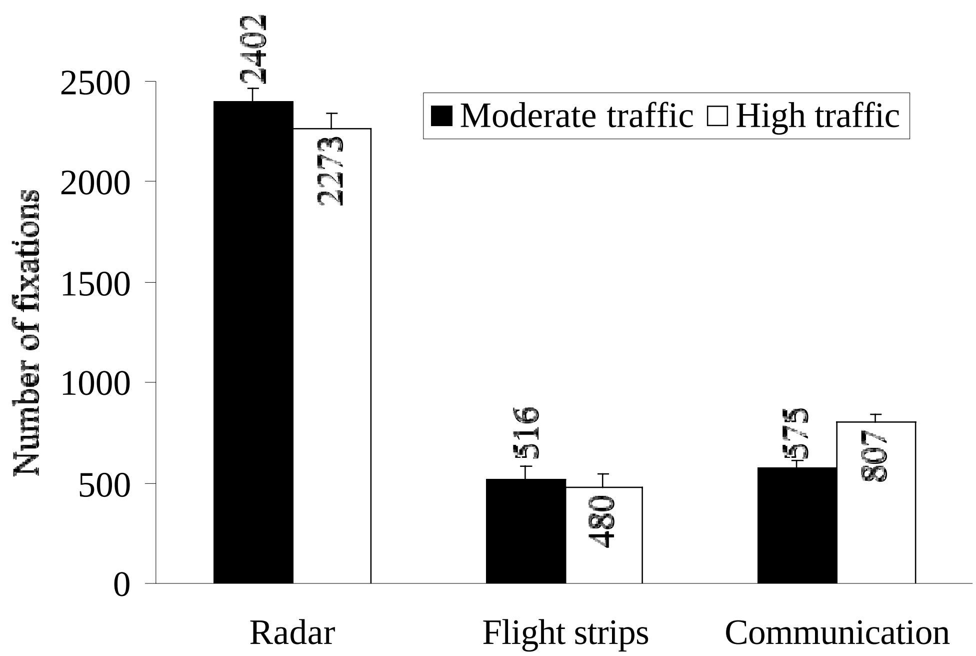


Figure 8.5: Number of fixations as a function of traffic density and area of interest

<u>Duration of fixations.</u> The duration of fixations was significantly different between the areas of interest, $F(2, 10) = 29.75$, $p < .0001$. The longest fixations were found on the communication area ($M = 364.00$ ms; $SE = 7.16$ ms) followed by the radar ($M = 355.17$ ms; $SE =$

5.78 ms) and the flight strips (*M* = 282.75 ms; *SE* = 10.69 ms). The difference in the duration of fixations between high (*M* = 328.44 ms; *SE* = 11.05 ms) and moderate traffic density (*M* = 339.50 ms; *SE* = 10.76 ms) did not reach significance, $F(1, 5) = 1.95$, $p > .05$. The interaction between traffic density and area of interest had no significant effect on the duration of fixations, $F(2, 10) = .84$, $p > .05$.

<u>*Number of dwells.*</u> The number of dwells was significantly different in the areas of interest, $F(2, 10) = 57.02$, $p < .0001$. The most dwells were on the radar (*M* = 198.50; *SE* = 9.99), followed by the communication areas (*M* =122.35; *SE* =4.15) and the flight strips (*M* =92.26; *SE* = 10.80). Overall, traffic density had no effect on the number of dwells, $F(1, 5) = .88$, $p > .05$. Figure 8.6 shows the interaction between traffic and area of interest, $F(2, 10) = 3.09$, $p = .09$. Traffic density had a significant effect on the number of dwells on the flightstrips, $F(1, 5) = 5.98$, $p = .06$, but not on the number of dwells on the radar, $F(1, 5) = .48$, $p > .05$, or the communication areas, $F(1, 5) = .01$, $p > .05$.

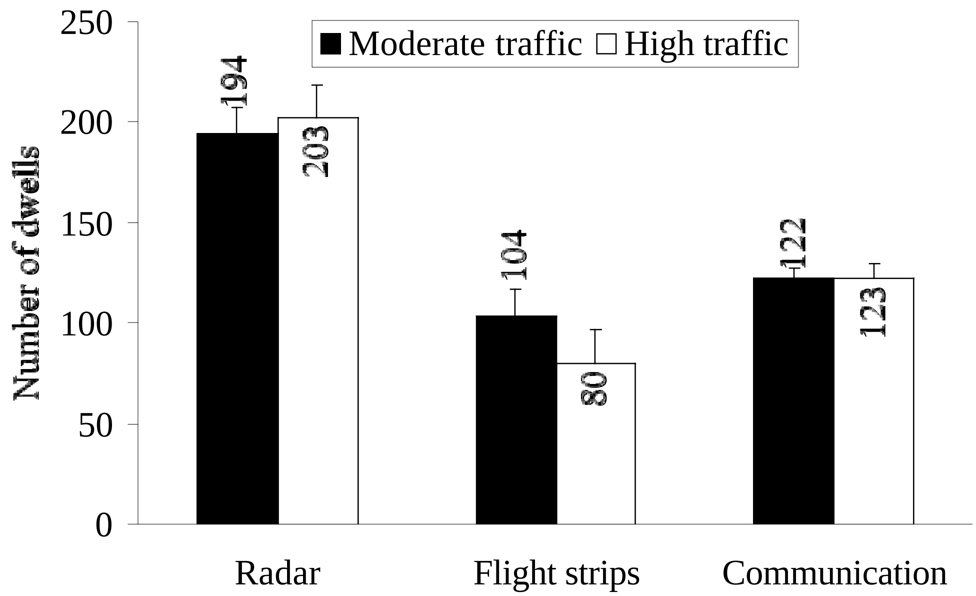


Figure 8.6: Number of dwells as a function of traffic density and area of interest

<u>*Dwell duration.*</u> Figure 8.7 displays dwell durations. There was no significant difference in dwell durations between moderate (*M* = 2.57 s; *SE* = .37 s) and high traffic (*M* = 2.71 s; *SE* = .31 s), $F(1, 5) = .67$, $p > .05$. The duration of dwells was significantly different between the different areas of interest, $F(2, 10) = 41.65$, $p < .0001$. The longest dwells were found on the

radar (*M* = 4.34 s; *SE* = .31 s) followed by the flight strips (*M* = 1.50 s; *SE* = .08 s) and the communication areas (*M* = 2.08 s; *SE* = .15 s). The interaction between traffic density and area was significant, $F(2, 10) = 6.84$, $p = .01$. While the difference in dwell durations on the communication areas was significant, $F(1, 5) = 8.92$, $p < .05$, the difference in dwell durations failed to reach significance for the radar, $F(1, 5) = 2.35$, $p > .05$, and the flight strips, $F(1, 5) = .88$, $p > .05$.

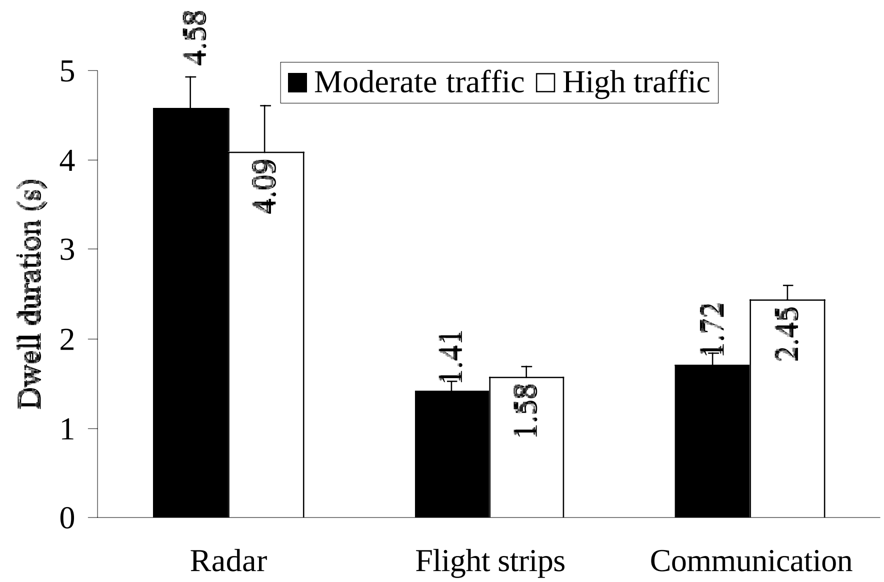


Figure 8.7: Dwell duration as a function of traffic density and area of interest

Dwell time. Figure 8.8 shows dwell times that were obtained by multiplying the number by the duration of dwells. Dwell times were not different between moderate (*M* = 408.46 s; *SE* = 80.30 s) and high traffic density (*M* = 404.04 s; *SE* = 70.06 s), $F(1, 5) = .32$, $p < .05$. Dwell times on the different areas were significantly different, $F(2, 10) = 188.85$, $p < .0001$. Dwell time was longest on the radar (*M* = 829.65 s; *SE* = 26.57 s), followed by the communication areas (*M* = 252.05 s; *SE* = 16.13 s), and the flight strips (*M* = 137.07 s; *SE* = 17.82 s). The interaction between traffic and area of interest was significant, $F(2, 10) = 10.04$, $p < .01$. While dwell times were reduced on the radar, $F(1, 5) = 7.97$, $p < .05$, they were increased on the communication areas, $F(1, 5) = 14.84$, $p = .01$, under high compared to moderate traffic conditions. No difference was found on the flight strips, $F(1, 5) = 1.41$, $p > .05$.

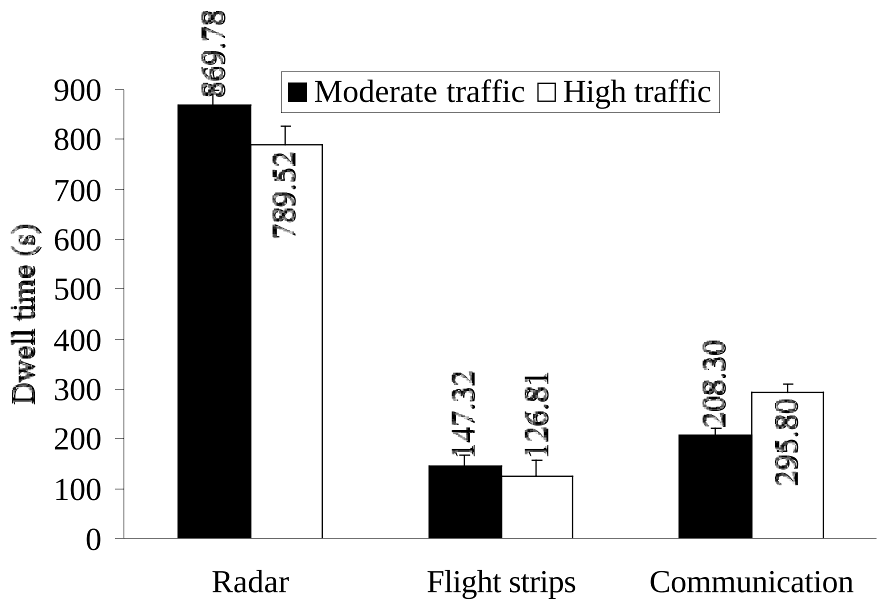


Figure 8.8: Dwell time as a function of traffic density and area of interest

8.3.5 Subjective ratings of mental workload

Controllers rated their subjective mental workload significantly higher when traffic density was high (*M* = 70.97; *SE* = 2.61) than when it was moderate (*M* = 50.83; *SE* = 3.67), $F(1, 14) = 44.37$, $p < .001$. No significant effects were found for type of feedback, $F(2, 14) = .96$, $p > .05$, or the interaction between traffic density and feedback type, $F(2, 14) = .21$, $p > .05$.

8.3.6 Trust and self-confidence

Trust ratings ranged from 50 to 100 with an average of 82.60 (*SE* = 1.95). Traffic density, $F(1, 14) = .22$, $p > .05$, feedback types, $F(2, 14) = .40$, $p > .05$, or the interaction, $F(2, 14) = 1.13$, $p > .05$, did not have significant effects on trust ratings.

Ratings of self-confidence ranged from 10 to 100 with an average of 69.48 (*SE* = 3.51). Figure 8.9 shows the ATCo's ratings of self-confidence to perform without the automation aid. While under high traffic, self-confidence was highest for the enhanced visual feedback, under moderate traffic density self-confidence was lowest for the enhanced visual feedback, $F(1, 14) = 8.61$, $p < .01$. Traffic, $F(1, 14) = .03$, $p > .05$, or feedback type, $F(2, 14) = 1.23$, $p > .05$, did not have significant effects on the ratings.

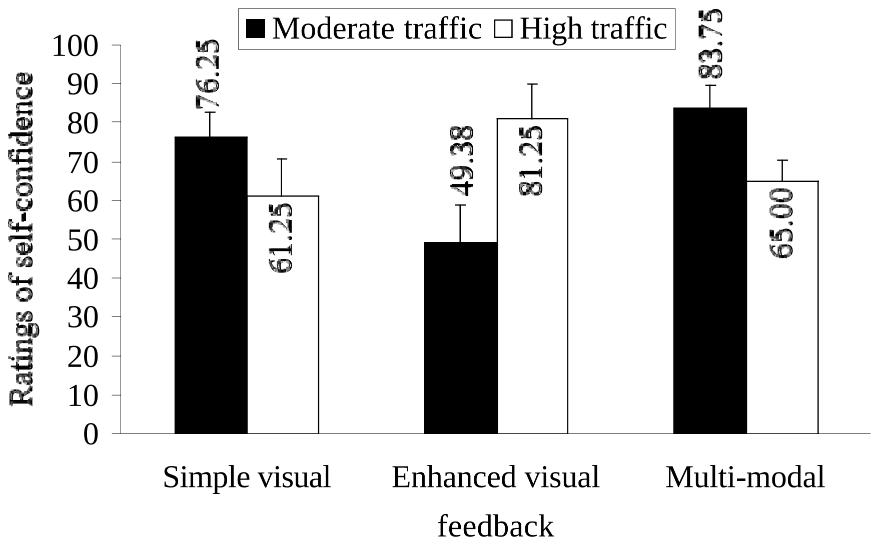


Figure 8.9: Self-confidence ratings as a function of traffic density and feedback type

8.4 Discussion

The purpose of the study was to investigate the effects of traffic density on the distribution of visual attention as indicated by eye movements under FF conditions. It was speculated that high traffic and the associated requirement for communication on the datalink could divert attention from the radar. Further, it was examined if a decision aid with visually enhanced and multi-modal feedback would improve conflict detection performance. It was hypothesized that multi-modal feedback could improve advance notification and lead to an earlier detection than purely visual feedback by better guiding visual attention. A performance benefit was also expected for the enhanced visual aid by providing more transparency on the conflict prediction. Given that ATCos will be required to respond to potential conflicts faster under FF conditions to avoid the loss of separation, the earliest possible detection of potential conflicts would be highly beneficial for system safety.

Several interesting findings resulted from this study. First, the distribution of visual attention as indicated by eye fixations and dwells across the displays on an ATC workstation with a digital datalink display reflected the importance of the different displays to the ATCo tasks. The area that received the most visual attention was the radar display, followed by the communication areas and the flight strips. Overall, about 66% of all fixations were on the radar display, a large proportion, but less than what other researchers found. Karsten, Goldberg, Rood, and Sultzer (1975) found that controllers spend about 80% of their time looking at the radar display, 13% at the flight strips, and 5% at input devices. That the radar was fixated the most was consistent with the radar being the most important display. Information for the most important task (i.e. conflict detection) is presented there. While communication is important, it is not of concern by itself. It is only subservient to conflict detection. Similarly, updating flight strips is secondary to ATCos and even less important than communicating. This was reflected in the little amount of visual attention allocated to the flight strips. Flight strips are important for planning, but under FF, flight strips loose their importance for conflict detection because pilots could change their intended flight path (as stated on the flight strips) at any moment. This distribution of visual attention was also consistent with data reported by Willems and Truitt (1999). That fewer fixations were made on the radar in this study than in the study by Karsten et al. (1975) could be due to the use of datalink in the present experiments. However, this can only be speculated.

The trend for reduced entropy or scanning randomness under high traffic density is consistent with findings by Hilburn (1996). This represents a narrowing or filtering of information under high workload and, as Wickens and Holland (2000) point out can reflect a perceptual process as well as an adaptive strategy. Task priorities guide the attentional filtering so that performance on the most important task remains at a constant level while tasks of lower priority are filtered out. This is an effective strategy as long as the prioritization matches the requirements of the environment, but could pose a problem if this is not the case.

Overall, no differences in fixation or dwell duration between moderate and high traffic were found. This is in contrast with other studies in which increased workload was associated with increased dwell durations in a cockpit (Tole et al., 1982; Harris et al., 1982) and an ATC simulation (Stein, 1992).

The most important finding, however, was the shift in attention allocation to the different sources of information from moderate to high traffic conditions. Visual attention to the communication areas was increased under high compared to moderate traffic at the expense of visual attention to the radar display. Due to the limited pool of attentional resources, additional attentional resources to communicate on the datalink had to be "borrowed" from a different area.

In this case, ATCos chose to “borrow” resources from the radar. This shift in attention allocation strategy could be due to the need for more communication under high than under moderate traffic. Even though communication is not the highest-priority task of controllers, it is very much driven by pilot-initiated transmissions (e.g. request for acceptance) that need to be responded to fast. The high traffic density increases the number of such transmissions considerably.

This finding has important implications for the design of an increasingly crowded ATC system and the increasingly visual nature of the ATC environment due to the introduction of datalink. If FF allows for the accommodation of increasing traffic, ATCo attention might be diverted away from the radar display, the most important source of information for conflict detection, because ATCos need to attend to other displays and sources of information associated with routine tasks such as updating flight strips and communicating. Each additional aircraft does not only increase ATCo workload because it needs to be considered for conflict detection, but also because each is associated with many routine or "housekeeping" tasks, communication, and coordination. In fact, ATCos report that these tasks represent a large part of their workload. In the current system, the eyes can remain fixated on the radar during communication. If datalink displays will be used in the future to accommodate the need for communication with an unprecedented amount of traffic and to reduce frequency congestion on the radio, ATCos will need to shift their eyes and visual attentional resources from the radar to the datalink. This points to the increasing importance to integrate different displays with each other instead of simply adding displays to the ATCo workstation. Systems need to be designed in a way that all tools within a system "fit together" and do not compete for the same attentional resources (Nijhuis, 1994). If this principle is violated, performance can deteriorate and lead to critical events that controllers might "fail to notice". This should be kept in mind for the implementation of datalink displays. The combination of increased traffic and a separate datalink or other displays that are not integrated with the radar could have disastrous consequences. Perhaps, if synthetic speech were used as a channel for datalink it would make use of an additional resource and free capacity in the pool of visual resources. An alternative suggestion would be to integrate the datalink capabilities on the radar display as in the study by Hilburn (1996). He did not find the same diversion of attention away from the radar under high traffic density.

The present experiment provided additional evidence that controller performance under FF can be improved with the help of effective automated decision aids. The near-perfect conflict detection shows that the availability of a conflict detection aid to the ATCos was successful in promoting good performance under FF conditions. This is a promising result with respect to the impending implementation of conflict detection aids into the ATC system.

However, the prediction that multi-modal feedback would result in better conflict detection performance (especially earlier detection) than simple visual feedback was not supported. The expected benefit of the visually enhanced feedback was also not found. The data also did not support the hypothesis that conflict detection benefits of visually enhanced or multi-modal feedback would be greater under high than under moderate traffic density. Self-separations were detected earlier under moderate than under high traffic density across all types of feedback. The percentage of detected conflicts was affected neither by traffic nor by feedback. Instead, the multi-modal feedback produced some negative effects for tasks other than conflict detection. It took ATCos longer to hand-off aircraft in the multi-modal feedback condition and ATCos missed to update more waypoints in the high traffic density and multi-modal feedback condition. Likewise, the fewest early waypoint updates were made in the multi-modal condition under high traffic. A lower number of early updates can be interpreted as being related to higher mental workload because ATCos experiencing high workload do not have spare time to update the waypoints ahead of time (even though they were instructed not to do so). Therefore, the reduced number of early updates in the multi-modal feedback condition under high traffic could indicate a negative effect of the multi-modal feedback. This can be interpreted in light of the preemption phenomenon (Wickens & Liu, 1988). Preemption considers the alerting characteristic of auditory stimulus presentation. Typically, auditory stimuli are more intrusive and alerting than visual stimuli. Therefore, the presentation of a discrete auditory stimulus during the performance of an ongoing visual task could call attention to the auditory stimulus and divert attentional resources away from the ongoing visual task. As a consequence, a performance benefit in the response to the discrete auditory stimulus (i.e. visual and auditory feedback) and task (i.e. conflict detection) can be found at the expense of performance in the ongoing visual task (i.e. handing-off aircraft, updating waypoints). This indicates that the use of multi-modal feedback should be carefully evaluated before such technology is implemented.

Multi-modal feedback might not always have positive or neutral effects. In some instances, it could be associated with performance decrements in concurrent visual tasks.

The high percentage of fixations on the radar display could explain why no difference in conflict detection performance was found for the different types of feedback. If ATCos attend to the radar most of the time it is unlikely that a salient visual aid would be missed. This finding and interpretation is consistent with basic research on cross-modal attention. Posner et al. (1976) conducted a study in which participants were asked to press one of two keys depending whether a tone was presented to the left or right side of the ear (auditory task) or whether an "X" appeared on the left or right side of a monitor in front of them (visual task). The participants' expectation of a visual or auditory task was manipulated. Posner et al. (1976) found that participants took longer to respond when they performed the unexpected task (i.e. the visual task when they were expecting the auditory task) than when they could not reliably predict or expect which task was going to occur. On the other hand, participants responded faster when they performed the expected task. Most importantly, however, the faster response to the auditory than to the visual task (as often found due to the greater alerting characteristic of auditory stimuli) was eliminated when the participants were expecting a visual task and had already oriented their attention to it. A similar mechanism could be responsible for the finding that auditory feedback did not have an effect in this study. ATCos were expecting conflicts and alerts to occur on the radar and had already oriented their eyes and attention to the radar as reflected in the large proportion of eye fixations on the radar. Therefore, the typical small advantage (in the order of milliseconds) of auditory over visual cues in redirecting attention was not found. If this finding would hold true for detection aids that are not integrated on the radar is on open question. Tools like URET present conflict information on a tabular display that is close to, but not integrated on the display of traffic. Results might be different with such a constellation.

Perhaps visual attention strategies in ATC are different from strategies in piloting an aircraft for which performance benefits of multi-modal aids have been found (e.g. Sklar & Sarter, 1999). The controllers primary display is the radar display and this is also where critical events would most likely unfold and have to be detected. Therefore, visual attention might be directed there by default. If the visual alert that indicates a conflict is integrated on the PVD, chances are low that it will be missed. For pilots, the most important areas are the out-of-the window view or the instruments (depending on meteorological conditions). Critical events such as another aircraft in close proximity or a failure of a subsystem are usually displayed in a separate display and therefore less likely to be detected. In this case, an omnidirectional feedback (i.e. auditory or tactile) captures and directs the attention of the pilot to the relevant display. The high number of fixations on the radar in this experiment also suggests that ATCos in the previous experiment probably did not miss to report conflicts in the presence of the aid because they did not see the aid. Insufficient trust and the underutilization of the aid seem to be a more likely cause for the lower percentage of detected potential conflicts in Experiment 1.

However, the high percentage of detected potential conflicts in this experiment indicates a ceiling effect, a problem also encountered by other researchers (Sklar & Sarter, 1999). Perhaps it is not appropriate to measure detection performance with detection rates when highly effective detection aids are used. Most likely, detection rates will be high resulting in a ceiling effect, little variability in data and therefore little success in establishing effects of the manipulation of the independent variable. Detection times seem more appropriate even though there was no effect of feedback modalities. Nevertheless, the study showed a practical benefit of the decision aid. Conflict detection was very good with automation irrespective of the feedback. The few undetected events could have been missed because the ATCos detected, but forgot to report them or because ATCos thought they had already reported the conflict, i.e. clicked the conflict button. A shortcoming of the simulation was the lack of feedback if a controller had already reported a conflict. Several controllers commented on this.

Consistent with findings of the previous experiment and Galster et al. (2001), a negative impact of high traffic density was found. Advance notification times, especially for self-separations, were shorter under high than moderate traffic density even with the support of a conflict detection aid. The negative impact of high traffic density was also reflected in the performance of routine communication tasks. A higher percentage of aircraft was missed to hand-off before the end of the scenario and it took controllers longer to hand-off aircraft under high than under moderate traffic conditions. More aircraft were handed off early under moderate than under high traffic. This could reflect the ATCos' strategy to get ahead when they could and controllers had more resources and time to keep up with routine tasks under moderate than high traffic. However, this is inconsistent with the finding of Experiment 1 in which more early hand-offs were made when the aid was absent, especially under high traffic. Measures of secondary performance, subjective ratings of mental workload and entropy indicated higher workload under high than moderate traffic density. No effects of feedback type on subjective measures of workload were found.

Hence, even when conflict detection was automated, ATCo performance and workload varied as a function of traffic density. This indicates that performance and workload are not only determined by the task of conflict detection, but that the communication and coordination tasks can be a considerable source of workload especially under high traffic conditions.

That controllers would trust the enhanced versions of the aid more than the simple visual version because it indicated where and why a conflict was about to appear could not be confirmed. Reported trust was not affected by feedback type. It was also predicted that ATCos would be less self-confident to perform without the aid under high than under moderate traffic. While this was true for the simple visual and the multi-modal feedback conditions, ATCos reported more self-confidence to perform with the aid under high than under moderate traffic in the enhanced visual condition. This result is difficult to explain. If it were caused by the additional clutter on the screen due to the enhanced visual aid, the same result should have been found under multi-modal conditions, unless ATCos felt that the auditory alert in the multi-modal condition compensated for the clutter on the screen. The comments by a few controllers that they did not like the enhanced visual display because the lines cluttered the display would support this view, however.

Overall, conflict detection in this experiment was better than in the previous experiment. While in the previous experiment about 75% of all potential conflicts were detected with the aid of automation, ATCos detected almost 98% of all potential conflicts. Potential conflicts were also reported earlier in this experiment, even when the one-minute difference in look-ahead times between the aid in the previous and the present experiment was taken into account. Improved performance was also reflected in the communication tasks to accept and hand-off aircraft and the secondary task. Subjective ratings of mental workload, however, were roughly the same in both experiments. The improved performance could be due to the improved training in this compared to the previous experiment. More information on the functionality of the aid was provided for the controllers with specific emphasis on the differences between the STCA controllers currently use in their facilities and the more advanced functions of the aid in the study. Perhaps the improved training lead to a better understanding of the functionality of the aid and therefore increased trust in the aid. If controllers trusted the aid more, they might have used it more to improve their performance. Indeed, ratings of trust in the conflict detection aid were higher in the present experiment compared to the previous one (83 versus 63). Of course, a comparison between the present and the previous experiment does not allow for an explanation of training as the cause of the performance differences between the two experiments. However, the focus of the study was not training. The purpose was to create conditions in which controllers would trust the aid and make use of it. It can be assumed that ATCos in the real world will receive adequate training before the implementation of tools.

The results of these experiments compare to the "success" of FF in airborne studies (Lozito et al., 1997; van Gent et al., 1998; Dunbar et al., 1999) and lead to the conclusion that FF could be feasible with the support of decision aids for ATCos. Automation was successful in promoting ATCo performance in conflict detection and routine tasks and compensated for the negative effects of FF and high traffic density found in earlier studies. Even though automation still does not make the ATCo part of the decision-making loop, it improves ATCo performance by performing the ATCo's decision-making function. In fact, it could be argued that the automation removes the ATCos even further from the processes in the system because ATCos now become passive monitors not only of pilot actions, but also of the automation. This is acceptable as long as the ATCo is not required to intervene. However, even the best conflict detection aid can fail or become inaccurate and this raises the issue if ATCos will be able to intervene in case airborne separation fails and the decision aid does not point out the particular conflict. This will be the topic of the next experiment.

9. Experiment 3: Effects of a decision aid under reliable and failure modes of operation

9.1 Introduction

The previous two experiments have clearly shown the benefits of a conflict detection aid on ATCo performance and mental workload under FF and demonstrated that automation can compensate for some of the negative effects of FF that earlier studies have found (Galster et al., 2001; Endsley et al., 1997; Metzger & Parasuraman, in press). Yet, these two experiments have only investigated ATCo performance and mental workload under reliable automation conditions. Problems can occur when automation fails, becomes inaccurate, or is given contextually-inappropriate or incorrect information. FF removes the ATCo from the decision-making process by transferring authority to the pilots. Previous studies have shown that ATCo performance is poor if ATCos are required to intervene in case airborne separation fails. Automation can improve performance, but just like FF, it moves the ATCo further away from the decision-making process. As long as the automation performs the conflict detection function reliably system safety is maintained. It remains to be studied if ATCos would be able to intervene in case airborne separation and automation fail.

Accidents, incidents, and previous research have shown that humans can become complacent and less likely to detect system malfunctions when relying on automation (National Transportation and Safety Board, 1973, 1997; Parasuraman et al., 1993). Hence, it is important not only to investigate the effects of automation on performance and mental workload when the automation works as expected, but also when it becomes unreliable. In fact, the NRC report (Wickens et al., 1998a) advocated that human factors analyses under degraded modes of operation are performed before implementing any decision support tools into the ATC system. It recommended

"investing sufficient resources in studies of human response to low-probability emergencies; actively pursuing failure modes/fault tree analysis, particularly to identify situations in which two or more coordinating agents receive information that are incongruous or contradictory; and involving human factors specialists in the development and testing of system recovery procedures. "

Recovery from an automation failure is of great concern under FF conditions (Galster et al., 2001). Under manual conditions or low levels of automation, system throughput is low. Relatively few aircraft can be accommodated and controllers have plenty of time to respond to unexpected critical events. However, the goal of FF and automation is to increase capacity and system throughput. More aircraft will be accommodated in the same amount of airspace creating a denser airspace and leaving the controller with less time to respond to emergencies. At the same time, automation and FF can increase the time ATCos need to make decisions and recover from a critical event (Metzger & Parasuraman, in press). If the time ATCos require is greater than the time ATCos have available to recover from a critical situation, danger is imminent.

Automating the conflict detection function in ATC is a challenging task and even more so under FF conditions. Unlike other system operators (e.g. in process control) that are controlling physical and closed-loop processes, ATCos are controlling other human beings (i.e. pilots) or more specifically, other human-machine systems (e.g. pilot-aircraft systems) in a dynamic environment that cannot easily be predicted. A prediction of conflicts well in advance requires the accurate and up-to-date projection of the state of the system into the future. However, this is not easy. The future status of the ATC system is determined by the current status of aircraft (e.g. aircraft location, aircraft performance parameters), pilot intent for the future, as well as current and future meteorological conditions at all points in the airspace (e.g. wind, temperature). While information on the current status in the system is relatively easy to obtain given today's technology, information on meteorological conditions is more difficult to gather. Incidents related to clear air turbulence demonstrate how difficult it still is to predict meteorological conditions. Further aggravating the prediction problem is the introduction of FF. While pilot actions currently are relatively easy to predict because they are tightly controlled by ATC, this might change. FF would allow pilots to modify their intent at any moment (e.g. to self-separate and resolve a conflict, due to a TCAS alert, or for any other reason). While modern conflict detection and resolution algorithms are extremely powerful and reliable, these limitations make any projection of the state of the system into the future probabilistic and potentially inaccurate.

As Bilimoria (1998) notes, changes in pilot intent, might in some cases not be received in time or not received at all by the ATC computer system from which URET receives the information required by its conflict prediction algorithm. These changes in the intended flight path might therefore not be available for analysis by URET or other conflict detection aids and could cause the detection aid to miss a conflict (error of omission) or report a conflict when in fact there is none (error of commission). Even though the automation algorithm might work 100% reliably, conflict prediction could become inaccurate because the automation does not have complete or the most-up-to-date information. Although it might become possible that all intent changes could be entered into the computer system or the system could at least detect that a deviation has occurred, it is doubtful that the prediction would always be 100% accurate, especially when the exact nature of the deviation is not known and when the changes in intent create a conflict in the very near future. Hence, conflict detection aids such as URET will probably have lower reliability under FF conditions when pilots will be allowed to change their intended flight path at any moment than they would under current conditions. While any human factors analysis should involve the analysis of degraded modes of operation, the potential for a reduced reliability of URET under FF represents an even greater reason to conduct such studies.

The question is whether the ATCo will be able to detect a potential conflict if the automation does not. This requires the ATCo to continuously and carefully monitor the automation while performing other tasks. However, the literature on human performance with automation has shown that human monitoring of automated systems is often poor, especially in multi-task environments (Parasuraman et al., 1993). When a system is automated and other tasks have to be accomplished, operators become complacent (i.e. the detection of system malfunctions deteriorates dramatically over time). While complacency effects are well documented in accidents and incidents in the aviation as well as other domains (e.g. National Transportation and Safety Board, 1973, 1997) and in basic research (e.g. Parasuraman et al., 1993), they have not yet been studied empirically in the ATC environment. It could be speculated that ATCos might not be as likely to become complacent because they are aware of the dynamic nature and the challenges of the system under their control, especially under FF. On the other hand, it could be expected that workload becomes so high under traffic densities expected for the future that they will have to rely on the automation in order to be able to handle the traffic and be just as complacent as pilots or the general population. Only empirical studies will be able to answer this question. Another concern pertains to the timeliness of conflict detection. Metzger and Parasuraman (in press) found that ATCo required more time to detect conflicts under passive monitoring than under active control conditions. Decision aids could further aggravate this effect because both, automation and FF, move the ATCo away from the active decision-making process. However, if there is a very limited amount of time in cases when the automation fails to detect a quickly developing conflict, detection performance could break down with serious consequences for system safety. Hence, special consideration should be given to the investigation of the timeliness in detecting automation failures.

9.1.2 Hypotheses and research questions

The purpose of the present experiment was to investigate the effect of reliable and inaccurate conflict detection automation on ATCo performance, mental workload, and eye movements as an indicator of visual attention allocation. It was expected that conflict detection performance would be improved with the support of conflict detection automation, that is, that ATCos would detect more potential conflicts, detect potential conflicts earlier, and show better performance in routine ATC task when they had a conflict detection aid available than when they were manually detecting conflicts. Mental workload was expected to be reduced when ATCos had automation support than when they were manually controlling traffic. It was investigated whether ATCos would show complacency effects when using automation. The detection of a conflict that the automation failed to detect was compared to the detection of the same conflict under manual conditions. Higher detection rates of a conflict under manual conditions than under automated conditions when the automation failed to detect the conflict would indicate complacency. Because the availability of the decision aid might remove ATCos further from the decision-making process in FF, it was hypothesized that ATCos would detect a conflict earlier under manual conditions than under automated conditions when the automation failed to point it out. If complacency is due to high trust and reduced attention allocation to the automated task (Parasuraman et al., 1993), and attention and eye movements are associated at least to some degree, fewer eye fixations on the radar display would be expected under automated than under manual conditions. High trust should be associated with reduced detection of the automation failure.

9.2 Method

9.2.1 Participants

Twenty active full performance level ATCos from the Washington Center air route traffic control center (ARTCC; *n* = 14), Baltimore-Washington International (BWI; *n* = 2), Dulles (IAD; *n* = 3), and Andrews airforce base (*n* = 1) terminal radar control area (TRACON) facilities served as paid volunteers. Even though Andrews airforce base is a military facility, air traffic is controlled by civilian FAA ATCos. One of the twenty controllers had experience in both en route and TRACON environments. At the time of the study he had been working at the TRACON facility for 4 years, but had 9 years of experience in the en route environment. Therefore, he was categorized as an en route controller. This resulted in fourteen en route and six TRACON controllers ranging from 31 to 53 years of age (M = 37.65, SD = 5.05) with overall ATC experience from 8 to 22 years (M = 14.08, SD = 3.86). There was no significant difference in age, $F(1,18) = .43$, $p > .05$, or years on-the-job, $F(1, 18) = .003$, $p > .05$, between the six TRACON and fourteen en route controllers. Three (15%) en route controllers were female, all other ATCos were male. This reflects roughly the current gender ratio in the FAA facilities.

9.2.2 Apparatus

For a description of the ATC simulator and eye tracking equipment see the previous chapters. Tasks and dependent variables were the same as in the previous experiments. One exception was that in addition to detecting conflicts, controllers were asked to also provide a suggestion on how they would resolve the conflict. The experimenter recorded the verbal clearance given by the controllers. Eye movements were recorded as physiological measures of mental workload. Again, subjective ratings of mental workload, trust in the detection aid, and self-confidence to detect conflicts without the aid were obtained.

9.2.3 Design

The design was a one-factorial repeated measures design with four levels of treatment. Independent variable was the automation condition with the following four levels: (1) reliable automation, (2) automation failure with 2 minutes to recover, (3) automation failure with 4 minutes to recover, and (4) manual condition. All ATCos performed in all four conditions. The order of presentation was the following: One group of participants performed the manual condition *before* all the automated conditions (i.e. all other conditions), the other group performed the manual *after* the automated conditions. In both groups, the reliable automation condition was always presented before the two unreliable automation conditions. This was chosen deliberately so that the ATCos would get enough training and experience with a reliably operating automation aid and build trust before being exposed to failures. The order of the two automation failure conditions was so that half of the participants performed the two-minute failure condition before the four-minute failure condition and the other half performed the order in reverse. This resulted in a double cross-over design. The first cross-over resulted from the order of the manual versus automated conditions (i.e. all others). The second cross-over resulted from the order of the two automation failure conditions. This was nested in the first cross-over because it only applied to the automated conditions. Figure 9.1 visualizes the resulting four orders of presentation. All ATCos wore eye tracking equipment for the manual and both failure conditions. Shaded cells indicate when the controllers wore the eye tracking equipment. The dependent variables are listed in table 6.1.

		Automated conditions			
Order		Reliable auto	Auto failure conditions		
1:	Manual	Reliable	Auto failure (2 min)	Auto failure (4 min)	
2:	Manual	Reliable	Auto failure (4 min)	Auto failure (2 min)	
3:		Reliable	Auto failure (2 min)	Auto failure (4 min)	Manual
4:		Reliable	Auto failure (4 min)	Auto failure (2 min)	Manual

Figure 9.1: Order of scenarios

The four different automation conditions were created with five scenarios. The reliable automation condition included a reliable conflict detection aid and consisted of two scenarios. This was chosen so that ATCos could get enough experience and exposure to the reliable decision aid and build trust in the aid. The aid was the simple visual detection aid used in

Experiment 2 with a look-ahead time of 6 minutes, i.e. 6 minutes before the loss of separation occurred or would have occurred (in the case of a self-separation) the alert appeared on the radar screen. In the reliable condition, the aid reliably detected all five potential conflicts (two conflicts and three self-separations). In the two automation failure conditions, the same conflict detection aid detected the five potential conflicts reliably. However, the aid failed to detect a sixth event 21 minutes into the scenario. The event was a situation in which one aircraft deviated from its flight plan (e.g. after a TCAS alert) in order to avoid a conflict and climbed or descended into the path of another aircraft that also deviated from its altitude filed on the flight plan. Figure 9.2 depicts such a situation. Flights DLH 123 and UAL 456 at flight level 350 are predicted to be in conflict based on the conflict detection aid (i.e. circles around the aircraft targets). Flight DLH 123 climbs to flight level 360 in order to avoid the conflict. At the same time, flight USA 333 makes a tactical altitude change to flight level 360 (e.g. in order to avoid weather or because TCAS indicates a conflict that may or may not actually be there). Now flight DLH 123 and USA 333 are both changing their altitude to the same flight level and get into conflict. However, this conflict is unpredicted by the conflict detection aid because it is a short-term change and the information is not yet available to the main computer system, from which the conflict detection aid gathers its information.

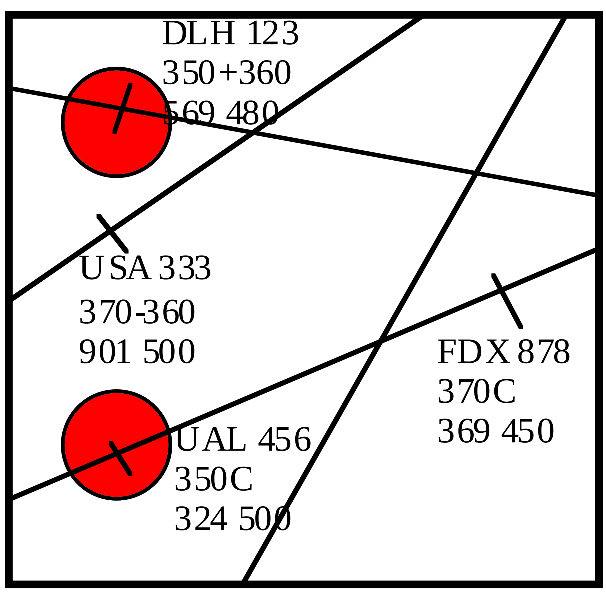


Figure 9.2: Situation in which an impending conflict remained undetected by the aid

In one scenario, the maneuvers left controllers with four minutes to detect and resolve the conflict before the loss of separation occurred. In the other scenario, the controllers had only two minutes for detection and resolution. Altitudes and altitude changes of the aircraft involved in this situation were slightly different in the two automation failure scenarios (e.g. an aircraft climbed in one and descended in another scenario) so that controllers would not easily recognize that the same situation was presented repeatedly. A fifth scenario was assigned for the manual condition in which no conflict detection aid was available. However, the controllers were presented with the same situation in which the automation failed in the automation condition and 4 minutes remained for detection. This allowed for a direct comparison of conflict detection performance between the manual and automated conditions.

Controllers were presented with five 25-minute scenarios that included on average about sixteen aircraft in a 50-mile radius sector after a 10-minute ramp-up period. As in previous studies, modified versions of the same scenario were used for maximum experimental control. In order to create a set of five scenarios, the sector and traffic patterns were rotated to simulate a different flow of traffic. Waypoints and flights were renamed so that the participants did not recognize that the scenarios were almost the same.

9.2.4 Procedure

After signing a consent form and providing biographical information, controllers were given instructions, a demonstration of the simulation, completed a fourteen-minute practice trial, and were familiarized with the NASA-TLX and the trust ratings. Then, controllers completed the five 25-minute scenarios and rated their mental workload on the NASA-TLX after each scenario. Ratings of trust and self-confidence were obtained after the automated conditions only.

Before completing the automated conditions, controllers were interviewed about their experience with conflict detection aids. They were asked if they knew any conflict detection aids, specifically the more intelligent ones that are planned to be introduced into the facilities, and if so, which ones they knew. If they did not know about any, they were asked if they knew URET. Participants who knew about URET were asked what they knew about it. All participants were queried if they thought that a conflict detection aid would be useful to them. After the interview, they were told that the following four scenarios would contain a conflict detection that was highly reliable, based on the flightplan of the aircraft (as opposed to just current speed and heading) and that it had a 6 minute look ahead time. ATCos received a detailed description of the aid that even pointed out some of its limitations and made them aware of the underlying principle of the aid and some of its limitations (see Appendix).

Finally, the controllers were given a brief demonstration of two aircraft in conflict and the aid before completing the four scenarios under automated conditions.

9.3 Results

When controllers were asked if they were familiar with any conflict probes or conflict detection aids, most controllers responded that they knew TCAS, the traffic collision avoidance system mandatory on the flight deck of most air carriers in the US. Asked about the ground side, most responded that they knew about the STCA that controllers currently have available. It is based on current speed and heading of the aircraft and has a two minute look ahead time. Controllers complained about the many false alarms the STCA creates. None of the controllers was familiar with the functionality of URET other than that a module of the system might eliminate paper flight strips. Some said they had heard the name, others had never heard of it. Overall, the familiarity with URET was very low.

Data from the two scenarios with reliable automation were averaged after initial analyses revealed no significant differences. The data of the twenty participants was analyzed with repeated measures ANOVAs with one four-level independent variable (reliable automation, failure 2 min, failure 4 min, and manual) and three planned orthogonal contrasts. According to the hypotheses, the contrasts analyzed if performance and mental workload were affected by (1) automated (i.e. the reliable condition and the two- and four-minute failure conditions) versus manual conditions, (2) reliable automation versus failure conditions, (3) failure conditions with two versus four minutes to detect a conflict. Initial analyses revealed that there were no effects of the order of presentation for the comparison between manual and automated conditions and the comparison between the failure conditions. Therefore, it was not included in further analyses (except for one exception discussed below).

In the following sections, *F*-values of the general ANOVA (i.e. one-way ANOVA with four levels of the independent variable) will be presented before the *F*-values of the planned orthogonal contrasts for all dependent variables.

9.3.1 Primary task performance: Detection of conflicts and self-separations with reliable automation

The automation condition had a significant effect on the detection of conflicts, $F(3, 57) = 8.14$, $p = .01$. More conflicts were detected under automated (M = 100%; SE = 0.00%) than under manual conditions (M = 85.00%; SE = 5.26%), $F(1, 19) = 8.14$, $p = .01$.

The automation condition had a significant effect on the detection of self-separations, $F(3, 57) = 9.98$, $p = .001$. More self-separations were detected under automated (M = 96.11%; SE = 1.39%) than under manual conditions (M = 76.67%; SE = 4.90%), $F(1, 19) = 13.11$, $p < .01$. A trend was also found for better detection of self-separations in the automation failure conditions (M = 97.50%; SE = 1.41%) than in the reliable conditions (M = 93.33%; SE = 3.06%) reflecting the order effect, $F(1, 19) = 3.07$, $p = .10$.

The automation condition had a significant effect on advanced notification of conflicts, $F(3, 57) = 5.28$, $p < .01$. Conflicts were detected earlier under automated (M = 327.89 s; SE = 6.90 s) than under manual conditions (M = 279.09 s; SE = 23.15 s), $F(1, 19) = 5.31$, $p < .05$. Conflicts were also detected earlier in the failure conditions (M = 338.38 s; SE = 6.73 s) than in the reliable conditions (M = 306.92 s; SE = 14.93 s), $F(1, 19) = 7.39$, $p = .01$ reflecting the order effect. The automation condition had no significant effects on advance notification of self-separations (M = 347.76 s; SE = 3.67 s), $F(3, 57) = .79$, $p > .05$. None of the contrasts was significant.

9.3.2 Primary task performance: Detection of conflicts and self-separations with unreliable automation

In two of the scenarios with automation aid, there were three self-separations and two conflicts reliably detected by the aid and one conflict that remained undetected by the detection aid, i.e. an automation failure. In one of the scenarios, the controllers had two minutes, in the other scenario four minutes to detect the automation failure and resolve the conflict before a loss of separation occurred. The same conflict was presented in the manual condition, but not in the scenarios with reliable automation. Table 9.1 shows descriptive statistics for the detection rates in the two automated and the manual condition.

Table 9.1: Detection rates as a function of automation condition

Condition	Auto failure 2-min (%)	Auto failure 4-min (%)	Manual (%)
n	20	20	18
Mean	35.00	40.00	55.56
SE	10.94	11.24	12.05
Minimum	0.00	0.00	0.00
Maximum	100.00	100.00	100.00
Mode	0.00	0.00	100.00
Median	0.00	0.00	100.00

Under automated conditions, only 35 and 40% of the controllers detected the conflict when they had 2 and 4 minutes available, respectively. In contrast, 55.56% of the controllers detected the conflict under manual conditions. There was no difference in the detection of the conflict under manual conditions between ATCos who performed the manual conditions first and those who performed it last, $F(1, 16) = .16$, $p > .05$. Two cells in the manual condition were missing due to technical difficulties and were replaced by the overall mean ($M = 55.56\%$; see table 9.1) so that the two subjects could be entered into the ANOVA. The analysis revealed a trend for an effect of the automation condition, $F(2, 38) = 1.78$, $p = .18$. Orthogonal contrasts revealed no significant effect between the 2 and 4-minute failure condition, $F(1, 19) = .32$, $p > .05$. However, the contrast comparing automated and manual conditions found a trend for better detection under manual than automated conditions, $F(1, 19) = 2.40$, $p = .14$. This finding of reduced detection performance under automated compared to manual conditions points toward a complacency effect.

Table 9.2 shows advance notification times in the automation and manual conditions. For more than 50% of the cells, no notification time was available due to the high number of missed events. Only five controllers detected the event in all three conditions (manual, 2-min failure, 4-min failure). This number was too low to calculate meaningful inferential statistics. Besides, the maximum advance notification time was restricted by the onset of the conflict (i.e. two or four minutes before the loss of separation occurred). For example, in the two-minute automation failure condition, the maximum possible advance notification time was 120 seconds, in the four-minute automation failure and manual conditions it was 240 seconds.

Nevertheless, the automation failure condition with four minutes can be compared to the manual condition in which also a four-minute period was chosen between the onset of the conflict and the loss of separation. The visual inspection of the descriptive statistics revealed no marked differences between the manual and automated (four-minute) condition even though the advance notification time in the automation condition was about 17 seconds earlier than the advance notification under manual conditions. Also, the minimum advance notification time in the four-minute automation condition (40.53 s) was greater than in the manual condition (7.39 s). However, the median performance was better in the manual condition.

Table 9.2: Advance notification times as a function of automation condition

Condition	Auto failure 2-min (s)	Auto failure 4-min (s)	Manual (s)
n	7	8	10
Mean	83.23	127.12	110.27
SE	12.19	24.26	23.53
Minimum	28.8	40.53	7.39
Maximum	118.01	217.52	216.25
Mode	-	-	-
Median	87.38	102.62	120.00

Again, it should be pointed out that there was no difference in the detection of the conflict under manual conditions between ATCos who performed the manual conditions first and those who performed it last, $F(1, 8) = .06$, $p > .05$. This will become important for the discussion of the results. Most ATCos either detected none of the two automation failures or both. Only three ATCos detected the automation failure in only one of the two failure scenarios. Two

ATCos detected the automation failure in the four-minute failure condition, but not in the two-minute failure condition even though both ATCos performed the four-minute condition before the two-minute automation failure. The third ATCo detected the failure in the two-minute condition, but not in the four-minute condition even though he performed in the two-minute condition first.

Six out of the twenty ATCos detected the automation failure in both, the 2-minute and 4-minute condition. For these ATCos, advance notification times were further analyzed. Because advance notification times depend on the time of the onset of the failure event (two or four minutes before the loss of separation), the two-minute and four-minute failure conditions cannot be compared and have to be analyzed separately.

The experience of an automation failure might change the operator's interaction with automation. An exploratory data analysis was conducted to investigate if the previous experience of a failure might have led to earlier detection the second time. Note that only six participants (i.e. three in each group) detected the failure in both failure conditions and could be included here. Only descriptive data is presented. As figure 9.3 shows, there was no large performance difference in the two-minute condition between ATCos who had been exposed to (and detected) the failure before in the four-minute condition (M = 81.86 s; SE = 26.60 s) and ATCos who were exposed to the failure and detected it for the first time (M = 73.01 s; SE = 8.83 s). In the four-minute condition, ATCos who had already been exposed to and detected the failure in the previous scenario, detected it earlier the second time (M = 167.99 s; SE = 47.42 s) than ATCos who had not been exposed to an automation failure yet (M = 123.81 s; SE = 32.24 s). Even though the number of available data was small, the standard errors large, and the exposure to the failure is confounded with practice, this could possibly indicate that ATCos improved their detection of an automation failure once they experienced that it might not be 100% reliable.

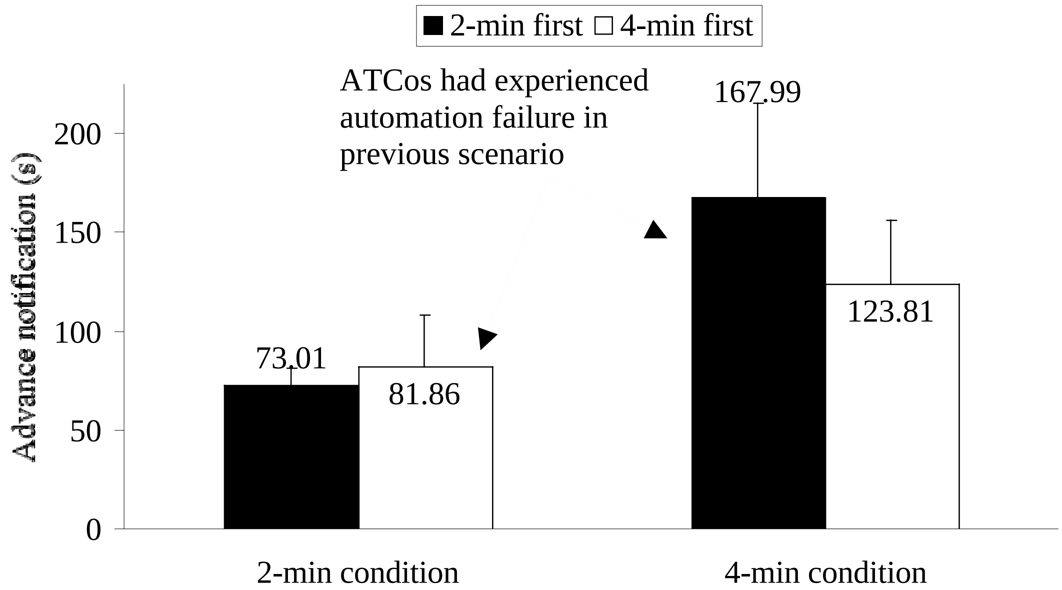


Figure 9.3: Advance notification as a function of failure condition and order of performance

9.3.3 Primary task performance: Accepting and handing-off aircraft

Controllers accepted more than 98% of the aircraft (*M* = 98.13%; *SE* = 0.32%) into their sector with an average response time of 36.79 seconds (*SE* = 2.39 s). There was a significant effect of automation condition on response times to requests for acceptance, $F(3, 57) = 3.40$, $p < .05$. The contrast between reliable (*M* = 39.36 s; *SE* = 5.61 s) and failure conditions (*M* = 32.04 s; *SE* = 3.42 s) was significant, $F(1, 19) = 5.28$, $p < .03$, reflecting faster responses in the failure condition probably due to more practice. A trend for faster response times under automated (*M* = 34.48 s; *SE* = 2.50 s) than under manual conditions (*M* = 41.14 s; *SE* = 7.15 s) was also found, $F(1, 19) = 2.71$, $p = .12$.

No significant effects were found for the percentage of successful hand-offs, $F(3, 57) = .36$, $p > .05$, or early hand-offs, $F(3, 57) = 1.95$, $p > .05$. Aircraft were handed-off faster in the failure (*M* = 26.42 s; *SE* = 2.49 s) than in the reliable (*M* = 31.58 s; *SE* = 3.54 s) condition, $F(1, 19) = 4.77$, $p < .05$, again reflecting the order effect.

9.3.4 Secondary task performance

A significant effect of the automation condition on the percentage of missed updates was found, $F(3, 57) = 4.28$, $p < .01$. Controllers missed to update more waypoints under manual ($M = 66.00\%$, $SE = 2.87\%$) than under automated conditions ($M = 56.48\%$, $SE = 2.46\%$), $F(1, 19) = 7.73$, $p = .01$.

One participant had to be excluded from the analysis of response times because he did not update any waypoints in three of the five scenarios. For the remaining participants, a significant effect of the automation condition was found, $F(3, 54) = 3.54$, $p < .05$. Contrasts showed that it took controllers significantly longer to update waypoints under automated ($M = 126.56$ s; $SE = 8.74$ s) than under manual conditions ($M = 97.15$ s; $SE = 12.20$ s), $F(1, 18) = 7.27$, $p < .05$. The automation condition did not have an effect on the percentage of early updates, $F(3, 57) = 1.47$, $p > .05$.

9.3.5 Physiological measures: Eye movements

Entropy. Entropy was calculated based on dwell transitions between the three areas of interest and was not significantly different between manual ($M = 2.18$; $SE = .04$) and automated conditions ($M = 2.18$; $SE = .07$), $F(1, 19) = .01$, $p > .05$.

Based on the hypothesis that complacency is due to reduced visual attention to the automated task under automated compared to manual conditions (Parasuraman et al., 1993), and the assumption that visual attention and eye movements are related at least to some extent, it was predicted that people who detect automation failures have different scan patterns than people who do not detect automation failures (i.e. who are complacent). As a consequence, eye movement data was analyzed using the variable detection or non-detection of the automation failure (i.e. non-complacent or complacent) as a between-subject variable. Most participants either detected the automation failure in both failure scenarios or did not detect it in either one. Only three participants detected the failure in one, but not the other scenario. These three participants were excluded from the analysis of the eye data. For the different eye data parameters, 3 (area) x 2 (automation condition: manual or automated) x 2 (group: did detect or did not detect) mixed-model ANOVAs were calculated with detection or non-detection of the automation failure as a between-subject variable.

Eye movements up to the point when the loss of separation after the automation failure occurred were included (i.e. 21 minutes and 20 seconds into the scenario). Because the study investigated differences in visual attention strategies leading to the detection or non-detection of the automation failure, the last 3 minutes and 40 seconds were excluded from the analysis. It is possible that ATCos changed their attention strategies if they realized that a failure had occurred. However, this was not of interest in this study. The study was concerned with the attentional processes before the detection or non-detection of an automation failure.

Number of fixations. The number of fixations on the different areas of interest was significantly different, $F(2, 30) = 849.19$, $p < .0001$. The most fixations were made on the radar display ($M = 2180.93$; $SE = 47.00$), followed by the communication areas ($M = 509.04$; $SE = 18.32$) and the flight strips ($M = 216.43$; $SE = 22.29$).

A significant interaction between area and group was found, $F(2, 30) = 4.08$, $p < .05$. ATCos who detected the automation failure had more fixations on the radar ($M = 2332.71$; $SE = 61.26$) than ATCos who did not detect the automation failure ($M = 2098.14$; $SE = 58.04$), $F(1, 15) = 5.85$, $p < .05$. There was no difference between the groups for the number of fixations on the flight strips ($M_{det} = 196.88$; $SE_{det} = 24.75$; $M_{non\text{-}det} = 227.09$; $SE_{non\text{-}det} = 31.87$), $F(1, 15) = .59$, $p > .05$ or the communication areas ($M_{det} = 496.33$; $SE_{det} = 20.10$; $M_{non\text{-}det} = 515.98$; $SE_{non\text{-}det} = 26.33$), $F(1, 15) = .16$, $p > .05$.

Figure 9.4 shows the marginally significant three-way interaction between automation condition, area of interest, and detection group, $F(2, 30) = 2.42$, $p = .11$. Fixations on the radar display are of the greatest interest because the radar display is the area where the automated task takes place. ATCos who detected the failure had significantly more fixations on the radar ($M = 2332.71$; $SE = 61.26$) than ATCos who did not detect the failure ($M = 2098.14$; $SE = 58.04$), $F(1, 15) = 4.85$, $p < .05$. The interaction between automation condition and detection group did not reach significance, $F(1, 5) = 1.94$, $p = .18$. There were no significant effects of detection group, $F(1, 15) = .29$, $p > .05$, automation condition, $F(1, 15) = .39$, $p > .05$, or the interaction, $F(1, 15) = 2.43$, $p = .14$ on the number of fixations on the flight strips. No significant effects of detection group, $F(1, 15) = .16$, $p > .05$, automation condition, $F(1, 15) = 1.87$, $p = .19$, or the interaction, $F(1, 15) = .01$, $p > .05$, on the number of fixations on the communication areas were found.

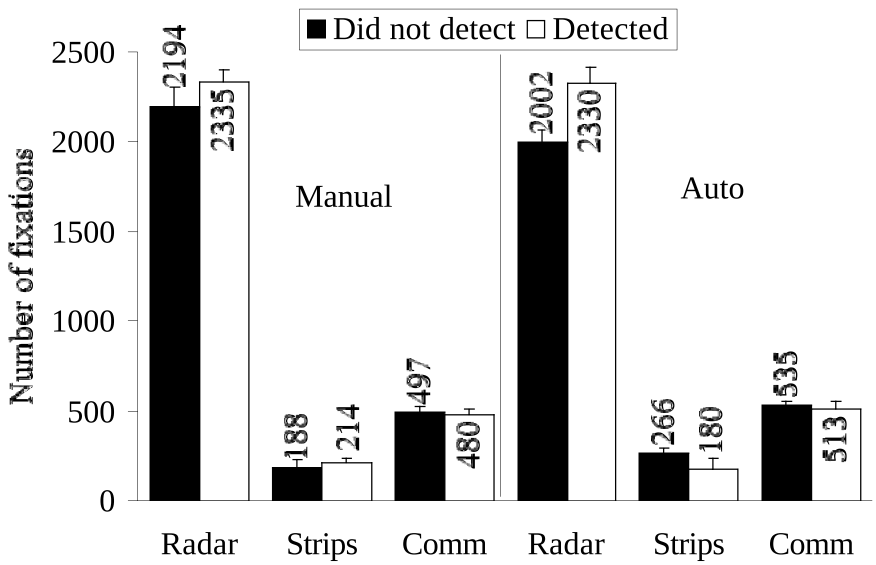


Figure 9.4: Number of fixations as a function of area of interest, automation condition, and detection performance

Duration of fixations. Few effects were found on the duration of fixations. The duration of fixations was significantly different between the different areas of interest, $F(2, 30) = 35.17$, $p < .0001$. Fixations were longest on the radar display (M = 353 ms; SE = 8 ms) followed by the communication areas (M = 349 ms; SE = 9 ms) and the flight strips (M = 276 ms; SE = 6 ms). A trend for a three-way interaction between automation condition, detection group and area of interest was found, $F(2, 30) = 2.09$, $p = .14$. No significant effects of detection group, $F(1, 15) = .60$, $p > .05$, automation condition, $F(1, 15) = .72$, $p > .05$, or the interaction, $F(1, 15) = 2.17$, $p = .16$, were found on the duration of fixations on the radar display. For fixation duration on the flight strips, no effects were found for detection group, $F(1, 15) = .87$, $p > .05$, automation condition, $F(1, 15) = .00$, $p > .05$, or the interaction, $F(1, 15) = 1.66$, $p > .05$. For the communication areas, no effects were found for detection group, $F(1, 15) = .03$, $p > .05$, automation condition, $F(1, 15) = .06$, $p > .05$, or the interaction, $F(1, 15) = .14$, $p > .05$.

Number of dwells. The number of dwells differed by area, $F(2, 30) = 162.59$, $p < .0001$. The most dwells were made on the radar display (M = 127.40; SE = 4.81) followed by the communication areas (M = 79.28; SE = 3.54) and the flight strips (M = 40.16; SE = 3.53). A significant interaction between the automation condition and detection group was found, $F(1, 15) = 3.70$, $p = .07$. While there was little difference in the number of dwells between manual ($M = 81.94$; $SE = 10.84$) and automated conditions ($M = 77.17$; $SE = 8.91$) for the ATCos who detected the automation failure, there was a difference between manual ($M = 76.76$; $SE = 6.92$) and automated conditions ($M = 90.77$; $SE = 8.09$) for the ATCos who did not detect the failure. Figure 9.5 shows the marginally significant three-way interaction between detection group, automation condition, and areas of interest, $F(2, 30) = 2.77$, $p = .08$. For the radar display, the interaction between detection group and automation condition was significant, $F(1, 15) = 6.14$, $p < .05$. For the ATCos who did not detect the automation failures, the difference in the number of dwells between automated and manual conditions was significant, $F(1, 10) = 6.81$, $p < .05$. For ATCos who detected the failures, the difference in the number of dwells between manual and automated conditions was non-significant, $F(1, 5) = 1.46$, $p > .05$. For the flights strips, there was no effect of detection group, $F(1, 15) = .19$, $p > .05$, automation condition, $F(1, 15) = .23$, $p > .05$, or the interaction, $F(1, 15) = 1.45$, $p > .05$. For the communication areas, no effects of detection group, $F(1, 15) = .39$, $p > .05$, automation condition, $F(1, 15) = 1.15$, $p > .05$, or the interaction, $F(1, 15) = .59$, $p > .05$ were found.

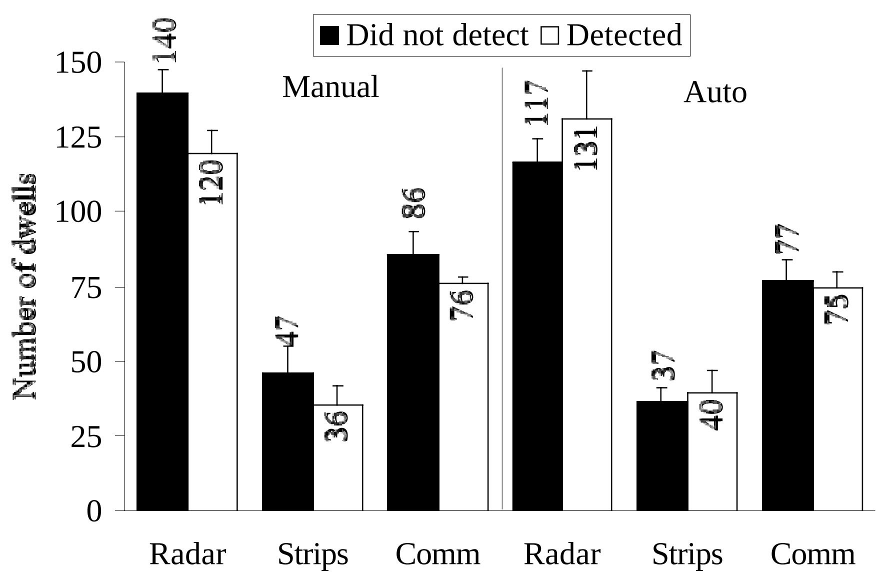


Figure 9.5: Number of dwells as a function of area of interest, automation condition, and detection performance

Duration of dwells. Dwells were longer under manual (M = 3.64 s; SE = 0.39 s) than under automated conditions (M = 3.20 s; SE = 0.31 s), $F(1, 15) = 3.81$, $p = .07$, indicating higher workload under manual than under automated conditions.

The duration of dwells was significantly different between areas of interest, $F(2, 30) = 141.13$, $p < .0001$. Dwells were longest on the radar display (M = 6.39 s; SE = .33 s), followed by the communication area (M = 2.40 s; SE = .18 s) and the flight strips (M = 1.47 s; SE = .08 s). The interaction between automation condition and detection group was significant, $F(1, 15) = 5.91$, $p < .05$. While there was no significant difference in the duration of dwells between manual (M = 3.50; SE = .63) and automated conditions (M = 3.57; SE = .60) for ATCos who detected the automation failure, $F(1, 5) = .07$, $p > .05$, there was a significant difference between manual (M = 3.71 s; SE = 0.49 s) and automated conditions (M = 3.00 s; SE = 0.36 s) for the ATCos who did not detect the automation failure, $F(1, 10) = 15.71$, $p < .01$. The interaction between automation condition and area of interest was significant, $F(2, 30) = 3.00$, $p = .06$. While there was no significant difference in dwell durations between manual (M = 1.47 s; SE = 0.10 s) and automated conditions (M = 1.46 s; SE = .14 s) on the flights strips, $F(1, 16) = .00$, $p > .05$, or on the communication areas (M_{man} = 2.46; SE_{man} = .31; M_{auto} = 2.33; SE_{auto} = .20), $F(1, 16) = .72$, $p > .05$, there was a significant difference in dwell durations between manual (M = 6.97 s; SE = .47 s) and automated conditions (M = 5.81 s; SE = .44 s) on the radar display, $F(1, 16) = 6.18$, $p < .05$.

Figure 9.6 shows the significant three-way interaction between detection group, automation condition, and area of interest, $F(2, 30) = 5.74$, $p < .01$. For the radar display, dwells were significantly longer under manual (M = 6.97; SE = .47) than under automated conditions (M = 5.81; SE = .44), $F(1, 15) = 4.04$, $p = .06$. The interaction between detection group and automation condition was significant, $F(1, 15) = 7.12$, $p < .05$. For the flight strips, no significant effect of the detection group, $F(1, 15) = .38$, $p > .05$, automation condition, $F(1, 15) = .02$, $p > .05$, or the interaction, $F(1, 15) = .11$, $p > .05$, were found. Likewise, for the communication area no significant effects were found for detection group, $F(1,15) = .03$, $p > .05$, automation condition, $F(1, 15) = .35$, $p > .05$, or the interaction, $F(1, 15) = .46$, $p > .05$.

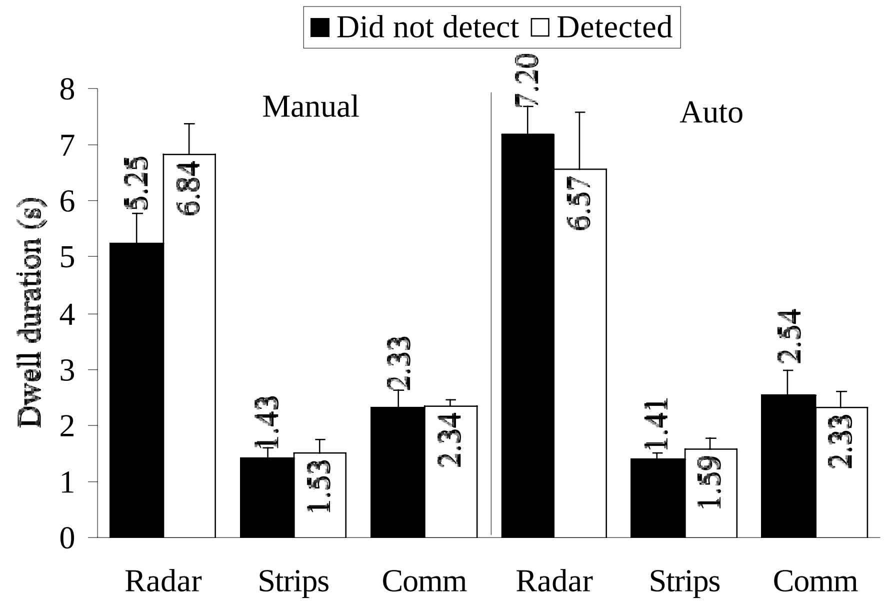


Figure 9.6: Dwell duration as a function of area of interest, automation condition, and detection performance

<u>*Dwell time.*</u> Dwell times were obtained by multiplying the number by the duration of dwells. ATCos spent the longest time on the radar display (M = 764.63 s; SE = 19.05 s) followed by the communication area (M = 178.62 s; SE = 8.63 s) and the flight strips (M = 61.05 s; SE = 6.48 s), $F(2, 30) = 657.53$, $p < .0001$. The interaction between automation condition and area of interest was significant, $F(2, 30) = 3.97$, $p < .05$. ATCos spent more time dwelling on the radar under manual (M = 799.89 s; SE = 18.91 s) than under automated conditions (M = 729.37 s; SE = 31.38 s), $F(1, 16) = 6.63$, $p < .05$. No significant effect of the automation condition was found for the flight strips (M_{man} = 54.69 s; SE_{man} = 6.57 s; M_{auto} = 67.41 s; SE_{auto} = 11.17 s), $F(1, 16) = 1.53$, $p > .05$, or the communication areas (M_{man} = 171.69 s; SE_{man} = 11.18 s; M_{auto} = 185.54 s; SE_{auto} = 13.27 s), $F(1, 16) = 1.47$, $p > .05$.

Figure 9.7 shows the significant interaction between automation condition, area of interest, and detection group, $F(2, 30) = 4.42$, $p < .05$. A significant difference between manual and automated conditions was found for the dwell time on the radar display, $F(1, 15) = 4.39$, $p = .05$. More dwell time was spent on the radar under manual (M = 729.37 s; SE = 31.38 s) than under automated conditions (M = 799.89 s; SE = 18.91 s). The interaction between detection group and automation condition was also significant, $F(1, 15) = 5.22$, $p < .05$. Neither the

detection group, $F(1, 15) = .14$, $p > .05$, nor automation condition, $F(1, 15) = .67$, $p > .05$, nor the interaction, $F(1, 15) = 1.77$, $p > .05$ had a significant effect on dwell time on the flight strips. Likewise, the effects of detection group, $F(1, 15) = .13$, $p > .05$, automation condition, $F(1, 15) = 1.07$, $p > .05$, or the interaction, $F(1, 15) = .10$, $p > .05$, on dwell times on the communication areas were all non-significant.

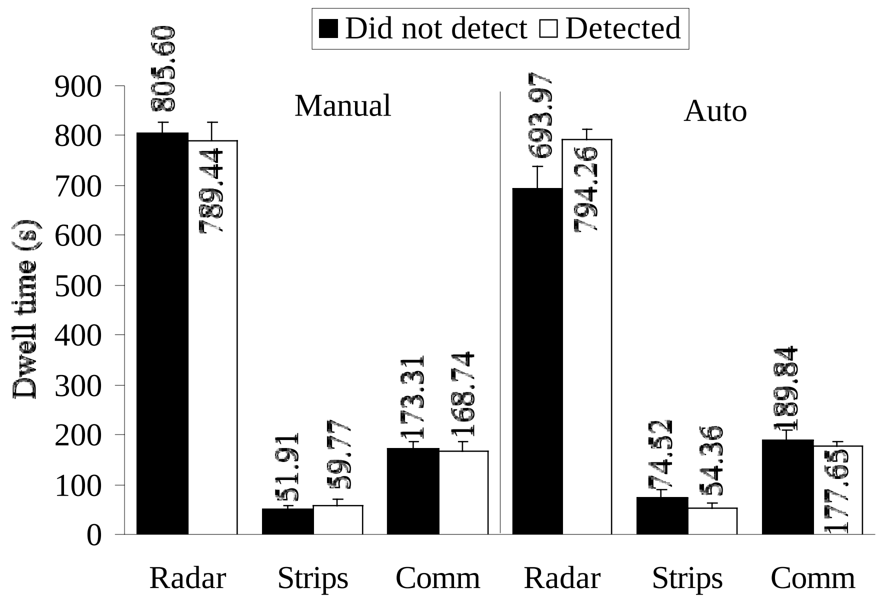


Figure 9.7: Dwell time as a function of area of interest, automation condition, and detection performance

9.3.6 Subjective ratings of mental workload

The effect of the automation condition on ratings of mental workload failed to reach significance, $F(3, 57) = 1.86$, $p > .05$. Contrasting automated versus manual conditions indicated a trend towards higher ratings of mental workload under manual ($M = 65.46$; $SE = 3.76$) than under automated conditions ($M = 60.03$; $SE = 1.71$), $F(1, 19) = 2.59$, $p = .12$.

9.3.7 Trust and self-confidence

Ratings of trust ranged from 0 to 100 with an average of 75.71 ($SE = 2.14$). Trust ratings differed significantly between the automation conditions, $F(2, 38) = 1.63$, $p > .05$. Controllers rated their trust higher under reliable ($M = 79.33$; $SE = 2.66$) than under failure conditions ($M =$

72.10; *SE* = 3.30), $F(1, 19) = 5.96$, $p < .05$. There was no difference in trust ratings between ATCos who detected both and ATCos who did not detect any automation failures, $F(1, 15) = .01$, $p > .05$. Even though trust ratings in ATCos who detected the automation failure indicated a greater drop from reliable ($M = 78.75$; $SE = 4.88$) to unreliable automation conditions ($M = 68.25$; $SE = 5.27$) than trust ratings in ATCos who did not detect the automation failure ($M_{rel} = 79.36$; $SE_{rel} = 4.03$; $M_{unrel} = 73.18$; $SE_{unrel} = 5.27$) the interaction was non-significant, $F(1, 15) = .35$, $p > .05$. Ratings of self-confidence ranged from 25 to 100 with an average of 65.70 ($SE = 2.42$). No differences between automation conditions were found for self-confidence.

9.4 Discussion

The purpose of the experiment was to investigate the effects of reliable and inaccurate automation conditions on ATCo performance in the detection of potential conflicts and communication tasks, mental workload, trust in the automation, and self-confidence to perform without automation. Of particular interest was the question whether ATCos would be able to intervene in cases when both airborne separation and the conflict detection aid failed. Performance in detecting a failure of airborne separation was studied under manual conditions and under automated conditions when the automation failed to point out an identical conflict. Further, it was studied if reliable automation could improve performance and reduce mental workload compared to manual performance.

Like in the previous two experiments, a marked benefit of the conflict detection automation on ATCo performance was found when the automation functioned 100% reliably. More potential conflicts were detected and conflicts were detected earlier under automated than under manual conditions. The automation effects did not carry over to the communication task of accepting and handing-off aircraft with the exception of a few order effects due to the fixed order of reliable and unreliable automation. In those tasks, ATCos performed better under unreliable conditions suggesting a practice effect. The performance of routine tasks imposes a considerable amount of workload, but did not benefit from the availability of a decision aid. Apparently, the aid did not free enough resources or the ATCos chose not to allocate them to improve communication performance.

Trends were found for reduced mental workload under automated compared to manual conflict detection conditions. ATCos rated their workload lower and updated more waypoints when they had conflict detection automation available. However, it took them longer to update the waypoints when they had automation available. This could represent either a speed-accuracy trade-off or a cost of the automation. Perhaps, it took ATCos longer to update waypoints from an automated or automation monitoring mode than from a manual mode. The ocular measure of mental workload found shorter dwell durations under automated than manual operations indicating reduced allocation of attentional resources under automated conditions. Scanning randomness or entropy did not reflect an automation effect. This is in contrast with other ATC research that found higher scanning randomness (indicating lower mental workload) under automated conditions (Hilburn, 1996). However, Hilburn (1996) used five areas of interest (i.e. traffic, datalink, time line, pre-acceptance, and hand-off area) and eye fixations were more equally distributed across these areas in his simulation of air traffic transitioning to TRACON. Because in the present study about two thirds of all fixations were on the radar and transitions could be made to only two other areas of interest (i.e. flightstrips and communication area), there might not have been enough scanning of other areas and not enough transitions between areas of interest for entropy to be sensitive to automation effects. In the past, the measure of entropy was mostly used to study scanning in the cockpit where there is more scanning *between* displays, instruments, and out-of-the window (Harris et al., 1986) than in the ATC environment where most of the scanning takes place *within* the radar display.

In general, automation had mostly beneficial effects as long as it functioned 100% reliably. Under inaccurate automation conditions however, the findings were not so positive. ATCos were more likely to detect a particular conflict when they were manually detecting potential conflicts than when they were assisted by automation and the automation failed to point out a particular conflict. Overall, trust in the automation was rated relatively high under reliable automation conditions (i.e. in the upper quartile) and was reduced after the automation failed to point out a conflict. That ATCos detected the four-minute automation failure earlier when they experienced it the second time could reflect the calibration of their trust with the experienced level of accuracy of the detection aid (Wickens, 2000). However, this should remain only a speculation as the analysis was purely exploratory and based on a very small number of participants.

Visual attention as measured by eye fixations and dwells indicated that ATCos who did not detect the automation failures reduced their visual attention to the radar (i.e. the automated task) under automated compared to manual operations. No difference in detection rates was found when ATCos had two versus four minutes available between the onset of the failure event and the loss of separation. Timeliness in the detection of a potential conflict was also not markedly different between manual performance and a comparable automation failure condition. No support was found for the view that ATCos under automated conditions would require more time to detect and respond to a conflict because they are further removed from the decision-making process. However, this was only an exploratory data analysis. It is possible that a longer time frame would have shown an effect. Two or four minutes might simply not have been enough to show a variation. However, inaccuracies in a conflict detection aid like URET are more likely to be short-term. Longer term changes in flightplan, for example, would eventually be available to URET so that they could be taken into account for the conflict or no-conflict decision.

These results show that the detrimental effects of FF conditions on the ATCo such as reduced conflict detection and increased mental workload found in earlier experiments (Galster et al., 2001; Endsley et al., 1997; Metzger & Parasuraman, in press) can be compensated for by supporting ATCos with automated decision aids. However, this study suggests that these automation benefits do not come without a cost. ATCos performed better in detecting conflicts without automation than when they had automation support that was less than 100% accurate. This points toward a complacency effect.

The vigilant reader may have noticed that the complacency effect was "only" a trend and not statistically significant. Still, it was interpreted. To study operator response to very rare failures of system components or other surprises, a surprising event can only be presented once or twice before the participants start to expect them and adapt their behavior accordingly (Molloy & Parasuraman, 1996; Wickens, 1998). However, low numbers of events result in low power and therefore a likelihood for statistically non-significant results. The described study addressed complex phenomena under multi-task conditions in which multiple human information-processing components are involved. This can lead to large variances in overall multi-task performance because variance in a multi-task situation is composed of the variance for each task component, variance for task-sharing, strategies, and trade-offs. Likewise, the response to surprises can lead to high variance between participants. This makes it evident that empirical data on the response to unexpected events is difficult, expensive, and time consuming to obtain, especially if it becomes necessary to keep the sample size in a study low to meet cost or time constraints, if a specific population is tested (e.g. air traffic controllers, pilots, astronauts, etc.) and expensive equipment is used (e.g. simulators, eye-tracking equipment). As a consequence, the analysis and interpretation of the results focused on practical considerations rather than statistical significance (Wickens et al., 1998b; Wickens, 1998; Bortz & Döring, 1999). In studying safety-critical environments such as the ATC system it is better to err on the side of caution and take a potentially detrimental effect for system safety serious, even if it is small and not statistically significant, than to reject the effect for purely statistical reasons and perhaps find out later in the real world that the effect was indeed of practical significance. Rather than relying exclusively on inferential statistics, we should also rely on the replication of results as suggested by Cohen (1994). In the case of the complacency effect, it has been demonstrated repeatedly and reliably in more basic laboratory simulations and has been reported by pilots and in accident reports. Therefore, the effect in the presented experiment should be taken seriously even if it did not reach significance. It should further be noted that the reliability of the detection aid in this study (one failure per scenario) was rather low, in fact, much lower than would be acceptable for a real world system. However, higher reliabilities are associated with even more complacent behavior (May et al., 1993). Therefore, the complacency effect in this study should be considered a rather conservative estimate. Automation-related complacency could be much more pronounced with the very high reliability of real world systems.

One limitation of the experimental design should be pointed out, however. The order of presentation of the reliable and unreliable automation was not balanced. ATCos always performed in the reliable automation before performing in the unreliable automation conditions so that they could get enough experience and build trust. Therefore, order was confounded with the reliability of the aid and it is possible that the reduced detection of an automation failure was due to effects other than the reliability. For example, one could argue that ATCos became tired after repeated performance in these scenarios and, as a result, did not detect the automation failures. Communication performance suggested quite the opposite, however. Communication performance was better in the unreliable than in the reliable condition suggesting a practice effect. Based on this finding, ATCos should be expected to be more, rather than less efficient in their task performance, including conflict detection. In addition, if fatigue were the cause of the complacency trend, then manual performance should be reduced in those ATCos that performed the manual condition last (order 3 and 4 in figure 9.1). Again, this was not found in the data. There was no difference in ATCos who performed the manual conditions first and those that performed it last making it unlikely that fatigue was the cause of the reduced conflict detection under automated conditions.

Different explanations for complacency have been proposed (Parasuraman et al., 1993; Farrell & Lewandowsky, 2000; Moray, 2000) and discussed previously (see 3.3). The results of this study support the view that complacency is associated with reduced attention allocation to the automated task under automated conditions compared to manual conditions (Parasuraman et al., 1993) assuming that eye movements and attention are associated at least to some extent. Attention allocation to the automated task (i.e. the radar display) as measured by the number of fixations and dwells and dwell time was reduced under automated compared to manual conditions in the ATCo group that did not detect the automation failure (i.e. the group that was complacent). Because eye movements were only analyzed up to the point when the loss of separation occurred, the difference in eye fixations and dwells between the ATCos who detected and did not detect the failure cannot be due to the fact that the ATCos who detected the event spent more time looking at the display after they realized that the automation had missed something.

However, recording and analyzing eye movements in the ATC environment points out a particular challenge. In contrast to eye movement studies performed in the cockpit or in process control, the elements of interest carrying relevant information (i.e. the aircraft and datablocks) are very small and not in a static location in the ATC environment. Instead, they move around the large radar display. Pinpointing which aircraft or datablock exactly an ATCo is fixating requires a very high accuracy and resolution of the eye tracking equipment and sophisticated analysis software which were not available for the present experiments. Therefore, it is possible that even though ATCos who did not detect the automation failure fixated on the radar less under automated conditions, they fixated the particular aircraft or the datablocks of the aircraft involved in the conflict undetected by the automation. Because they did not detect it, this is unlikely. However, it should be recalled that the relationship between visual attention and eye fixation is only of partial interdependence. Even though there is a functional tie between eye movements and attention, a fixation does not guarantee attention. Attention is necessary however to determine where the eye will fixate next ("mandatory shift hypothesis"; Pashler, 1998). A classic study by Mackworth and Kaplan (1964) found that even though critical signals on a display were fixated, study participants often missed reporting them. Duley et al. (1997) conducted a study in which they forced fixation on an automation monitoring task by superimposing it over the primary tracking task in a simulation of multiple flight tasks (modified mutli-attribute task or MAT battery; Parasuraman et al., 1993). Even though fixations were forced on the monitoring task, the detection of automation failures was not improved compared to the non-superimposed condition while tracking performance was preserved. Metzger, Duley, Abbas, and Parasuraman (2000) found that even though a group of students that was trained in that same simulation of multiple flight tasks with variable priority manipulations (e.g. Kramer, Larish, Weber, & Bardell, 1999; Gopher, 1996, Gopher, Weil, & Siegel, 1989) performed better than students who were trained with conventional whole-task or part-task training approaches, no difference in eye movements was found.

Thus, eye fixations and attention could have been dissociated in ATCos as well. They could have fixated on a datablock, but attend to stimuli in the periphery or to internal processing, for example in working memory. This seems unlikely in the ATC simulation though. The reason for the dissociation of eye movements and attention in the MAT battery could be due to the fact that the MAT display used in these studies was relatively small (17 inches) and attention could have been allocated to parts of the display using peripheral vision. Both, the primary tracking task and the automation monitoring tasks are dynamic. Changes could have been captured in the peripheral vision without requiring to foveate. The ATC simulation is different. First, the radar display is much larger (21 inches) and fills a large part of the visual field. The two other displays (the flightstrips and communication areas) were displayed on a second monitor of the same size. Transitioning from the datalink displays to the radar required the ATCos to move their head. In addition, the relevant data on the radar or the datalink displays was printed in relatively small font (about 12 point), similar to the real world systems. Extracting information from these datapoints (e.g. the datablock) most likely required the participants to fixate them. Therefore, it seems unlikely that ATCos were able to process information from the ATC simulation with peripheral vision only and could explain why attention and eye movements were associated in the ATC task, but dissociated in other studies such as the MAT task. With appropriate equipment and software, it would be interesting, however, to examine the allocation of attention on the basis of fixations on individual aircraft and aircraft datablocks and study the association and dissociation between attention and eye movements.

Of course, Moray's view (2000) cannot be refuted with these data because the present study did not compare visual sampling under automated conditions to an optimal sampling strategy. Due to the complexity of the ATC tasks, it is very difficult to establish an optimal sampling strategy. This difficulty in establishing the optimal sampling strategy might further be the reason why Moray or others have not been able to provide empirical support for their view in complex human-automation environments.

These findings have important implications for the introduction of automation. Unless automation is extremely reliable, operators might be better off performing manually than performing with automation that works unreliably. Automation should not be introduced into systems in the expectation that it “does not hurt” to have automation available. It has been shown that even when automation is extremely unreliable and should not be trusted (e.g. 25%; May et al., 1993), humans still rely on it and show (slightly) poorer detection performance under automated than manual operation. Mosier and Skitka (e.g. Mosier & Skitka, 1996) have argued that automation use acts like a heuristic in decision-making. Rather than relying on the raw data to make a decision, operators base their decision on the automation. If the automation is unreliable, this can have catastrophic consequences.

For highly reliable automation that is beneficial to operator and system performance, automation should be designed in a way that the risk for complacency is reduced. Depending on the assumed underlying mechanisms of complacency different options have been suggested. Based on the hypothesis that complacency is an attentional phenomenon several solutions have been proposed in the automation research literature. Adaptive automation combines the benefits of automation with the benefits of manual control and has been shown to reduce complacency in the MAT battery (Parasuraman, Mouloua, & Molloy, 1996) and provide performance benefits in an ATC simulation (Hilburn, 1996). In addition, it could reduce other costs of automation such as manual skill degradation. The advantage of adaptive over static automation is also consistent with the hypothesis that complacency reflects a weakening of the memory trace of the automated function over time (Farrell & Lewandowsky, 2000). If automation were able to communicate its level of accuracy to the operator, the control function could be allocated to the operator or the machine based on the automation's self-diagnosed level of accuracy. For example, if wind or weather are difficult to predict and conflict prediction consequentially could become inaccurate, the automation could return control to the ATCo. It has been suggested previously that complacency might have to do with visual factors, e.g. that the operator was distracted by a primary task and failed to detect the malfunction of the automated system because it was in peripheral rather than central vision. However, positioning the monitoring in the center of a monitor (Singh, Molloy, & Parasuraman, 1997) or superimposing the automated system on the primary task (i.e. in central vision; Duley et al., 1997) did not reduce the complacency effect suggesting that the effect is due to attentional rather than pure visual factors. Solutions need to be found to reduce the attentional demand in order to free resources so that controllers can pay attention to the automated system. The use of integrated displays has also been demonstrated to reduce complacency (Molloy & Parasuraman, 1994; Molloy, Deaton & Parasuraman, 1995). If reduced detection of automation failures is associated with reduced visual attention to the automated task, automation should be designed in a way that it does not require a lot of attentional resources for operators to detect a system malfunction. By forming an emergent feature such as an object or a shape, integrated displays decrease the demand for attentional resources associated with detecting malfunctions. Information on the malfunction can then be processed in parallel with other information. Molloy and Parasuraman (1994) showed the benefit of integrated displays in a simulation in which an engine-status display was presented to non-pilot participants either conventionally (i.e. four round gauges that had to be monitored) or in its integrated form (i.e. vertical bars with a bar as the emergent feature indicating a malfunction when the bars crossed the line). Molloy and Parasuraman (1994) found that subjects detected 70% of the malfunctions in the manual condition. In the automated condition, participants performed significantly better with the integrated (64% detection rate) than with the conventional display (36% detection rate). A replication of the study with pilot participants (Molloy et al., 1995) found similar results.

Training could represent a complementary approach to system design. There is strong evidence that variable priority training can improve time-sharing or task-coordination abilities in complex multi-task environments and make attention strategies more flexible, particularly in comparison to conventional whole or part-task (PT) training (Kramer et al., 1999; Gopher, 1996;

Gopher et al., 1989). Trainees in a variable priority training give (varying) priority to one of the tasks while still performing the others. This allows the trainee to experience the effects of different attention allocation strategies. Metzger et al. (2000) found a trend for reduced complacency in group of students that was trained with variable priority training strategy compared to groups trained with traditional part-task or whole-task strategies in the MAT battery, a multi-task battery simulating different flight tasks. This supports the hypothesis that complacency is due to suboptimal sharing of attentional resources and indicates that training might be a valuable approach to reduce complacency effects.

However, any of these approaches to reduce complacency need to be evaluated. As long as the ATCo does not have authority for separation and is not actively involved in the decision-making process, none of these techniques to reduce complacency might be useful.

While complacency effects have been reported in the NASA ASRS by pilots and have been shown reliably in simple PC-based multi-task batteries with student participants and pilots (Parasuraman et al., 1993; Dzindolet, Pierce, Dawe, Peterson, & Beck, 2000; Mosier & Skitka, 1996), this is the first study showing complacency in a mid-fidelity ATC simulation in a sample of professional ATCos. This is a very important finding because it indicates that ATCos could exhibit the same complacency effects that have been found in the general population (i.e. students) and pilots, both in the laboratory and in the field as some accident and incident reports show. So far, controllers have not been exposed to sophisticated automation, but rather to fairly simple and unreliable automation (e.g. the current conflict alert). In addition, ATCos are aware that the task of detecting and resolving conflicts is already a difficult one and can even become more difficult under FF conditions. Therefore, it could be speculated that ATCos would not be as susceptible to complacency and excessive trust as other groups. As the data showed, this was not the case. Operators in the ATC environment seem as susceptible to complacency effects as operators in other domains.

10. Discussion

The final chapter summarizes and integrates the findings of the empirical studies and concludes with the discussion of their implication for both, theory and the design of effective and safe human-automation systems in ATC and other domains.

10.1 Summary of the research

The ATC system is undergoing major changes to accommodate unprecedented amounts of traffic (RTCA, 1995; FAA, 1997). Authority for aircraft separation will shift to the flightdeck reducing the involvement of ATCo in the control of air traffic. However, ATCos are expected to intervene when airborne separation fails. Previous studies found reduced performance under such FF conditions and automated decision aids were suggested as a means to improve ATCo performance (Endsley et al., 1997; Galster et al., 2001; Metzger & Parasuraman, in press). While a few studies have shown benefits of automated decision aids under current ATC conditions (Hilburn, 1996; Schick, 1991a, 1991b), no literature was available examining the effects of automated decision aids on ATCo performance and workload under FF and high traffic density conditions. The present work was conducted to bridge this gap in the research literature. In particular, it was studied whether automated decision aids could remedy some of the negative effects associated with FF and high traffic density expected for the future. It was further examined how the potentially reduced utility of a decision aid (i.e. automation failures) would affect ATCo performance. In addition, a relatively new approach to human-automation interaction was studied. It was investigated if multimodal automation feedback would have beneficial effects in guiding attention in an increasingly visual environment.

The experiments demonstrated that increased traffic densities could result in reduced ATCo conflict detection and communication performance validating previous findings (Galster et al., 2001; Metzger & Parasuraman, in press). Conflict detection automation had many beneficial effects on performance and mental workload and could compensate for detrimental effects of high traffic density. However, despite the many beneficial effects that the decision aid had on ATCo mental workload and performance, there were also adverse effects when the aid failed. Fewer ATCos detected a particular conflict when an automation failure occurred than when they were manually detecting conflicts. Multimodal feedback was not as efficient in guiding ATCo attention as expected. In fact, evidence for a disruption of the performance in an ongoing visual task was found.

These findings will now be discussed as they apply to the model on the interrelationship of taskload, workload, strategies, and performance (Wickens et al., 1997; see figure 4.1) that was central to the research approach. Additionally, theoretical implications of the empirical findings (e.g. for complacency or cross-modal attention) will be covered.

10.2 Integration of empirical findings and theoretical implications

Figure 10.1 shows how the findings of the three empirical studies can be integrated and applied to the model (Wickens et al., 1997). Although automation might not be a direct taskload factor (like traffic density, e.g.), it can moderate the effects of taskload on workload, performance, and the choice of strategies. The experiments presented in chapters 7-9 investigated the effects of traffic density, the availability of automation, and automation display variations (i.e. feedback). These are all relevant factors with respect to future developments in ATC. The ATCos' adaptation to the changing demands of their environment is central to the model.

10.2.1 Traffic density

Traffic density had a great impact on ATCo workload, performance, and the choice of strategies. Mental workload increased significantly with increased traffic density. This was reflected in both subjective and physiological measures. ATCos managed the increased workload under high traffic density by postponing flight strip updates and some even chose to shed this low-priority task completely. Interesting was also the ATCos' strategy under moderate traffic conditions to update flight strips prematurely even though they were instructed not to do so. ATCos probably tried to accomplish these tasks whenever they had capacity to do so in an attempt to prepare for periods of higher load, ignoring the instructions. Both tasks, updating flight strips and handing-off aircraft, contain prospective memory components. ATCos have to remember to perform these tasks at a certain point later in time. Prospective memory has

Taskload →	**Workload** →	**Performance**
Traffic:	Increased WL (physiological, subjective)	Reduced and delayed detection of conflicts and self-separations; delayed communication
Automation:	Reduced WL (dwell duration, subjective)	Increased and earlier detection of conflicts and self-separations; earlier detection especially under high traffic (= compensation); increased detection rate under moderate traffic; reduced detection with auto failure; more timely communication
Feedback:	--	Delayed hand-offs with multimodal and enhanced FB

Strategies

Traffic:	postponing and shedding of flight strip updates; shift in attention allocation from radar (and strips) to communication
Automation:	reduced shedding, but greater delay of flight strip updates; shift in attention allocation from radar to communication (esp. for non-detection group); fewer early hand-offs under high traffic
Feedback:	High traffic: most shedding of flight strip updates with multimodal, least with enhanced FB; moderate traffic: most early updates with multimodal, least with enhanced FB; high traffic: most early updates with enhanced, least with multimodal FB

Figure 10.1: Integration of empirical findings into the model (Wickens et al., 1997)

been shown to be very susceptible to workload (Sauer, 2000). Therefore, it is reasonable to assume that performing these tasks earlier than instructed, represents a workload reduction strategy. If the task is completed, the ATCo no longer has to remember to perform it. In addition, handing-off aircraft as early as possible would result in a very efficient workload reduction for ATCos in the real world (if the ATCo in the adjacent sector accepted them early) because they would no longer have responsibility for these aircraft. They could drop the datablock and reduce visual load and load imposed by considering these aircraft in their decision making.

Increased traffic density also led to a shift in the attention allocation strategy as reflected in eye movements. Attention allocation to the datalink was increased to keep up with communication at the expense of attention allocation to the radar display. This is probably a consequence of the requirement for coordination and communication for each single aircraft. That the shift in strategies was not completely successful to maintain performance was reflected in the delayed communications under high traffic. Due to the human's limited supply of attentional resources, resources that are allocated to one task cannot be allocated to another. Resources allocated to communication had to be "borrowed" from a different area, in this case the radar display and, to a lesser extent, the flight strips. The reduced attention allocation to the radar under high traffic density was also associated with the reduced and delayed detection of potential conflicts.

10.2.2 Automation

Automation had numerous effects on mental workload, strategies, and performance. In the first experiment, mental workload and strategies were not affected. ATCos might have allocated the resources freed by the automation to other tasks as reflected in the improved performance in the communication tasks. Alternatively, the lack of an automation effect on workload could be due to the only moderate levels of trust and, as a consequence, the underutilization of the aid. ATCos might not have understood its functionality well enough to rely on it and, therefore, the availability of automation did not affect their workload. In the third experiment, in which ATCos rated trust considerably higher, mental workload as indicated by subjective ratings and reduced dwell durations was reduced with automation. Dwell durations can indicate the amount of information presented or the level of effort required for information extraction from a display. Therefore, the shorter dwell durations, particularly on the radar display, under automated conditions were interpreted as an indicator of reduced mental workload. In the third experiment, strategies were also affected by automation. More aircraft were handed-off prematurely under manual than under automated conditions. The great effectiveness of this strategy to reduce mental workload was already discussed above. Under automated conditions, more flight strips were updated successfully indicating that the automation might have freed attentional resources that could be allocated to this task of lower-priority.

However, ATCos delayed the flight strip updates longer under automated than under manual conditions. More research is needed to determine if this reflected a simple speed-accuracy trade-off or, more seriously, a cost of the automation. It might take ATCos longer to update the flight strips when they are removed from the decision-making loop (automated condition) than when they are part of the decision loop (manual condition). This could be an indicator for the ATCos' reduced awareness of the location or status of the elements in their airspace, which can negatively impact their decision-making.

Most importantly, however, the availability of conflict detection automation resulted in markedly increased and advanced detection of potential conflicts as long as the automation was reliable and even carried over to the communication tasks. ATCos responded faster to requests for acceptance into the sector and handed-off more aircraft successfully. The resources that were freed by the conflict detection automation were invested in the communication tasks. When the automation failed, however, fewer ATCos detected a conflict that the automation failed to point out under automated conditions than under manual conditions. Therefore, the effects of automation on ATCo performance have to be differentiated for reliable and unreliable automation.

Associated with the rather poor detection of automation failures, and perhaps the most interesting result, was an automation-related strategy shift revealed by eye movements. The availability of automation was associated with a reduction in visual attention to the radar. This strategy shift was linked to performance in the detection of the automation failure. ATCos who did not detect automation failures allocated fewer attentional resources, as indexed by eye fixations, to the radar (where the automated task was located) under automated than under manual conditions. ATCos who detected conflicts even though the automation failed to point them out allocated the same amount of visual attention to the radar under manual and automated conditions.

Theoretical implications: Complacency. If it is assumed that eye fixations and attention allocation are related, this supports the attention-related explanation of complacency that automation failures are not detected because fewer attentional resources are allocated to the automated task (Parasuraman et al., 1993). However, although trust was rated relatively high and dropped in the unreliable condition, there was no difference in trust ratings between ATCos who detected and ATCos who did not detect the failure. Therefore, no support was found for the hypotheses that complacency is due to high trust in the aid as suggested by Parasuraman et al. (1993). The immediate implications of this and other interpretations for system design will be discussed below.

10.2.3 Automation as a moderator of traffic density effects

Of particular interest is how automation moderates the effects of traffic density. This is central to the research question whether automation would be able to compensate for the negative effects of traffic density. Again, more aircraft were handed-off prematurely under manual than under automated conditions. However, this became especially evident under high traffic density. That ATCos made the most use of this strategy in the manual high density traffic condition when taskload was highest of all conditions shows how efficient ATCos were in managing their workload. Perhaps as a consequence of this, mental workload was not affected by the interaction between automation and traffic.

Most important, however, was the moderating effect of automation on the detection of potential conflicts. While the number of detected self-separations benefited the most from the aid under moderate traffic conditions, advance notification of potential conflicts had the greatest benefit from the aid under high traffic density. Without automation, potential conflicts were detected later under high than under moderate density. Not only did advance notification improve considerably with the aid, advance notification under high traffic density exceeded performance levels under manual conditions at both traffic levels. Bearing in mind that future airspace will be much denser and more efficient leaving the ATCo less time to detect and resolve problems, the improved timeliness in the detection of potential conflicts is a very notable and encouraging finding. That the greatest effect was found for advance notification of conflicts as opposed to self-separations matches the greater relevance of the detection of conflicts for system safety. Self-separations represent successful airborne separation and do not require ATCo intervention. Conflicts, however, are the situations in which ATCos would be required to intervene. This indicates that automation could diminish and fully compensate for the negative impact of traffic density on advance notification of potential conflicts and, to a lesser extent, on the detection of self-separations.

That conflict detection performance was better maintained when automation was available at high levels of traffic density in Experiment 2 than in Experiment 1 could be due to the ATCos' stronger reliance on the reliable decision aid in Experiment 2. The stronger reliance could have compensated for the effects of traffic density and the reduced allocation of attention to the radar under high traffic density.

10.2.4 Automation feedback

Display design is another important workload driver. Display type (i.e. visual, enhanced visual, and multimodal automation feedback) of the conflict detection aid had fewer effects on mental workload, strategies or ATCo performance than traffic density or automation. In fact, display type had no effects on mental workload and, interestingly, on the conflict detection performance. Rather, it affected strategies and communication performance. There was a tendency for a greater hand-off delay in the multimodal and enhanced visual conditions than in the simple visual conditions. This could reflect the influence of display clutter and distraction in the search for aircraft ready for hand-off because both, enhanced visual and multimodal feedback, included an additional red line indicating the location of the detected potential conflict. ATCo complaints of clutter in these conditions would support this interpretation. The fewest early flight strip updates under high traffic density and the most early updates under moderate traffic density were made with multimodal feedback. Even though multimodal feedback should allow ATCos to shift their attention to other displays away from the radar, more flight strip updates were missed in the multimodal than in the visual feedback conditions under high traffic. Multimodal feedback seemed to disrupt rather than facilitate performance in this task.

Theoretical implications: Cross-modal attention. The preemption phenomenon could provide an explanation for these findings (Wickens & Liu, 1988). Due to the great alerting characteristic of an auditory stimulus (e.g. Posner et al., 1976; Spence & Driver, 1997a; Perrott et al., 1991), attention is diverted away from an ongoing visual task (e.g. updating flight strips) and shifted to the source of the auditory alert (i.e. the radar) leading to disruption of performance in the ongoing visual task. This is also consistent with findings by Spence and Driver (1997b, 1997c) who found performance costs when participants had to shift their attention from one modality to the other. They interpreted their results as evidence against the view that there are different independent attentional mechanisms allocating attention to different modalities and in favor of the view that one supramodal mechanism might be responsible for the allocation of attention to both modalities.

10.2.5 System performance

System performance is another component of the model by Wickens et al. (1997) that has not been addressed yet. To the extent that operators play a role in system performance, operator performance and workload assessments allow conclusions on system performance. In fact, predicting system performance often is the ultimate goal of performance and workload assessments (unless e.g. the effects of automation on operator stress and health are of interest by themselves). Based on this research, the conclusion can be drawn that automation in future ATM systems can have beneficial effects on system performance and safety because it can compensate for the negative effects on operator performance associated with high traffic density and the FF concept. However, measures need to be taken to assure that the operator does not become complacent to the automation thereby reducing safety. This is not to say that the operator is to blame for complacency and resulting safety glitches. Rather, complacency results from the interaction with a system that was designed without taking into account the capabilities and limitations of human performance. That humans are not good at monitoring under multi-task conditions is well established in the research literature and reflected in many accident and incident reports. If systems impose a high monitoring demand on the operator, resulting errors are not to blame on the human, but are design-induced.

That ATCos missed conflicts in these studies is not to say that, in the real world, there would have been a midair collision every time they missed one. Of course, in addition to ATCos other players and their respective systems contribute to system performance and safety. Most important among them are pilots and airline dispatchers. They were not addressed in this research and integrating all elements of the system is a huge endeavor well beyond the capabilities of this project. Still, further research is needed to investigate how automated decision aids can support not just the ATCos, but all elements of the system jointly in achieving the goals of increased safety and efficiency. Research efforts are currently under way at the NASA-Ames Research Center. A particular problem from the system perspective that is not being addressed yet is the interaction between ATCos and pilots that arises from the different algorithms for conflict detection and resolution on the ground and in the air. There is no single agreed upon algorithm for conflict detection and resolution. That is, pilots will have different algorithms than ATCos and most likely different airlines will install different algorithms on their aircraft. Because algorithms differ in how they predict conflicts (e.g. due to different wind models), they could come to different conclusions in terms of the time or severity of potential conflicts and their resolutions. How different predictions and recommendations for resolution will affect the interaction and negotiations between ATCos and pilots and ultimately system safety has not been addressed in the research literature.

To summarize, the findings suggest that the negative effects of FF on ATCo performance, mental workload, and eventually system safety found in previous studies (Galster et al., 2001; Endsley et al., 1997; Metzger & Parasuraman, in press) could be mitigated by providing advanced decision aids to the ATCos. The support of a 100% reliable conflict detection aid improved ATCo performance significantly and reduced mental workload under FF conditions and high traffic. Under FF, authority for separation is transferred to the pilots and ATCos are only expected to intervene in case airborne self-separation fails. This is quite difficult for ATCos given that the transfer of authority to the pilots and the lack of intent information removes them from the decision-making loop. However, automation can compensate for these negative consequences. Even though the ATCo now becomes a monitor of pilot separations and automation and is even further removed from the decision-making loop, automation alerts ATCos of critical situations in which they might be required to intervene. The findings of all three experiments conform with previous findings of automation performance benefits under current ATC conditions and reliable operation of the automation (Hilburn, 1996; Schick, 1991a, 1991b; Völckers, 1991). However, even though modern automated systems are extremely reliable (e.g. 99.9%), it is unlikely that they are 100% reliable. Automation is designed by humans and humans can make errors in the design of a system. Further, even if the algorithm performs reliably, the decision aid might not get complete or up-to-date information. Due to uncertainties in a FF environment ("unanticipated variation", Roth, Bennett & Woods, 1987) this is more likely under FF than under current ATC conditions. Indeed, when the automation failed or became inaccurate ATCos were even less likely to detect a failure of airborne separations when automation was provided than when they were manually performing.

Both FF and automation shift the ATCo's role from an active participant in the decision process to a monitor with the consequences that the ATCo is unable to act as a back-up in case self-separations and automation fail. This indicates that the expectation that the ATCo could act as a last resort and intervene in case both agents (i.e. pilots and automation) fail to detect a conflict might be a dangerous illusion. In fact, the system is designed in a way that the human is left to do what humans are very poor at, that is to passively monitor a system without active involvement in the decision processes. Active involvement in the decision-making process is crucial to operator performance and system safety (Metzger & Parasuraman, in press). If operators are not actively involved in controlling the system and instead are removed from the decision loop and left to monitor the system, it can take them longer to detect system malfunctions. Longer detection times, however, leave less time to recover. Consequently, the success of FF and automation might depend on the active involvement or at least the choice of active involvement of the operator. If operators are actively involved they should be better able to revert to manual control in a timely manner in case of a failure of airborne self-separation or automation. It could be investigated if the benefits of advanced decision automation in terms of operator and system performance under current ATC conditions and active ATCo involvement (Völckers, 1991; Schick, 1991a, 1991b; Hilburn, 1996) would persist in case the automation fails. No empirical data is available to answer this question yet.

10.2.6 Usefulness of research approach

The empirical findings emphasize the importance and usefulness of the model by Wickens et al. (1997) for studying ATCo and other operator interaction with automated systems. Only the joint investigation of taskload, workload, strategies, and performance allowed to capture the complex relationship between these factors and to map the changes in operator-system interaction induced by automation. Observing the pattern of interaction of the elements in the model (e.g. shedding of a low-priority task to reduce workload and maintain performance in the more important conflict detection task) leads to a fuller understanding of the effects of automation on operator performance and to the extent that ATCo performance affects system performance, on system safety.

These findings of sometimes quite complex interrelationships between the central components of the model (i.e. workload, strategies, and performance) also validate the use of operator-in-the-loop simulations as a very appropriate approach for this research. While modeling approaches allow for the economical prediction of the effects of system parameters on operator and system performance, they do not take operator strategies into account. Laboratory-based tasks, on the other hand, typically lack ecological validity. They lack the complexity of real world systems and therefore do not elicit the same strategies and interactions between demands in the environment and operator responses as in the real system. Typically, participants untrained and unfamiliar with the domain of interest are tested. Most likely, they do not use the same strategies as subject-matter experts. While the analysis of accidents or incidents might give some information on workload, strategies, and (unsuccessful) performance in the real system with real operators, it does not allow for the manipulation of taskload factors. In fact, oftentimes the taskload factors can only be reconstructed or guessed after the fact and can sometimes not be determined at all. It is not possible to observe how operators adjust to the varying demands of the situation. Besides, this approach only allows for the analysis of system parameters already implemented in the system and is not valuable for the evaluation of future systems.

Humans do not passively respond to the demands of the environment. Rather, their nature is to adapt to the demands of the environment and even manipulate the environment according to their needs and capabilities by employing strategies. Operator-in-the-loop simulations allow the operator to make use of this human capability and at the same time, allow the researcher to observe and map such adaptation processes.

10.3 Implications for system design

The presented research yielded some important implications for system design. Three examples will now be given.

10.3.1 Reducing complacency

Depending on the assumed causes of complacency, different solutions to the problem result. Moray (2000) suggested that the failure to detect system malfunctions is due to sub-optimal sampling of the automated system and the unpredictability of the failures. If this is true, alarms are the only way to alert the operator and improve the detection of system malfunctions. Parasuraman et al. (1993) proposed that complacency is associated with reduced attention allocation to the automated task. The empirical findings of this study supported this view. If complacency is due to reduced attention allocation to the automated task, systems need to be designed in a way that system malfunctions can be detected with little expenditure of attentional resources. This can be achieved through the use of integrated displays (Molloy & Parasuraman, 1994) or ecological designs (Vicente & Rasmussen, 1992). Integrated displays are designed so that little attention allocation is required in order to process the information they convey. If only little attentional resources are required, information is more likely to be attended to and processed. The adaptive implementation of automation periodically returns control to the operator (either based on a model, performance, workload, or hybrid approaches) and counteracts the shift in attention allocation strategies (away from the automated task) that occurs over time when automation is used (Parasuraman, Mouloua, & Molloy, 1996). A complementary approach to design strategies is training (Metzger et al., 2000). Variable-priority training has been shown to make attentional strategies more flexible and reduce complacency in a laboratory study (Metzger et al., 2000). If this would be a viable approach in the real world remains to be studied, however.

The differential design implications of different theories show the importance of understanding the underlying mechanisms of human interaction with automation. If systems and operator training are designed according to the causes of complacency, complacent behavior could be reduced.

10.3.2 The use of multimodal feedback

The use of multimodal feedback in human-automation interaction has recently attracted a lot of attention in the literature, even in ATC (Newman & Allendoerfer, 2000), which traditionally did not use auditory feedback as much as other domains. Based on other research (e.g. Sklar & Sarter, 1999) it was expected that multimodal feedback could capture and guide ATCo attention in an increasingly visual environment. This was not the case. Instead, multimodal feedback had a tendency to disrupt ongoing visual tasks. Therefore, the implementation of auditory feedback should be used only after careful evaluation of its effects. In addition to the problem that auditory feedback can become a nuisance (especially with false alarms), they might actually disrupt ongoing visual tasks by calling attention to the automation feedback. While traditional alarms usually indicate an immediate problem, decision aids project further into the future. Therefore, traditional alarms might benefit from an auditory component. Modern decision aids, however, that leave operators with enough time to respond to critical situations should make it unnecessary, or even disruptive, to back-up visual with auditory feedback.

10.3.3 The impact of datalink

Even though the impact of datalink was not the main topic of this work and was not experimentally manipulated, the results have implications for its expected effects. High traffic density and the availability of conflict detection automation was associated with increased attention to the communication tasks performed on the datalink. This additional visual attention allocated to the datalink display was “borrowed” from the radar display. Voice transmission, however, allows ATCos to keep visual attention on the radar during communication. Therefore, datalink, to the extent that it is based on visual information and is not integrated on the radar, could lead to reduced attention allocation to the radar and the increased risk to miss relevant information there.

The use of datalink in this study was similar to its use envisioned for the future when most routine communications will be transmitted by datalink. However, the real world transmission delays of up to 30 seconds were not present. Waiting times of that order can pose a heavy burden on ATCo working memory and reduce the time available to maneuver aircraft in case it becomes necessary. In a study comparing different delay times, mental workload increased as message transfer delays increased. In addition, increasing aircraft separation was reported as a strategy to cope with long delay times in a few reports. Therefore, instead of increasing capacity and efficiency, they were reduced (e.g. Talotta & Cole, 1992a; Talotta & Cole, 1992b). Hence, the effects of datalink in the present experiments might actually underestimate the effects of a non-integrated visual datalink display. Although the literature has found beneficial effects of datalink on working memory load and reduced confusion through individual addressing of aircraft, reduced attention allocation to the radar and the long delay times might neutralize these benefits. The potential of datalink to divert attention away from the radar could be reduced by either integrating the datalink on the radar (e.g. on the datablock) or the use of synthetic speech. Synthetic speech would allow the ATCos to keep their eyes and attention on the radar while communicating with potential benefits for the detection of conflicts.

10.4 Limitations of the studies

While the research led to many conclusions and implications, several limitations have to be pointed out as well. Among the most important is the problem of dealing with ill-defined and changing concepts such as FF. Exact FF procedures are still not established and the actual implementation of the concept or its automated systems has not been determined yet. Studying FF is like chasing a moving target. The challenge is to study and test a concept or an "envisioned world" (Dekker & Woods, 1999) that does not exist yet and keeps changing as new findings becomes available. Therefore, specific assumptions on procedures or technology have to be made even though they might not be the ones eventually implemented (and perhaps so as a response to unfavorable results of such research). This could reduce the validity of the findings to the extent that the assumptions are different from the actual implementation. Thus, there is the challenge to test concepts or systems that are not well established, yet to make predictions about future concepts early in system development so that modifications to the concept can still be made. If concepts or systems are tested at later stages of the system development the concepts and systems might be better defined, but there is the danger that it is too late to implement changes. Often the human factors researcher is called then to "fix" problems that were not recognized early on. In the presented research, a rather mature level of FF was assumed to test the worst-case scenario of FF in which the ATCo's role will shift from an active decision maker to a monitor of pilot actions and automation. Also, automation of a particular type was chosen and implemented in a particular way. However, this might not necessarily be the actual implementation.

It should also be noted that traffic in the simulation scenarios was not live or recorded traffic, but traffic created by the researcher with the input of a subject matter expert (i.e. an ATCo with a background in Human Factors research). In the real world, ATCos can rely on information stored in long-term memory (e.g. all aircraft flown by Southwest are B737s; knowledge of airspace and typical traffic patterns). This was not possible in these experiments. All ATCos could rely on their experience with the airspace from the demonstration and practice periods only. However, under FF conditions experience with a certain airspace might not play a large role either. Typical traffic patterns would be given up under FF and ATCos would have to carefully monitor which routes the pilots decide to take. The pattern could change at any moment (e.g. due to a change in weather). Therefore, the conditions in the experiment might resemble those under FF quite closely.

Another issue is whether experience and learning could reduce the negative impact of FF. Perhaps ATCos who were all trained to operate under current conditions would get used to the new system. Hilburn and Parasuraman (1997) did not find any negative effects of FF in British military ATCos who already work in a system similar to FF. Perhaps experience and training could remedy some of the negative effects associated with FF. However, if this also applies to the impact of automation inaccuracies needs to be studied. ATCos were not much more succesful in detecting the automation failure the second time around. Most ATCos (except for three) either detected the failure both times or not at all.

In the presented studies, taskload was manipulated by the number of aircraft in the sector. While the number of aircraft is a major contributor to mental workload under FF conditions, it is not the only one. Conflict geometries, the proportion of climbing or descending to level aircraft, the percentage of aircraft flying at significantly lower speeds than other aircraft and many other factors can affect ATCo mental workload. Research on dynamic density and airspace complexity (Mogford et al., 1994; Mogford et al., 1995; Laudeman et al., 1998; Wyndemere, 1996) is trying to establish the factors that determine ATCo mental workload under FF conditions. However, this was not central to the thesis and the number of aircraft was used to manipulate taskload.

Benefits and costs of automation in the real system will depend among other factors on the implementation of the particular decision aid. For example, if a large amount of cognitive overhead is involved in engaging the automation it might not be used and therefore not improve performance or reduce mental workload (Parasuraman & Riley, 1997; Kirlik, 1993; Wiener & Curry, 1980). The implementation of automation in this study was simple (e.g. it did not require any cognitive overhead to engage it) and integrated on the primary radar display, but system designers may choose other ways of implementing a conflict detection aid. In fact, URET, the aid chosen by the FAA is being implemented an a separate tabular display. Such an implementation might have different benefits and costs than the ones found in this study. However, it should be emphasized that the particular human-computer interface was not of interest in this study. Rather, the goal was to identify more general issues of the implementation of automation into the ATC and other systems.

10.5 Future directions for research

Several issues for future research were already described. Additional topics in need of further investigation will now be covered.

According to the model of types and levels of automation (Parasuraman et al., 2000), decision-making can be aided at different stages of information-processing and at different levels. The aid used in these experiments supported ATCos in data integration and analysis at a relatively high level. As discussed above, the aid was associated with benefits, but also costs when the aid failed. Research on the effects of automation is ambiguous. While some researchers have found positive effects of automation (e.g. on maintaining situation awareness), others have found negative effects. Recently, the application of the model of types and levels of automation has shown some promise for the more reliable prediction of costs and benefits of automation. For example, automation of information acquisition or analysis can lead to attentional tunneling. When a soldier's attention is directed to a specific target location he or she is less likely to detect uncued higher-priority threats elsewhere than if no cueing was provided (e.g. Yeh & Wickens, 2000). So-called "action-tunneling" (Wickens, 2000) could occur if an action recommended by a decision aid is executed while an alternative better action that is not recommended is overlooked. It could be speculated that automation-related complacency would be stronger the more advanced the type of automation is because the operator is further removed from the decision-making process the higher the type of automation. For example, it could be hypothesized that operators are less likely to become complacent when information analysis rather than action implementation is automated.

However, further research is needed, to study what the specific consequences of each type and level of automation on different aspects of performance are. There is a need for studies that directly compare the impact of different types and levels of automation to elucidate the mechanisms of human-interaction with automation and to better predict the specific costs of automation. Eventually, this would allow to make system design recommendations. It should also be noted that the model of types and levels of automation does not just apply to ATC, but to all automated systems (e.g. medical, maritime, space, cockpit, vehicle systems) in which advanced decision aiding is introduced.

A more fundamental question is whether to automate the decision process, especially if it is associated with high risk as in ATC, medical and other systems. Alternatively, routine actions such as handing-off aircraft could be supported by automation. Based on the empirical findings and discussions with ATCos, routine tasks such as communication and coordination represent a large taskload especially as traffic density increases. Supporting ATCos in these functions has the potential to reduce mental workload considerably and free resources that could be allocated to functions that bear higher risks.

An issue associated with FF is mixed equipage. While it was assumed that all aircraft participated in FF in the described simulation experiments, this will not be the case in the real world. During a transition phase only few aircraft will be fully equipped to participate in FF (e.g. with CDTI, TCAS, GPS, etc.), while most others will require the ATCo's attention similar to current conditions. As more aircraft are equipped, this proportion will change. However, there will always be some aircraft that require the ATCo's attention similar to current conditions while others are allowed to maneuver freely and require the ATCo's attention only in cases when airborne separation fails. It remains to be studied whether ATCos will be able to detect and resolve conflicts among FF aircraft and among FF and non-FF aircraft if their role is to only monitor separation assurance and act as a back-up to the pilots.

Technology is moving from automating low to higher-order cognitive functions such as decision-making or planning. In the future, there will most likely be several highly complex automated systems within a system such as the ATCo’s workplace some of them coupled to each other. System safety will depend to a large part on the appropriate integration of these systems. The appropriate integration and the assessment of these systems in human-in-the-loop studies is important to avoid unexpected and negative effects from the interaction between different systems.

Last, but not least, the effects of automation do not only depend on the individual operator's performance. The effects of automation are determined at many levels, among them team, management, or organizational levels (Reason, 1990). If the management institutes a policy with regard to the use of automation, for example that the automation cannot be overruled and the operator is not free to choose between manual and automated modes of operation as in the tragic accident involvement of a commuter train (Parasuraman & Riley, 1997; Jenner 2000) or the policy that pilots are required to follow a TCAS alert, the management is at least partially responsible for the outcome of the operator's interaction with the automation. Managers need to be educated about the immediate impact of their policies or actions on system safety even though they might be far removed from the actual process. The ultimate decision to use or not to use automation should be made by the operator.

Individual and cultural differences in human interaction with automation have also been noted although research on this issue is scarce (Wickens et al., 1998a). In the same way that humans in different cultures interact with each other differently, humans in different cultures could interact with automation differently. This analogy is particularly appropriate as automation becomes more human-like in its capabilities. Apart from the fact that it is not known how individual or cultural factors should affect system design, it would be too costly to design large systems for different cultures or even individuals. It should be possible, however, to make systems adaptable to user preferences or abilities. Moreover, a better understanding of differences in human interaction with automation could guide the design of training curricula. Similar to the way crews are trained to interact with each other (crew resource management training; Wiener, Kanki, & Helmreich, 1993), training curricula could be developed for effective interaction with automation.

10.6 Conclusion

The introduction of automation into future aviation systems is advancing fast, much faster than the research. Even though the implementation of automated decision aids in future ATM and other systems is immediately imminent, still little is known about the consequences for operator performance, mental workload, and ultimately system performance and safety. The described research provided first empirical evidence on the impact of automated decision aids on future ATM. The numerous benefits of automation did not come without a cost when the automation became inaccurate. However, this is not to say that advanced decision aids should not be implemented in high-risk systems like ATC or others. Automation has brought innumerable benefits and has become indispensable in many domains. Rather, this thesis advocates the need for a better understanding of the capabilities and limitations of humans in their interactions with automation. If safety is not to be compromised, the impact of automation needs to be understood. The gained knowledge can then be applied to the design of systems that complement the human operator. The goal is to take advantage of the benefits of automation while minimizing the cost on human performance and system safety.

11. References

Aasman, J., Mulder, G., & Mulder, L. J. M. (1987). Operator effort and the measurement of heart-rate variability. *Human Factors, 29*, 161-170.

Arad, B. A. (1964). The control load and sector design. *Journal of ATC, May*, 12-31.

Arthur, W., Jr., Bennett, W., Jr., Stanush, P.L. and McNelly, T.L. (1998). Factors that influence skill decay and retention: a quantitative review and analysis. *Human Performance, 11*, 57-101.

ASL (1999). *Eyenal* [Software program]. Bedford, MA: Author.

Attneave F. (1959). *Applications of information theory to psychology: A summary of basic concepts, methods, and results.* New York, NY: Holt, Rinehart & Winston.

Aviation Week & Space Technology (1998). Answers to the gridlock. February 2, pp. 42-62.

Backs, R. W. & Boucsein, W. (2000). *Engineering psychophysiology*. Mahwah, NJ: Lawrence Erlbaum Associates.

Bainbridge, L. (1983). Ironies of automation. *Automatica, 19*, 775-779.

Ball, M., DeArmon, J. S., & Pyburn, J. O. (1995). Is free flight feasible? Results from initial simulations. *Journal of ATC, 1*, 14-17.

Barrer, J. N. (1982). *Testing of workload probe models.* MITRE Memo No. W41-M6071. McLean, VA: Mitre.

Becker, W. (1991). Saccades. In R. H. S. Carpenter (Ed.), *Eye movements* (pp. 95-137), Boca Raton, FL: Macmillan.

Begault, D. R., & Pittman, M. T. (1996). Three-Dimensional Audio Versus Head-Down Traffic Alert and Collision Avoidance System Displays. *International Journal of Aviation Psychology, 6*, 79-93.

Bellenkes, A. H., Wickens, C. D., & Kramer, A. F. (1997). Visual scanning and pilot expertise: The role of attentional flexibility and mental model development. *Aviation, Space, and Environmental Medicine, 68, 7,* 569-579.

Biers, D. W. & McInerney, P. (1988). An alternative to measuring workload: Use of SWAT without the card sort. In Proceedings of the Human Factors and Ergonomics Society 32nd Annual Meeting (pp. 1136-1139). Santa Monica, CA: HFES.

Bilimoria, K.D. (1998). A methodology for the performance evaluation of a conflict probe. Presented at AIAA Guidance, Navigation, and Control Conference, Boston, August 10-12. Report No. AIAA-98-4238. Reston, VA: American Institute of Aeronautics and Astronautics.

Billings, C. E. (1997). *Aviation automation: The search for a human-centered approach.* Mahwah, NJ: Lawrence Erlbaum Associates.

Billings, C. E., Lauber, J. K., Funkhouser, H., Lyman, G., & Huff, E. M. (1976). *NASA Aviation Safety Reporting System* (Technical Report TM-X-3445). Moffett Field, CA: NASA Ames Research Center.

Bortz, J. & Döring, N. (1999). *Forschungsmethoden und Evaluation für Sozialwissenschaftler* (2nd Edition). Berlin: Springer.

Boucsein, W. (1991). Arbeitspsychologische Beanspruchungsforschung heute – eine Herausforderung an die Psychophysiologie. *Psychologische Rundschau, 42,* 129-144.

Brickman, B. J., Hettinger, L. J., & Haas, M. W. (2000). Multisensory interface design for complex task domains: Replacing information overload with meaning in tactical crew stations. *The International Journal of Aviation Psychology, 10,* 273-290.

Broadbent, D. E. (1958). *Perception and communication.* Oxford, England, UK: Oxford University Press.

Brookings, J. B., Wilson, G. F., & Swain, C. R. (1996). Psychophysiological responses to changes in workload during simulated air traffic control. *Biological Psychology, 42*, 361-377.

Brown, I. D. & Poulton, E. C. (1961). Measuring the spare mental capacity of car drivers by a subsidiary task. *Ergonomics, 4*, 35-40.

Brudnicki, D. J. & McFarland, A. L. (1997). *User request evaluation tool (URET) conflict probe performance and benefits assessment* (Technical report). McLean, VA: MITRE.

Byers, J. C., Bittner, A. C., & Hill, S. G. (1989). Traditional and raw Task Load Index (TLX) correlations: Are paired comparisons necessary? In A. Mital (Ed.), *Advances in industrial ergonomics and safety I* (pp. 481-485). London: Taylor & Francis.

Byrne, E.A. (1994a). *CSLacq* [Computer software]. Washington, DC: Cognitive Science Lab.

Byrne, E. A. (1994b). *CSLstat* [Computer software]. Washington, DC: Cognitive Science Laboratory, The Catholic University of America (Version 1.07).

Byrne, E. A., Chun, K., & Parasuraman, R. (1995). Differential sensitivity of heart rate and heart rate variability as indices of mental workload in a multi-task environment. *Proceedings of the 8th International Symposium on Aviation Psychology* (pp. 881-885). Columbus, OH: Ohio State University.

Byrne, E. A. & Parasuraman, R. (1996). Psychophysiology and adaptive automation. *Biological Psychology,42, 249-268.*

Cale, M. L., Paglione, M., Ryan, H., Timotea, D. & Oaks, R. (1998). *User request evaluation tool (URET) conflict prediction accuracy report* (Technical report DOT/FAA/CT-TN98/8). Atlantic City International Airport, NJ: FAA Technical Center.

Callan, D. J. (1998). Eye movement relationships to excessive performance error in aviation. *Proceedings of the Human Factors and Ergonomics Society 42nd Annual Meeting* (pp. 1132-1136). Santa Monica, CA: HFES.

Castaño, D. & Parasuraman, R. (1999). Manipulation of pilot intent under free flight: a prelude to not-so-free flight. *Proceedings of the Tenth International Symposium on Aviation Psychology* (pp. 170-176). Columbus, OH: Ohio State University.

Cohen, J. (1994). The earth is round ($p < .05$). *American Psychologist, 49*, 997-1003.

Cooper, G. E. (1957). Understanding and interpreting pilot opinion. *Aeronautical Engineering Review*, 16, 47-51.

Cooper, G. E. & Harper, R. P. (1969). *The use of pilot rating in the evaluation of aircraft handling qualities* (Technical report NASA-TN-D-5153). Washington, D.C.: National Aeronautics and Space Administration.

Corker, K., Fleming, K., & Lane, J. (1999). Measuring controller reactions to free flight in a complex transition sector. *Journal of ATC, 4*, 9-16.

Corker, K. (2000). Cognitive models and control: Human and system dynamics in advanced airspace operations. In N. B. Sarter and R. Amalberti (Eds.), *Cognitive Engineering in the Aviation Domain* (pp. 13-42). Mahwah, NJ: LEA.

Dekker, S. W. A. & Woods, D. D. (1999). To Intervene or not to Intervene: The Dilemma of Management by Exception. *Cognition, Technology and Work, 1*, 86-96.

Deutsch, J. A. & Deutsch, D. (1963). Attention: Some theoretical considerations. *Psychological review, 70*, 80-90.

Duley, J. A., Westerman, S., Molloy, R., & Parasuraman, R. (1997). Effects of display superimposition on monitoring of automation. *Proceedings of Ninth International Symposium on Aviation Psychology* (pp. 322-328). Columbus, OH: Ohio State University.

Dunbar, M., Cashion, P., McGann, A., Macintosh, M.-A., Dulchinos, Jara, D., & Jordan, K. (1999). Air-ground integration issues in a self-separation environment. In *Proceedings of the 10th International Symposium on Aviation Psychology* (pp. 183-189). Columbus, OH: Ohio State University.

Dzindolet, M. T., Pierce, L. G., Dawe, L. A., Peterson, S. A. & Beck, H. P. (2000). Building trust in automation. *Proceedings of the Human Performance, Situation Awareness, and Automation Conference: User-Centered Design for the New Millenium* (pp. 63-69). Marietta, GA: SA Technologies.

Egelund, N (1982). Spectral analysis of heart rate variability as an indicator of driver fatigue. *Ergonomics, 25*, 663-672.

Eggemeier, F. T. & Wilson, G. F. (1991). Performance-based and subjective assessment of workload in multi-task environments. In D. L. Damos (Ed.), *Multiple-task performance.* Washington, D.C.: Taylor and Francis.

Ellis, S. R. & Stark, L. (1986). Statistical dependency in visual scanning. *Human Factors, 28, 4,* 421-438.

Endsley, M. R. (1996). Automation and situation awareness. In R. Parasuraman & M. Mouloua (Eds.), *Automation and Human Performance: Theory and Applications* (pp. 163-181). Mahwah, NJ: Lawrence Erlbaum Associates.

Endsley, M. R. & Kiris, E. O. (1995). The out-of-the-loop performance problem and level of control in automation. *Human Factors, 37,* 381-394.

Endsley, M. R. & Rodgers, M. D. (1998). Distribution of attention, situation awareness and workload in a passive ATC task: Implications for operational errors and automation. *Air Traffic Control Quarterly, 6, 1,* 21-44.

Endsley, M. R., Mogford, R. H., Allendoerfer, K. R., Snyder, M. D., & Stein, E.S. (1997). *Effect of free flight conditions on controller performance, workload, and situation awareness* (DOT/FAA/CT-TN97/12). Atlantic City International Airport: Federal Aviation Administration William J. Hughes Technical Center.

Erzberger, H., B. D., McNally, D., Foster, M., Chiu, D., & Stassart, P. (1999). *Direct-To Tool for En Route Controllers, ATM '99: IEEE Workshop on Advanced Technologies and their Impact on Air Traffic Management in the 21st Century*. Available: http://www.ctas.arc.nasa.gov

Eurocontrol (1998). *Operational concept document*. Brussels, Belgium: Author.

FAA Human Factors Team (1996). *The interface between flightcrews and modern flight deck systems.* Washington, D. C.: Author

FAA (1997). *ATS Concept of Operations for the National Airspace System in 2005.* Department of Transportation, Federal Aviation Administration. Washington, D.C.: Author.

FAA (2000). *FAA Strategic plan*. Washington, DC: Author. Available: http://api.hq.faa.gov/sp00/sp2000.htm

Farrell, S. & Lewandowsky, S. (2000). A connectionist model of complacency and adaptive recovery under automation. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 26, 2,* 395-410.

Fitts, P. M., Jones, R. E., & Milton, J. L. (1950). Eye movements of aircraft pilots during instrument landing approaches. *Aeronautical Engineering Review, 9*, 24-29.

Fowler, F. D. (1980). Air traffic control problems: a pilot's view. *Human Factors, 22*, 645-653.

Frankmann, J. P. & Adams, J. A. (1962). Theories of vigilance. *Psychological Bulletin, 59*, 257-272.

Galster, S. M. (1998). *Effects of aircraft self-separation on controller conflict detection performance and workload in mature free flight.* Unpublished Master's thesis. Washington, D.C.: The Catholic University of America.

Galster, S. M., Duley, J. A., Masalonis, A. J., & Parasuraman, R. (2001). Air traffic controller performance and workload under mature Free Flight: Conflict detection and resolution of aircraft self-separation. *International Journal of Aviation Psychology, 11*, 71-93.

Garner, W. R. (1962). *Uncertainty and structure as psychological concepts.* New York, NY: Wiley.

Goldberg, M. E. (2000). The control of gaze. In E. Kandel, J. H. Schwartz, & T. M. Jessell (Eds.), *Principles of Neural Science* (4th Ed., pp. 782-800). New York: McGraw-Hill.

Gopher, D. (1996). Attention control: explorations of the work of an executive controller. *Cognitive Brain Research, 5,* 23-38.

Gopher, D., Weil M. & Siegel, D. (1989). Practice under changing priorities: An approach to the training of complex skills. *Acta Psychologica, 71,* 147-177.

Hadley, J., Sollenberger, R., D'Arcy, J.-F., & Bassett, P. (2000). *Interfacility boundary adjustment*. (Technical report DOT/FAA/CT-TN00/06). Atlantic City International Airport, NJ: FAA Technical Center.

Harris, R. L., Tole, J. R., Stephens, A. T., & Ephrath, A. R. (1982). Visual scanning behavior and pilot workload. *Aviation, Space, and Environmental Medicine, 53,* 1067-1072.

Harris, R. L., Glover, B. J., & Spady, A. A. (1986). *Analytical techniques of pilot scanning behavior and their application* (NASA Technical Paper 2525). Washington, D.C.: NASA.

Hart, S. G. (1975). Time estimation as a secondary task to measure workload. In *Proceedings of the Annual Conference on Manual Control* (Report No. NASA TM X-62, 464, pp. 64-77). Washington, DC: US Government Printing Office.

Hart, S. G. & Staveland, L. E. (1988). Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. In P. A. Hancock & N. Meshkati (Eds.), *Human mental workload* (pp. 139-183). Amsterdam: North-Holland.

Harwood, K., Sanford, B. D. & Lee, K. K. (1998). Developing ATC automation in the field: It pays to get your hands dirty. *Air Traffic Control Quarterly, 6, 1,* 45-70.

Hilburn, B. G. (1996). *The impact of advanced decision aiding automation on mental workload and human-machine system performance*. Unpublished Dissertation. Washington, D.C.: The Catholic University of America.

Hilburn, B. G., & Parasuraman, R. (1997). Free flight: Military controllers as an appropriate population for evaluation of advanced ATM concepts. In *Proceedings of the 10th International CEAS Conference on Free Flight.* Amsterdam: CEAS.

Hilburn, B. G., Bakker, M. W. P., Pekela, W. D., & Parasuraman, R. (1997). The effect of free flight on air traffic controller mental workload, monitoring, and system performance. In *Proceedings of the 10th International CEAS Conference on Free Flight (pp. 14-1-14-12).* Amsterdam: Confederation of European Aerospace Societies.

Hill, S. G., Iavecchia, H. P., Byers, J. C., Bittner, A. C., Zakland, A. L., & Christ, R. E. (1992). Comparison of four subjective workload rating scales. *Human Factors, 34*, 429-439.

Hoffman, J. E. (1998). Visual attention and eye movements. In H. E. Pashler (Ed.), *Attention*. Hove, East Sussex, UK: Psychology Press.

Hopkin, V. D. (1999). *Human factors in air traffic control.* London: Taylor and Francis.

Huey, B. M. & Wickens, C. D. (1993). *Workload transitions: Implications for individual and team performance.* Washington, D.C.: National Academy Press.

Human Solutions (1999). *Human factors action plan for Free Flight Phase One*. Washington, DC: FAA Free Flight Phase One Program Office.

ICAO (1993). *Human Factors in air traffic control.* ICAO-Circular 241-AN/145. Montreal, Canada: ICAO.

Inagaki, T. (1999). Situation-adaptive autonomy: Trading control of authority in human-machine systems. In M.W. Scerbo & M. Mouloua (Eds.), *Automation technology and human performance: Current research and trends* (pp. 154-158). Mahwah, NJ: Lawrence Erlbaum Associates.

Isreal, J. B., Wickens, C. D., Chesney, G. L. & Donchin, E. (1980). The event-related brainpotential as an index of display-monitoring workload. *Human Factors, 22,* 211-224.

Jenner, S. M. (2000). The role of automation in the collision on Washington's rapid transit system. *Proceedings of the Human Performance, Situation Awareness, and Automation Conference: User-Centered Design for the New Millennium* (p. 34-39). Marietta, GA: SA Technologies.

Jorna, P. G. M. A. (1992). Spectral analysis of heart rate and psychological state: A review of its validity as a workload index. *Biological Psychology, 34*, 237-257.

Kahneman, D. (1973). *Attention and effort*. Englewood Cliffs, NJ: Prentice-Hall.

Kalsbeek, J. W. H. (1971). Standards of acceptable load in ATC tasks. *Ergonomics, 14, 5*, 641-650.

Kantowitz, B. H., Bortolussi, M. R., & Hart, S. G. (1987). Measuring workload in a motion base simulator: III. Synchronous secondary task. In *Proceedings of the 31st Annual Meeting of the Human Factors Society* (pp. 834-837). Santa Monica, CA: Human Factors and Ergonomics Society.

Kantowitz, B. H., Hart, S. G., & Bortolussi, M. R. (1983). Measuring pilot workload in a moving-based simulator: I. Asynchronous secondary choice-reaction task. In *Proceedings of the 27th Annual Meeting of the Human Factors Society* (pp. 319-322), Santa Monica, CA: Human Factors and Ergonomics Society.

Kantowitz, B. H., Hart, S. G., Bortolussi, M. R., Shively, & Kantowitz, (1984). Measuring pilot workload in a moving-based simulator: II. Building levels of load. In *Proceedings of the Annual Conference on Manual Control, 20,* 359-372.

Karsten, G., Goldberg, B., Rood, R. & Sultzer, R. (1975). *Oculomotor measurement of air traffic controller visual attention* (FAA-NA-74-61). Atlantic City International Airport, NJ: DOT/FAA Technical Center.

Kasarskis, P., Stehwien, J., Hickox, J., Arentz, A., & Wickens, C. D. (2001). Comparison of expert and novice scan behaviors during VFR flight. *Proceedings of the 11th International Symposium on Aviation Psychology*. Columbus, OH: Ohio State University.

Kirlik, A. (1993). Modeling strategic behavior in human-automation interaction: why an aid can (and should) go unused. *Human Factors, 35*, 221-242.

Kramer, A. F. (1991). Physiological metrics of mental workload: A review of recent progress. In D. L. Damos (Ed.), *Multiple-task performance*. Washington, D.C.: Taylor and Francis.

Kramer, A. F., Larish, J. L., Weber, T. A., & Bardell, L. (1999). Training for executive control: Task coordination strategies and aging. In D. Gopher & A. Koriat (Eds.), *Attention and Performance XVII Cognitive Regulation of Performance: Interaction of theory and application* (pp. 617-652). Cambridge, MA: MIT Press.

Kramer, A., Tham, M., Konrad, C., Wickens, C., Lintern, G., Marsh, R., Fox, J., & Merwin, D. (1994). Instrument scan and pilot expertise. *Proceedings of the Human Factors and Ergonomics Society 38th Annual Meeting*. Santa Monica, CA: HFES.

Lamoureux, T. (1999). The influence of aircraft proximity data on the subjective mental workload of controllers on the air traffic control task. *Ergonomics, 42, 11*, 1482-1491.

Laudeman, I.V., Shelden S.G., Branstrom, R., & Brasil, C.L. (1998*) Dynamic Density: an air traffic management metric (NASA-TM-1998-112226)*. Moffett Field, CA: NASA Ames Research Center.

Lee, J. D., & Moray, N. (1992). Trust, control strategies and allocation of function in human-machine systems. *Ergonomics, 35*, 1243-1270.

Lee, J. D., & Moray, N. (1994). Trust, self-confidence, and operators' adaptation to automation. *International Journal of Human-Computer Studies, 40*, 153-184.,

Lee, J. D. & Sanquist, T. (1996). Maritime automation. R. Parasuraman & M. Mouloua (Eds.), *Automation and Human Performance: Theory and Applications* (pp. 365-384). Mahwah, NJ: Lawrence Erlbaum Associates.

Lind, A. T. (1993). *Two simulation studies of precision runway monitoring of independent approaches to closely spaced parallel runways* (DOT/FAA/NR-92/9). Lexington, MA: Lincoln Laboratory.

Luffsey, W. S. (1990). *Air traffic control: How to become an air traffic controller*. New York: Random House.

Lozito, S., McGann, A., Mackintosh, M., & Cashion, P. (1997). *Free flight and self-separations from the flight deck perspective*. Paper presented at The First United States/European Air Traffic Management Research and Development Seminar, Saclay, France.

Mackworth, N. H. (1948). The breakdown of vigilance during prolonged visual search. *Quarterly Journal of Experimental Psychology, 1*, 6-21.

Mackworth, N. H. (1950). *Researches on the measurement of human performance*. (Medical Research Council Special Report Series 268). London: His Majesty's Stationery Office.

Mackworth. N. H. & Kaplan, I. T. (1964). Eye movements during vigilance. *Perceptual and Motor Skills, 18*, 397-402.

Manzey, D. (1998). Psychophysiologie mentaler Beanspruchung. In F. Rösler (Ed.), *Enzyklopädie der Psychologie: Themenbereich C: Theorie und Forschung, Serie 1: Biologische Psychologie, Band 5: Ergebnisse und Anwendungen der Psychophysiologie*. Göttingen: Hogrefe.

Masalonis, A. J. (1999). *Effects of situations-specific reliability on trust and usage of automated decision aids.* Unpublished dissertation. Washington, DC: The Catholic University of America.

Masalonis, A. J., Le, M. A., Klinge, J. C., Galster, S. M., Duley, J. A., Hancock, P. A., Hilburn, B. G., & Parasuraman, R. (1997). Air traffic control workstation mock-up for Free Flight experimentation: Lab development and capabilities. *Proceedings of Human Factors & Ergonomics Society 41st Annual Meeting* (pp. 1379). Santa Monica, CA: HFES.

Masalonis, A.J., Duley, J.A., Galster, S.M., Castaño, D.J., Metzger, U., & Parasuraman, R. (1998). Air traffic controller trust in a conflict probe during Free Flight. *Proceedings of Human Factors & Ergonomics Society 42nd Annual Meeting, (p. 1601).* Santa Monica, CA: HFES.

May, P. A., Molloy, R. J., & Parasuraman, R. (1993). *Effects of automation reliability and failure rate on monitoring performance in a multi-task environment*. Technical Report. Washington, D.C.: Cognitive Science Laboratory, The Catholic University of America.

McNally, B. D., Bach, R. E. & Chan, W. (1998). *Field test evaluation of the CTAS conflict prediction and trial planning capability*. Boston MA: American Institute of Aeronautics and Astronautics Guidance, Navigation, and Control.

Meshkati, N. (1988). Heart rate variability and mental workload assessment. In P. A. Hancock & N. Meshkati (Eds.), *Human mental workload* (pp. 101-115). Amsterdam: North-Holland.

Metzger, U., Duley, J. A., Abbas, R., & Parasuraman, R. (2000). Effects of variable-priority training on automation-related complacency: Performance and eye movements. *Proceedings of the 14th Triennial Congress of the International Ergonomics Association and the 44th Annual Meeting of the Human Factors and Ergonomics Society* (pp. 2-346-349). Santa Monica, CA: HFES.

Metzger, U. & Parasuraman, R. (1999). Free Flight and the air traffic controller: Active Control versus Passive Monitoring. *Proceedings of the Human Factors & Ergonomics Society 43rd Annual Meeting (pp. 1-5).* Santa Monica, CA: HFES.

Metzger, U. & Parasuraman, R. (in press). The role of the air traffic controller in future air traffic management: An empirical study of active control versus passive monitoring. *Human Factors*.

Meyer, J. & Bitan, Y. (in press). Why better operators receive worse warnings. *Human Factors*.

Michon, J. A. (1966). Tapping regularity as a measure of perceptual motor load, *Ergonomics, 9*, 401-412.

Mogford, R. & Tansley, B. W. (1991). *Studies of the air traffic controller's mental model*. Paper presented at the annual meeting of the Canadian Human Factors Association, Vancouver, B.C., August 27, 1991.

Mogford, R. H., Murphy, E. D. and J. A. Guttman (1994). Using Knowledge Exploration Tools to Study Airspace Complexity in Air Traffic Control. *The International Journal of Aviation Psychology*, *4*, 29-45.

Mogford, R. H., Guttman, J. A., Morrow, S. L., and Kopardekar, P. (1995). *The complexity construct in air traffic control: A review and synthesis of the literature*. (Report No. DOT/FAA/CT-TN95/22). Atlantic City International Airport, N. J.: FAA Technical Center

Molloy, R. & Parasuraman, R. (1994). Automation-induced monitoring inefficiency: The role of display integration and redundant color coding. In M. Mouloua & R. Parasuraman (Eds.) *Human performance in automated systems: Current research and trends* (pp. 224-228). Hillsdale, NJ: Erlbaum.

Molloy, R. & Parasuraman, R. (1996). Monitoring an automated system for a single failure: Vigilance and task complexity effects. *Human Factors, 38,* 311-322.

Molloy, R., Deaton, J. & Parasuraman, R. (1995). Monitoring performance with the EMACS display. *Proceedings of the 8th International Symposium on Aviation Psychology* (pp. 68-71). Columbus, OH: Ohio State University.

Moray, N. (1967). Where is capacity limited: A survey and a model. *Acta Psychologica, 27*, 84-92.

Moray, N. (1986). Monitoring behavior and supervisory control. In K. R. Boff & L. Kaufman (Eds.), *Handbook of perception and human performance. Vol. 2: Cognitive processes and performance.* New York: John Wiley & Sons.

Moray, N. (2000). Are observers really complacent when monitoring automated systems? *Proceedings of the 14th Triennial Congress of the International Ergonomics Association and the 44th Annual Meeting of the Human Factors and Ergonomics Society* (pp. 1-592-595). Santa Monica, CA: HFES.

Morphew, M. E. & Wickens, C. D. (1998). Pilot performance and workload using traffic displays to support Free Flight. In *Proceedings of the Human Factors and Ergonomics Society 42nd Annual Meeting* (pp. 52-56). Santa Monica: HFES.

Morrison, R., & Wright, R.H. (1989). ATC control and communications problems: An overview of recent ASRS data. In R. S. Jensen (Ed.,) *Proceedings of the Fifth International Symposium of Aviation Psychology* (pp. 902-907), Columbus, OH: Ohio State University.

Morrow, D., Rodvold, M., & Lee, A. (1994). Nonroutine transactions in controller-pilot communication. *Discourse processes, 17*, 235-258.

Mosier, K. L., Skitka, L. J., & Korte, K. J. (1994). Cognitive and social psychological issues in flight crew-automation interaction. In M. Mouloua and R. Parasuraman (Eds.), *Human performance in automated systems: Current research and trends* (pp. 191-197). Hillsdale, NJ: Lawrence Erlbaum Associates.

Mosier K. L. & Skitka, L. J. (1996). Human decision-makers and automated decision aids: Made for each other? In R. Parasuraman & M. Mouloua (Eds.), *Automation and Human Performance: Theory and Applications* (pp. 201-220). Mahwah, NJ: Lawrence Erlbaum Associates.

Mosier, K. L., Skitka, L. J., Heers, S., & Burdick, M. (1998). Automation bias: decision making and performance in high-tech cockpits. *The International Journal of Aviation Psychology, 8*, 47-63.

Mundra, A. (1989). *A new automation aid to air traffic controllers for improving airport capacity*. (MP-89W00034). McLean, VA: The MITRE Corporation.

Mundra, A. & Levin, K. M. (1990). *Developing automation for terminal air traffic control: Case study of the imaging aid* (MP90W0029). McLean, VA: The MITRE Corporation.

NASA Ames Research Center (1986). *NASA Task Load Index (TLX): Paper and Pencil Version.* Moffett Field, CA: NASA Ames Research Center Aerospace Human Factors Research Division.

National Transportation Safety Board (1973). *Eastern Airlines L-1011, Miami Florida, 20 December 1972* (Rep. NTSB-AAR-73-14). Washington, DC: Author.

National Transportation Safety Board (1997). *Grounding of the Panamanian passenger ship Royal Majesty on Rose and Crown shoal near Nantucket, Massachusetts, June 10, 1995* (Rep. NTSB/MAR-97-01). Washington, DC: Author.

Navon, D. (1984). Resources – A theoretical soupstone? *Psychological Review, 91,* 216-234.

Neumann, O. (1985). Die Hypothese begrenzter Kapazität und die Funktionen der Aufmerksamkeit. In O. Neumann (Ed.), *Perspektiven der Kognitionspsychologie.* Berlin: Springer.

Neumann, O. (1996). Theories of attention. In O. Neumann & A.F. Sanders (Eds.), *Handbook of perception and action, Vol. 3: Attention.* (pp. 389-446). London: Academic Press.

Newman, R. A. & Allendoerfer, K. (2000). *Assessment of current and proposed audio alarms in terminal air traffic control* (Technical report). Atlantic City International Airport, NJ: FAA Technical Center.

Nijhuis, H. B. (1994). *A study into the consequences of data-link for the mental workload of the air traffic controller.* Technical report (PHARE - Programme for harmonised air traffic management research in Eurocontrol). Brussels, Belgium: Eurocontrol.

Nolan, M. S. (1990). *Fundamentals of air traffic control.* Belmont, CA: Wadsworth.

Norman, D. & Bobrow, D. J. (1975). On data and resource limited processes. *Cognitive Psychology, 7*, 44-66.

Norman, D. A. (1990). The "problem" of automation: Inappropriate feedback and interaction, not "over-automation." *Philosophical Transactions of the Royal Society of London, B. 327*, 585-593.

Nygren, T. E. (1991). Psychometric properties of subjective workload measurement techniques: Implications for their use in the assessment of perceived mental workload. *Human Factors, 33*, 17-31.

O'Donnell, R. D. & Eggemeier, F. T. (1986). Workload assessment methodology. In J. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of human perception and performance, Vol. II. Cognitive processes and performance* (pp. 41-1-42-49). New York, NY: Wiley.

Palmer, S. E. (1998). *Vision Science*. Cambridge, MA: MIT Press.

Parasuraman, R. (1979). Memory load and event rate control sensitivity decrement in sustained attention. *Science, 205*, 924-927.

Parasuraman, R. (1990). Event-related brain potentials and human factors research. In Rohrbaugh, J. W. and Parasuraman, R. (Eds.), *Event-related brain potentials: Basic issues and applications*. (pp. 279-300). New York, NY, USA: Oxford University Press.

Parasuraman, R. (Ed.) (1998). *The attentive brain*. Cambridge, MA: MIT Press.

Parasuraman, R. (2000). Designing automation for human use: empirical studies and quantitative models. *Ergonomics, 43, 7*, 931-951.

Parasuraman, R, Bahri, T., Deaton, J.E., Morrision, J.G., & Barnes, M. (1992). *Theory and design of adaptive automation in aviation systems*. Progress Report No. NAWCADWAR-92033-60. Warminster, PA: Naval Air Warfare Center, Aircraft Division.

Parasuraman, R., Molloy, R. & Singh, I. L. (1993). Performance consequences of automation-induced "complacency". *International Journal of Aviation Psychology, 3 (1),* 1-23.

Parasuraman, R., Mouloua, M., Molloy, R., Hilburn, B. (1996). Monitoring of automated systems. In Parasuraman, R. & Mouloua, M. (Eds.), *Automation and human performance: Theory and applications.* (pp. 91-115). Mahwah, NJ, USA: Lawrence Erlbaum Associates.

Parasuraman, R. & Mouloua, M. (1996) (Eds.). *Automation and human performance: Theory and applications*. Mahwah, NJ: Lawrence Erlbaum Associates.

Parasuraman, R., Mouloua, M., & Molloy, R. (1996). Effects of adaptive task allocation on monitoring of automated systems. *Human Factors*, 38(4), 665-679.

Parasuraman, R., Hancock, P. A., & Olofinboba, O. (1997). Alarm effectiveness in driver-centered collision-warning systems. *Ergonomics*, 40, 390-399.

Parasuraman, R. & Riley, V. (1997). Humans and automation: Use, misuse, disuse, abuse. *Human Factors, 39,* 230-253.

Parasuraman, R., Duley, J. A., & Smoker, A. (1998). Automation tools for controllers in future air traffic control. *The Controller: Journal of Air Traffic Control, 37,* 7-13.

Parasuraman, R., Sheridan, T. B., & Wickens, C. D. (2000). A model for types and levels of human interaction with automation. *IEEE Transactions on systems, man, and cybernetics – Part A: Systems and humans, 30, 3*, 286-297.

Parasuraman, R. & Hancock, P. A. (2001). Adaptive control of mental workload. In Hancock, P. A. and Desmond, P. A. (Eds.), *Stress, workload, and fatigue*. (pp. 305-320). Mahwah, NJ: Lawrence Erlbaum Associates.

Pashler, H. E. (1998). *The psychology of attention.* Cambridge, MA: MIT Press.

Pawlak, W. S., Bowles, A., Goel, V., & Brinton, C. (1997). *Initial evaluation of the dynamic resectorization and route coordination (DIRECT) system concept* (Final report for NASA SBIR Contract # NAS2-97057). Boulder, CO: Wyndemere.

Perrott, D. R., Sadralodabai, T., Saberi, K. & Strybel, T. Z. (1991). Aurally aided visual search in the central visual field: Effects of visual load and visual enhancement of the target. *Human Factors, 33*, 389-400.

Perry, T. S. (1997). In search of the future of air traffic control. *IEEE Spectrum, August*, 19-35.

Posner, M. I., Nissen, M. J., & Klein, R. M. (1976). Visual dominance: An information-processing account of its origins and significance. *Psychological review, 83*, 157-171.

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

Redding, R. E. (1992). Analysis of operational errors and workload in air traffic control. *Proceedings of the 36th Annual Meeting of the Human Factors Society* (pp. 1321-1325). Santa Monica, CA: Human Factors Society.

Reid, G.B. & Colle, H.A. (1988). Critical SWAT values for predicting operator overload. In *Proceedings of the Human Factors Society 32nd Annual meeting* (pp. 1414-1418). Santa Monica, CA: Human Factors Society.

Reid, G. B. & Nygren, T. E. (1988). The subjective workload assessment technique: A scaling procedure for measuring mental workload. In P.A. Hancock & N. Meshkati (Eds.), *Human mental workload* (pp. 185-218). Amsterdam: North-Holland.

Reid, G.B., Potter, S.S., & Bressler, J.R. (1989). *Subjective workload assessment technique (SWAT): A user's guide* (Report No. AAMRL-TR-89-023). Wright-Patterson Air Force Base, OH: Harry G. Armstrong Aerospace Medical Research Laboratory.

Remington, R. W., Johnston, J. C., Ruthruff, E., Gold, M., Romera, M. (2000). Visual search in complex displays: Factors affecting conflict detection by air traffic controllers. *Human Factors, 42,* 349-366.

Riley, V. (1996). Operator reliance on automation: theory and data. In R. Parasuraman & M. Mouloua (Eds.), *Automation and Human Performance: Theory and Applications* (pp. 19-36). Mahwah, NJ: Lawrence Erlbaum Associates.

Rodgers, M. D., Mogford, R. H., & Strauch, B. (2000). Post hoc assessment of situation awareness in air traffic control incidents and major aircraft accidents. In M. R. Endsley & D. J. Garland (Eds.), *Situation Awareness Analysis and Measurement* (pp. 73-112). Mahwah, NJ: Lawrence Erlbaum Associates.

Roscoe, A. H. (1987). In-flight assessment of workload using pilot ratings and hear rate. In A. H. Roscoe (Ed.), *The practical assessment of pilot workload* (pp. 78-82*),* AGARDograph No. 282. Meuilly sur Seine: Advisory Group for Aerospace Research & Development.

Rose, I. J., Kilner, A. R., & Hook, M. K. (1997). *PUMA support to new Scottish Centre Modelling*. (R & D report 9720). London, UK: Department of ATM Systems Research, Strategy and Development Directorate, National Air Traffic Services Ltd.

Roth, E. M.., Bennett, K, B. & Woods, D. D. (1987). Human interactions with an "intelligent" machine. In E. Hollnagel, G. Mancini, and D. D. Woods (Eds.). *Cognitive engineering in complex dynamic worlds* (pp. 23-51). London, UK: Academic Press.

Rouse, W. B. (1988). Adaptive aiding for human/computer control. *Human Factors, 30*, 431-443.

Rowe, D. W., Sibert, J., and Irwin, D. (1998). Hear rate variability: Indicator of user state as anaid to human-computer interaction. In: *Proceedings of the ACM CHI conference* (pp. 480-487). Los Angeles, CA.

RTCA (1995). *Report of the RTCA Board of Director's Select Committee on Free Flight*. Washington, D.C.: RTCA.

Sarter, N. B. (2000). The need for multisensory interfaces in support of effective attention allocation in highly dynamic event-driven domains: The case of cockpit automation. *The International Journal of Aviation Psychology, 10, 3*, 231-245.

Sarter, N. B. & Woods, D. D. (1994). Pilot interaction with cockpit automation II: An experimental study of pilots' model and awareness of the flight management system. *The International Journal of Aviation Psychology, 4, 1*, 1-28.

Sarter, N. B. & Woods, D. D. (1995a). How in the world did we ever get into that mode? Mode error and awareness in supervisory control. *Human Factors, 37*, 5-19.

Sauer, J. (2000). Prospective memory: a secondary task with promise. *Applied Ergonomics,* 31, 131-137.

Schick, F. V. (1991a). Evaluation of the COMPAS Experimental System. In Schick, F. V. & Völckers, U. (Eds.), *The COMPAS system in the ATC environment* (pp. 3-1 – 3-18). Mitteilung Deutsche Forschungsanstalt für Luft- und Raumfahrt. Braunschweig: DLR Institut für Flugführung.

Schick, F. V. (1991b). Evaluation of the COMPAS Operational System. In Schick, F. V. & Völckers, U. (Eds.), *The COMPAS system in the ATC environment* (pp. 6-1 – 6-19). Mitteilung Deutsche Forschungsanstalt für Luft- und Raumfahrt. Braunschweig: DLR Institut für Flugführung.

Schneider, W. & Shiffrin, R. M. (1977). Controlled and automatic human information-processing: I. Detection, search and attention. *Psychological review, 84,* 1-66.

Schroeder, D. J. & Nye, L. G. (1993). An examination of the workload conditions associated with operational errors/deviations at Air Route Traffic Control Centers. In M. D. Rodgers (Ed.), *An examination of the operational error database for air route traffic control centers* (Report No. DOT/FAA/AM-93/22). Washington, D.C.: Federal Aviation Administration.

Sheridan, T. B. & Verplank, W. L. (1978). *Human and computer control of undersea teleoperators*. Cambridge, MA: MIT Man-Machine Systems Laboratory Report.

Sheridan, T. B. (1992). *Telerobotics, automation, and human supervisory control.* Cambridge, MA: MIT Press.

Shiffrin, R. M. & Schneider, W. (1977). Controlled and automatic human information-processing: II. Perceptual learning, automatic attending and a general theory. *Psychological Review, 84*, 127-190.

Singh, I. L., Molloy, R. J., & Parasuraman, R. (1997). Automation-related monitoring efficiency: The role of display location. *International Journal of Human-Computer Studies, 46*, 17-30.

Skitka, L. J., Mosier, K. L., Burdick, M. (1999). Does automation bias decision-making? *International Journal of Human-Computer Studies, 51*, 991-1006.

Sklar, A. E. & Sarter, N. B. (1999). Good vibrations: Tactile feedback in support of attention allocation and human-automation coordination in event-driven domains. *Human Factors, 41,* 543-552.

Smith, K., Scallen, S. F., Knecht, W., Hancock, P. A. (1998). An Index of Dynamic Density. *Human Factors, 40*, 69-78.

Sorkin, R. D. (1988). Why are people turning off our alarms*? The Journal of the Acoustical Society of America, 84*, 1107-1108.

Sorkin, R. D., Kantowitz, B. H., & Kantowitz, S. C. (1988). Likelihood alarm displays. *Human Factors, 30*, 445-459.

Spence, C. & Driver, J. (1996). Audiovisual links in endogenous covert spatial attention. *Journal of Experimental Psychology: Human Perception & Performance, 22*, 1005-1030.

Spence, C. & Driver, J. (1997a). Audiovisual links in attention: implications for interface design (pp. 185-192). In D. Harris (Ed.), *Engineering psychology and cognitive ergonomics. Volume 2: Job design and product design.* Aldershot, UK: Ashgate.

Spence, C. & Driver, J. (1997b). On measuring selective attention to an expected sensory modality. *Perception & Psychophysics, 59,* 389-403.

Spence, C. & Driver, J. (1997c). Audiovisual links in exogenous covert spatial orienting. *Perception & Psychophysics, 59*, 1-22.

Sperandio, J. C. (1971). Variation of operator's strategies and regulating effects on workload. *Ergonomics, 14*, 571-577.

Sperandio, J. C. (1978). The regulation of working methods as a function of workload among air traffic controllers. *Ergonomics, 21,* 195-202.

Stager, P., Hameluck, D., & Jubis, R. (1989) Underlying factors in air traffic control incidents. *In Proceedings of the Human Factors Society 33rd Annual Meeting* (pp. 43-46). Santa Monica, CA, USA: Human Factors and Ergonomics Society.

Stager, P., Ho, G., & Garbutt, J. M. (2000). An Automated Measure of Sector Workload. In P*roceedings of the Human Performance, Situation Awareness and Automation: User-Centered Design for the New Millennium* (pp. 28-33*)*. Savannah, GA: SA Technologies, Inc.

Stein, E. S. (1985). *Air traffic controller workload: An examination of workload probe.* Technical report DOT/FAA/CT-TN84/24. Atlantic City International Airport: FAA Tech Center.

Stein, E. S. (1989). *Air traffic controller scanning and eye movements in search of information – A literature review* (Technical Report DOT/FAA/CT-TN89/9). Atlantic City, NJ: FAA Technical Center.

Stein, E. S. (1992). *Air traffic control visual scanning* (Technical report DOT/FAA/CT-TN92/16). Atlantic City International Airport, NJ: FAA Technical Center.

Sternberg, S. (1966). High-speed scanning in human memory. *Science, 153*, 652-654.

Swedish, W. J. (1982). *Proposed algorithm for AERA sector density probe.* MITRE memo No. W41-M5676. McLean, VA: MITRE.

Swedish, W. J. & Niedrighaus, W. P. (1983). *Workload probe letter to Dr. E. Stein*. Mitre Memo No. W41-3316. McLean, VA: MITRE.

Tan, G. & Lewandowsky, S. (1996). A comparison of operator trust in humans vs. machines. Cyberg International Electronic Ergonomics Conference. Available: http://www.curtin.edu.au/conference/cyberg/centre/outline.cgi/frame?dir=tan

Talotta, N.J. (1992) *Controller evaluation of initial datalink terminal ATC services: Mini study 2 vol 1* (Report DOT/FAA/CT-92/2.1). Washington DC: US Department of transportation/FAA.

Talotta, N. J. (1992) *Controller evaluation of initial datalink terminal ATC services: Mini study 2 vol 2* (Report DOT/FAA/CT-92/2.2). Washington DC: US Department of transportation/FAA.

Tattersall, A., & Hockey, G. (1995). Level of operator control and changes in heart rate variability during simulated flight maintenance. *Human Factors, 37*, 682-698.

Teichner, W. H. (1974). The detection of a simple visual signal as a function of time on watch. *Human Factors, 16*, 339-353.

Thackray, R. I. & Touchstone, R. M. (1989). Detection efficiency on an air traffic control monitoring task with and without computer aiding. *Aviation, Space, and Environmental Medicine, 60*, 744-748.

Tole, J. R., Stephens, A. T., Harris, R. L., Ephrath, A. R. (1982). Visual scanning behavior and mental workload in aircraft pilots. *Aviation, Space, and Environmental Medicine*, 53, 1, 54-61.

Tsang, P. S. & Vidulich, M. A. (1994). The role of immediacy and redundancy in relative subjective workload assessment. *Human Factors, 36*, 503-513.

Van Gent, R. N. H. W., Hoekstra, J. M., & Ruigrok, R. C. J. (1998). *Free Flight with airborne separation assurance: A man-in-the-loop simulation study. (Technical Report).* Amsterdam, The Netherlands: National Aerospace Laboratory NLR.

Van Orden, K. F., Limbert, W., Makeig, S., & Jung, T.-P. (in press). Eye activity correlates of workload during a visuospatial memory task. *Human Factors*.

Velichkovsky, B.M. & Hansen, J.P. (1996). New technological windows into mind: There is more in eyes and brains for human-computer interaction. In *CHI-96: Human factors in computing systems*. NY: ACM Press.

Vicente, K. J., Thornton, D.C., & Moray, N. (1987). Spectral analysis of sinus arrhythmia: a measure of mental effort. *Human Factors*, *29*, 171-182

Vicente, K. & Rasmussen, J. (1992) Ecological interface design: Theoretical foundations. *IEEE Transactions on Systems, Man and Cybernetics*. SMC-22, 589-606.

Vidulich, M. A. & Tsang, P. S. (1987). Absolute magnitude estimation and relative judgement approach to subjective workload assessment. *In Proceedings of the Human Factors and Ergonomics Society 31st Annual Meeting* (pp. 1057-1061). Santa Monica: CA.

Vidulich, M. A., Ward, G. F., & Schueren, J. (1991). Using the subjective workload dominance (SWORD) techniquefor projective workload assessment. *Human Factors, 33*, 677-691.

Völckers, U. (1991). Application of planning aids for air traffic control: Design principles, solutions, results. In Wise, J. A, Hopkin, V. D., & Smith, M. L. (Eds.), *Automation and systems issues in air traffic control* (pp. 169-172). Berlin: Springer.

Wainwright, W. A. (1987). Flight test evaluation of crew workload. In A. H. Roscoe (Ed.), *The practical assessment of pilot workload* (pp. 60-68), AGARDograph No. 282. Meuilly sur Seine: Advisory Group for Aerospace Research & Development.

Warm, J. S., Dember, W. N., & Hancok, P. A. (1996). Vigilance and workload in automated systems. In R. Parasuraman & M. Mouloua (Eds.), *Automation and human performance: Theory and Applications* (pp. 183-200). Mahwah, NJ: LEA.

Welford, A. T. (1978). Mental workload as a function of demand, capacity, strategy, and skill. *Ergonomics, 21,* 151-167.

White House Commission on Aviation Safety and Security (1997). *Final report to President Clinton. Vice President Al Gore, Chairman.* (February 12). Washington DC: Author.

Wickens, C. D. (1980). *The structure of attentional resources*. In R.S. Nickerson (Ed.).Attention and performance, VIII (pp. 239-257). Hillsdale, NJ: Erlbaum.

Wickens, C. D. (1984). Processing resources in attention. In R. Parasuraman & D. R. Davies (Eds.), *Varieties of attention* (pp. 63-102). Orlando, FL: Academic Press.

Wickens, C. D. (1992). *Engineering psychology and human performance (2nd ed.).* Scranton, PA: Harper Collins.

Wickens, C.D. (1994). Designing for situation awareness and trust in automation. In *Proceedings of the IFAC Conference on Integrated Systems Engineering.* Baden-Baden, Germany.

Wickens, C. D. (1998). Commonsense statistics. *Ergonomics in Design, 6, 4,* 18-22.

Wickens, C. D. (2000). Imperfect and unreliable automation and its implications for attention allocation, information access and situation awareness. Technical report ARL-00-10/NASA-00-2. Aviation Research Lab, Institute of Aviation, Urbana-Champaign, Illinois.

Wickens, C. D., Hyman, F., Dellinger, J., Taylor, H., & Meador, M. (1986). The Sternberg memory search task as an index of pilot workload. *Ergonomics*, *29*, 1371-1383.

Wickens, C. D. & Liu, Y. (1988). Codes and modalities in multiple resources: A success and a qualification. *Human Factors*, 30, 5, 599-616.

Wickens, C. D., Mavor, A., & McGee, J. (1997). *Flight to the future.* Washington, D.C.: National Academy Press.

Wickens, C. D., Gordon, S. E., & Liu, Y. (1998b). *An Introduction to Human Factors Engineering.* New York, NY: Longman.

Wickens, C. D., Mavor, A., Parasuraman, R., & McGee, J. (1998a). *The future of air traffic control: Human operators and automation.* Washington, D.C.: National Academy Press.

Wickens, C. D. & Hollands, J. G. (2000). *Engineering psychology and human performance (3rd ed.).* Upper Saddle River, NJ: Prentice Hall.

Wiener, E. L. & Curry, R. E. (1980). Flight-deck automation: promises and problems. *Ergonomics, 23,* 995-1011.

Wiener, E. L. (1989*). Human Factors of Advanced Technology ('glass cockpit') Transport Aircraft*, Tech. Rep. 117528. Moffet Field, CA: NASA Ames Research Center.

Wiener, E. L., Kanki, B. G., & Helmreich, R. L. (1993). *Cockpit resource management.* San Diego, CA: Academic Press.

Wierwille & Casali, (1983). A validated rating scale for global mental workload measurement applications. *In Proceedings of the Human Factors and Ergonomics Society 27th Annual Meeting* (pp. 129-133). Santa Monica, CA: HFES.

Wierwille, W. W. & Connor, S. A. (1983). Evaluation of 20 workload measures using a psychomotor task in a moving-base aircraft simulator. *Human Factors, 25*, 1-16.

Wierwille, W. W., Rahimi, M., Casali, J. G. (1985). Evaluation of 16 measures of mental workload using a simulated flight task emphasizing mediational activity. *Human Factors, 27,* 489-502.

Willems, B., Allen, R. C., and Stein, E. S. (1999). *Air traffic control specialist visual scanning II: Task load, visual noise, and intrusion into controlled airspace*. (Technical report DOT/FAA/CT-TN99/23). Atlantic City International Airport, NJ: FAA Technical Center.

Willems, B. & Truitt, T. R. (1999). *Implications of Reduced Involvement in En Route Air Traffic Control*. Technical report (DOT/FAA/CT-TN99/2). Atlantic City International Airport, NJ: FAA Technical Center.

Wilson, G.F. & Eggemeier, F. T. (1991). Psychophysiological assessment of workload in multi-task environements. In D. L. Damos (Ed.), *Multiple-task performance.* Washington, D.C.: Taylor and Francis.

Wilson, G.F. (1992). Applied use of cardiac and respiration measures: practical considerations and precautions. *Biological Psychology, 34*, 163-178.

Wyndemere (1996). *An evaluation of air traffic control complexity*. Final report NASA contract NAS2-14284. Boulder, CO: Author.

Yarbus, A. L. (1967). *Eye movements and vision* (B. Haigh & L. A. Riggs, Trans.). New York: Plenum. (Original work published 1965)

Yeh, Y. Y. & Wickens, C. D. (1988). Dissociation of performance and subjective measures of workload. *Human Factors, 30*, 111-120.

Yeh, M. & Wickens, C. D. (2000). Effects of cue reliability, realism, and interactivity on biases of attention and trust in augmented reality. *Proceedings of the IEA/HFES 2000 Meeting.* Santa Monica: Human Factors and Ergonomics Society.

Zijlstra, F. R. H. & Doorn, L. van (1985). *The construction of a scale to measure subjective effort* (Technical report). Delft: Delft University of Technology.

12. Appendix

12.1 Study protocol and consent for Experiment 1

DYNAMIC AUTOMATION TOOLS FOR AIR TRAFFIC MANAGEMENT

STUDY PROTOCOL

INVESTIGATORS: Raja Parasuraman, Ph.D.
Brian Hilburn, Ph.D.
Diego Castano, M.S.
Jackie Duley, M.S.
Scott Galster, B.A.
Anthony Masalonis, M.A.
Ulla Metzger, Dipl.-Psych.

PHONE NUMBER TO CALL IF QUESTIONS ARISE: 202-319-5825

PURPOSE OF THE STUDY

This research seeks to examine how advanced computer automation and new procedures will affect the performance of air traffic controllers and pilots to maintain safe and efficient separation of aircraft during simulated flight and simulated air traffic management. In particular, new automation concepts, including flexible decision aiding and dynamic task allocation, will be investigated. New procedures will also be studied. The present study will examine effects of these automation concepts and procedures on controller performance and workload during simulated air traffic control.

DESCRIPTION OF PROCEDURES

In this experiment participants will be required to perform tasks that will be presented on the color monitor of a computer workstation. The tasks simulate the types of functions often required of air traffic controllers. A primary visual display (PVD) will display aircraft and their associated flight paths. Each aircraft symbol will display a "data block" containing variables such as the aircraft name, airspeed, altitude, etc. A "data-link" interface will allow you to "query" a particular aircraft and to issue commands to the aircraft (such as a command to descend to a particular altitude). Participants will interact with the system using a trackball device. Their overall goal will be to keep the flow of air traffic smooth and to identify and act upon any potential "conflicts", i.e. when two flight paths come within a specified distance of each other. The details of the task will be described to participants in detail prior to the beginning of data collection. Participants will receive several training and practice sessions in which to learn to perform the task.

The measures to be collected are noninvasive and involve little or no risk to participants. The measures include performance indices derived from the trackball device (errors, reaction times, patterns of information acquisition, etc). In addition, mental workload will be measured using subjective measures of perceived mental workload (the NASA Task Load Index) and using objective measures of heartrate variability. In order to measure heartrate, three sensors will temporarily be placed on your arms. An additionial sensor around your lower ribcage will monitor you respiration. Finally, participants will complete a brief biographical questionnaire and a questionnaire assessing their aviation and computer knowledge.

The experiment will last approximately four hours, including all breaks. Participation is this study is voluntary. All individuals will be told that they are free to discontinue participation at any time.

CONTRIBUTIONS

The results of this study are expected to provide information relevant to the design and implementation of future systems for air traffic management. The results should also advance knowledge of how people interact with dynamic automation tools in carrying out complex problem solving tasks.

RISKS AND DISCOMFORTS

Previous experience with participants performing similar tasks indicates that the potential risk or discomfort from participating in this study will be minimal. The air traffic control simulation task is challenging, much like an arcade videogame, and most persons find them interesting and stimulating. Fatigue or other discomfort should not be a major factor because frequent rest breaks will be given.

CONFIDENTIALITY

The data obtained from participants will be recorded with coded numbers to preserve confidentiality. Only the principal investigator will have access to the codes, which will be kept securely. Participants will not be identified by name in any report of the results.

INFORMED CONSENT FORM

I understand that I may refuse to participate or discontinue my participation at any time without loss of benefits to which I am entitled. If for any reason I wish to withdraw from the experiment before it is completed, I am free to do so at any time, by notifying the experimenter. Prorated amounts for compensation based on participation will be paid if I do not complete the experiment either due to voluntary withdrawal or inability to perform the task. I understand that I will not be identified by name in any report or publication that may result from this research.

I understand that any information about me obtained as a result of participation in this research will be kept as confidential as legally possible. I understand that my research records, just like my hospital records, may be subpoenaed by court order.

I have had an opportunity to ask any questions about the research and/or my participation in the research, and these have been answered to my satisfaction.

I have received a signed copy of this consent form. I volunteer to participate in the above study.

If I have any concerns at the end of this study related to the procedures involved or how the study was conducted I should direct them to Ulla Metzger at the end of the study. I may also contact the Secretary of the Committee for the Protection of Human Subjects at (202) 319-5218. The secretary is located in the Office of Sponsored Research on the CUA campus.

SIGNATURE DATE

INVESTIGATOR'S SIGNATURE DATE

12.2 Study protocol and consent for Experiments 2 and 3

DYNAMIC AUTOMATION TOOLS FOR AIR TRAFFIC MANAGEMENT

STUDY PROTOCOL

INVESTIGATORS: Raja Parasuraman, Ph.D.
Brian Hilburn, Ph.D.
Jackie Duley, M.S.
Scott Galster, M.A.
Ulla Metzger, Dipl.-Psych.

PHONE NUMBER TO CALL IF QUESTIONS ARISE: 202-319-5825

PURPOSE OF THE STUDY

This research seeks to examine how advanced computer automation and new procedures will affect the performance of air traffic controllers and pilots to maintain safe and efficient separation of aircraft during simulated flight and simulated air traffic management. In particular, new automation concepts, including flexible decision aiding and dynamic task allocation, will be investigated. New procedures will also be studied. The present study will examine effects of these automation concepts and procedures on controller performance and workload during simulated air traffic control.

DESCRIPTION OF PROCEDURES

In this experiment participants will be required to perform tasks that will be presented on the color monitor of a computer workstation. The tasks simulate the types of functions often required of air traffic controllers. A primary visual display (PVD) will display aircraft and their associated flight paths. Each aircraft symbol will display a "data block" containing variables such as the aircraft name, airspeed, altitude, etc. A "data-link" interface will allow you to "query" a particular aircraft and to issue commands to the aircraft (such as a hand-off command). Participants will interact with the system using a trackball device. Their overall goal will be to keep the flow of air traffic smooth and to identify and act upon any potential "conflicts", i.e.

when two flight paths come within a specified distance of each other. The details of the task will be described to participants in detail prior to the beginning of data collection. Participants will receive several training and practice sessions in which to learn to perform the task.

The measures to be collected are noninvasive and involve little or no risk to participants. The measures include performance indices derived from the trackball device (errors, reaction times, patterns of information acquisition, etc). In addition, mental workload will be measured using subjective measures of perceived mental workload (the NASA Task Load Index) and using objective measures of pupil size. <u>To measure pupil size and study eye movements, you will be wearing eye-tracking equipment, worn as a headband.</u> Finally, participants will complete a brief biographical questionnaire and a questionnaire assessing their aviation and computer knowledge.

The experiment will last approximately 3-4 hours, including all breaks. Participation in this study is voluntary. All individuals will be told that they are free to discontinue participation at any time.

CONTRIBUTIONS

The results of this study are expected to provide information relevant to the design and implementation of future systems for air traffic management. The results should also advance knowledge of how people interact with dynamic automation tools in carrying out complex problem solving tasks.

RISKS AND DISCOMFORTS

Previous experience with participants performing similar tasks indicates that the potential risk or discomfort from participating in this study will be minimal. The air traffic control simulation task is challenging, much like an arcade video-game, and most persons find them interesting and stimulating. Fatigue or other discomfort should not be a major factor because frequent rest breaks will be given. <u>Due to the nature of eye movement data collection, some people may find the eye tracking equipment uncomfortable after a period of time. Participants will be permitted to discontinue wearing the headband or discontinue participation completely at any time.</u>

CONFIDENTIALITY

The data obtained from participants will be recorded with coded numbers to preserve confidentiality. Only the principal investigator will have access to the codes, which will be kept securely. Participants will not be identified by name in any report of the results.

INFORMED CONSENT FORM

I understand that I may refuse to participate or discontinue my participation at any time without loss of benefits to which I am entitled. If for any reason I wish to withdraw from the experiment before it is completed, I am free to do so at any time, by notifying the experimenter. Prorated amounts for compensation based on participation will be paid if I do not complete the experiment either due to voluntary withdrawal or inability to perform the task. I understand that I will not be identified by name in any report or publication that may result from this research.

I understand that any information about me obtained as a result of participation in this research will be kept as confidential as legally possible. I understand that my research records, just like my hospital records, may be subpoenaed by court order.

I have had an opportunity to ask any questions about the research and/or my participation in the research, and these have been answered to my satisfaction.

I have received a signed copy of this consent form. I volunteer to participate in the above study.

If I have any concerns at the end of this study related to the procedures involved or how the study was conducted I should direct them to Ulla Metzger at the end of the study. I may also contact the Secretary of the Committee for the Protection of Human Subjects at (202) 319-5218. The secretary is located in the Office of Sponsored Research on the CUA campus.

____

Participant Name (please print)   Participant Signature   Date

__________________________   ____________________

Investigator’s Signature   Date

12.3 Biographical information sheet

NAME(optional)______________________________AGE_____GENDER_______

HANDEDNESS: RIGHT_____LEFT_____BOTH_____

EDUCATION: NUMBER OF YEARS COMPLETED: _____ (e.g. high school senior = 12)

COMPUTER FAMILIARITY: LOW_____MEDIUM_____HIGH_____

DO YOU HAVE 20/20 VISION OR CORRECTED 20/20 VISION? YES_____NO_____

POSITION_________________ RETIRED___ FPL___ TMU___SHIFT________________

NAME OF FACILITY____

YEARS OF ATC EXPERIENCE_________OVERALL

EXPERIENCE IN OTHER AIR TRAFFIC ENVIRONMENTS:

CIVILIAN

YEARS OF EXPERIENCE_________TOWER LOCATION_______________________

YEARS OF EXPERIENCE_________TRACON LOCATION_______________________

YEARS OF EXPERIENCE_________EN ROUTE LOCATION_______________________

MILITARY

YEARS OF EXPERIENCE_________TOWER LOCATION_______________________

YEARS OF EXPERIENCE_________TRACON LOCATION_______________________

YEARS OF EXPERIENCE_________EN ROUTE LOCATION_______________________

OTHER (e.g. oceanic, etc.): ____

WHAT DOES THE TERM "FREE FLIGHT" MEAN TO YOU?

____

____

WHAT COMMENTS, IF ANY, DO YOU HAVE REGARDING FREE FLIGHT?

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ARE YOU INTERESTED IN PARTICIPATING AS A PAID VOLUNTEER IN ANY FUTURE STUDIES ? YES__ NO__

12.4 Instructions

This is what you will see on the screen. *Show screenshots of sector and datalink*. This is a sector. *Show octangle*. You will be responsible for all aircraft you see within this sector. There are basicly four different tasks:

The first is to accept aircraft that are coming into your sector. The second task is to monitor their flight path and the third is to hand off aircraft to the next sector. The four – and most important task – is detecting potential conflicts.

1. Accepting incoming aircraft

You have to accept all aircraft that enter your sector. For each aircraft that enters your sector you will get an incoming message on the datalink. *Show datalink*.. The datalink is a means of communication between the pilot and the air traffic controller and substitutes voice communication. Open the message by double-clicking on it with the left mouse button. Read the message and click accept to take over responsibility for that aircraft. On the radar, the call sign of the aircraft will change from orange to green. On the datalink, you will get a message saying "Roger" to indicate that the pilot received your message of acceptance. If you click on the call sign of the aircraft in the list of flights the flight strip will open up. *Show*. The flight strip gives you the most important information for an aircraft, e.g. its callsign, the waypoints, its speed and altitude. You need the flight strip to monitor the flight plan of the aircraft which is your second task in this experiment.

2. Monitoring the flight path

You will have to monitor the flightpath of each aircraft. As soon as an aircraft passes one of the waypoints, click on the waypoint it just passed on the flightstrip. The waypoint will be highlighted as soon as you click it.

3. Handing-off in a FF scenario

When an aircraft reaches this circle you have to hand it off to the next sector giving the next air traffic controller responsibility of the aircraft. You hand off by clicking and highlighting the call sign of the aircraft in the flight list and then click the auto hand-off button. As soon as the aircraft is handed-off the call sign of the aircraft on the radar will turn orange and you will see an R next to that flight on the flight list. This tells you that you don't have responsibility for that aircraft anymore. It is more important to hand-off an aircraft than to monitor the flightplan.

I will give you a demonstration of what I just explained and then there will be a practice scenario where you can practice the tasks. If you have questions, please ask at any time.

4. Detecting conflicts

The fourth task, detecting conflicts, is the most important task. Whenever you think you see a potential conflict you are to report the conflict. A potential conflict can result in an actual conflict where the aircraft involved loose separation. It can also result in a self-separation in which one of the two aircraft makes an evasive maneuver by changing speed, heading, or altitude to avoid the impending conflict. In either case, conflict or self-separation, please report a potential conflict as soon as possible.

How to report a conflict

If you would like to report a conflict, click on the datablock of the aircraft involved using the left mouse button. The datablock will change from green to white to give you feedback that you selected the aircraft. Then click the conflict button in the upper right corner of the right side monitor [show]. After clicking the conflict button, the datablocks will change back to green.

Conflict resolution (Experiment 3 only)

Also, if you detect a conflict, decide on how you would resolve the conflict by issuing a clearance. So, for example, if you there is a conflict between AAL123 and USA 456 and you would resolve the conflict by telling USA to descend to FL 350 say "USA 456, climb and maintain FL350". I will record your resolution suggestion. However, the resolution in the scenario might be different, but that doesn't matter. I am not evaluating how good your resolution is.

There will be no feedback which conflicts you have already reported. If you're not sure if you already reported a conflict or not, report it again. There is no penalty for reporting a conflict more than once. If you report a conflict more than once, only the first report will be counted.

Demonstration of a scenario

Here you see the sector, the datalink and the different aircraft coming in. The data block on each aircraft tells you the aircraft's call sign, its altitude, if the aircraft is descending (indicated by a -), climbing (indication by a +) or remains at a constant altitude (C), a computer identification number and its ground speed.

Fore, Back, Range buttons

With those buttons, you can change the foreground and background color of the screen and change the range of the screen. With + you can zoom in, with - you can zoom out.

J-Ring, History, Vector

History and Vector are general and affect all aircraft. J-Ring can be turned on and off for each single aircraft.

Self-separation, Conflict

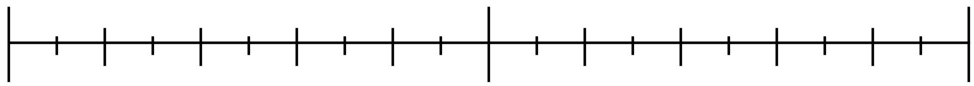
As soon as two aircraft get too close to each other (5nm horizontal and 1000 feet vertical) you will see a red bubble around them (similar to a J-Ring). This indicates that they could crash or that they self-separate without a problem. If you think you can see a conflict, please let me know as soon as possible by reporting it to me.

12.5 Description of the conflict detection aid Experiment 3

"As the demands on the NAS continue to increase, there is a need for ATM decision support tools that assist controllers in conflict detection and other tasks. Conflict detection aids predict conflicts in advance using information on aircraft position, speed and flight plans along with forecasts of wind and temperature profiles. Conflict detection aids would be especially useful in a Free Flight environment with a less structured traffic flow compared to the current environment. Conflict detection aids merely provide information to the controller; the controller retains authority and responsibility for safe separation of air traffic. Flight intent information is available to a conflict detection aid through the current flight plan obtained from the host. Changes in flight intent information are known to the relevant pilots and controllers and in most cases are known to the conflict detection aid through a filed flight plan amendment obtained from the host. In some cases, changes in flight intent information are not explicitly available to the conflict probe, e.g. when flight plan amendments are not entered into the host. The conflict probe is simply providing you with information. It is your choice to use it or not. The controller retains authority and responsibility for safe separation of air traffic."

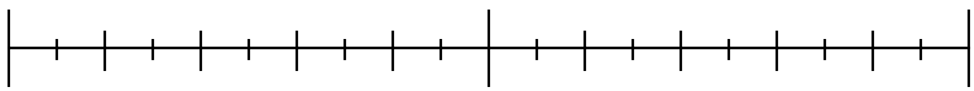
12.6 Trust and self-confidence rating scales

1. To what extent did you **trust (i.e. believe in the accuracy of)** the conflict detection aid in this scenario?



Extremely | Not at all

2. To what extent were you **self-confident** that you could accurately detect conflicts **without the conflict detection aid** in this scenario?



Extremely | Not at all

Comments:

13. Curriculum Vitae

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Grundschule Eich, 1977-1981

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Grundstudium: Johannes-Gutenberg Universität Mainz, 1990-1992

Vordiplom Psychologie, 1992

Hauptstudium: Technische Universität Darmstadt, 1992-1996

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Wissenschaftliche Tätigkeit

Vermont Alcohol Research Center, Colchester, VT, USA, 1995-1996

Wissenschaftliche Hilfskraft

Friedrich-Schiller Universität Jena, 1996 - 1997

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Veröffentlichungen

Nenadic, I., Volz, H. P., Gaser, C., Facius, M., Rammsayer, T., Metzger, U., Kaiser, W. A., Sauer, H. (1997). Cerebral activation during time estimation and frequency discrimination in healthy volunteers. *Pharmacopsychiatry, 30: 204*.

Krause, W., Kotkamp, N., Tietze, H., Metzger, U., Möller, E., & Schack, B. (1999). Kann man Klassifizierungsprozesse sichtbar machen? Abruf von Kategoriebegriffen aus dem Gedächtnis und EEG-Kohärenzanalyse. In E. Witruk & H.-J. Lander (Eds.), *Informationsverarbeitungsanalysen (pp. 67-82).* Leipzig: Leipziger Universitätsverlag.

Masalonis, A.J., Duley, J.A., Galster, S.M., Castaño, D.J., Metzger, U., & Parasuraman, R. (1998). Air traffic controller trust in a conflict probe during Free Flight. *Proceedings of Human Factors & Ergonomics Society 42nd Annual Meeting, (p. 1601).* Santa Monica, CA: HFES.

Metzger, U. & Parasuraman, R. (1999). Effects of a conflict detection aid and traffic density on controller mental workload and performance in an ATC task simulating Free Flight. *Proceedings of the 10th International Symposium on Aviation Psychology (pp. 541-547).* Columbus, OH: Ohio State University.

Metzger, U. & Parasuraman, R. (1999). Free Flight and the air traffic controller: Active Control versus Passive Monitoring. *Proceedings of the Human Factors & Ergonomics Society 43rd Annual Meeting (pp. 1-5).* Santa Monica, CA: HFES.

Metzger, U., Duley, J. A., Rovira, E., & Parasuraman, R. (1999). The effect of training on monitoring of an automated system. *Proceedings of the Human Factors & Ergonomics Society 43rd Annual Meeting (p. 1406).* Santa Monica, CA: HFES.

Metzger, U., Duley, J. A., Abbas, R., & Parasuraman, R. (2000). Training to reduce inefficiencies in monitoring of automated systems: Performance and eye movements. *Proceedings of the 14th Triennial Congress of the International Ergonomics Association and 44th Annual Meeting of the Human Factors and Ergonomics Society (pp. 2-346-349).* Santa Monica, CA: HFES.

Metzger, U. & Parasuraman, R. (2000). Improving Conflict Detection Performance under Free Flight with Automated Detection Aids. *Proceedings of the Human Performance, Situation Awareness, and Automation Conference: User-Centered Design for the New Millennium (p. 355). Savannah, GA: SA Technologies, Inc.*

Metzger, U. (in press). [Book review of *Human Performance: Cognition, Stress and Individual Differences* von Matthews, G., Davies, D. R., Westerman, S. J., & Stammers, R. B.]. Ergonomics in Design.

Metzger, U. & Parasuraman, R. (in press). Conflict detection aids for air traffic controllers in Free Flight: Effects of reliable and failure modes on performance and eye movements. *Proceedings of the 11th International Symposium on Aviation Psychology*. Columbus, OH: Ohio State University.

Metzger, U. & Parasuraman, R. (in press). The Role of the Air Traffic Controller in Future Air Traffic Management: An Empirical Study of Active Control versus Passive Monitoring. *Human Factors*.

Vorträge/Poster

Metzger, U. & Parasuraman, R. (1999, May). Effects of a conflict detection aid and traffic density on controller mental workload and performance in an ATC task simulating Free Flight. Paper presented at the 10th International Symposium on Aviation Psychology, Columbus, OH.

Metzger, U. & Parasuraman, R. (1999, September). Free Flight and the air traffic controller: Active Control versus Passive Monitoring. Paper presented at the Human Factors & Ergonomics Society 43rd Annual Meeting, Houston, TX.

Metzger, U., Duley, J. A., Rovira, E., & Parasuraman, R. (1999, September). The effect of training on monitoring of an automated system. Poster presented at the Human Factors & Ergonomics Society 43rd Annual Meeting, Houston, TX.

Metzger, U., Duley, J. A., Abbas, R., & Parasuraman, R. (2000, August). Training to reduce inefficiencies in monitoring of automated systems: Performance and eye movements. Paper presented at the 14th Triennial Congress of the International Ergonomics Association and 44th Annual Meeting of the Human Factors and Ergonomics Society, San Diego, CA.

Metzger, U. & Parasuraman, R. (2000, October). Improving Conflict Detection Performance under Free Flight with Automated Detection Aids. Poster presented at the Conference on Human Performance, Situation Awareness, and Automation: User-Centered Design for the New Millenium, Savannah, GA, Oct. 15-19, 2000.

Metzger, U. & Parasuraman, R. (2001, March). Conflict detection aids for air traffic controllers in Free Flight: Effects of reliable and failure modes on performance and eye movements. Paper presented at the 11th International Symposium on Aviation Psychology, March 5-8, 2001, Columbus, OH: Ohio State University.

Stand: 23-Jul-01