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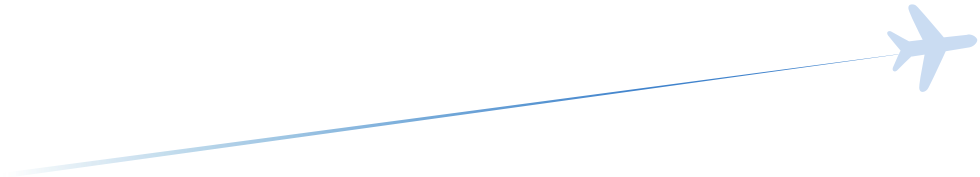

State of the Art report

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MINIMA

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STATE OF THE ART REPORT

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Abstract

An increase of automation in air traffic control can have negative effects on the air traffic controller's performance. The effects are known as out-of-the-loop phenomenon. The MINIMA Project will develop a vigilance and attention controller to mitigate these effects. A highly automated arrival management task will be used as a case study. Psychophysiological measurements like EEG will be used to identify the state of the Air Traffic Controller and combined with adaptive task activation. This will allow for activating tasks based on the Air Traffic Controllers state to keep their performance on a high level and to ensure safe operations.

This document reports about the state of the art review executed at the beginning of the MINMA project. Specifically, the out-of-the-loop phenomenon is analysed in detail.to identify problems that can be expected when automation in air traffic control is increased. Further, existing solutions to mitigate these problems are analysed. Thereby, the focus is put on adaptions of the task. Moreover, psychophysiological measures and their suitability to determine air traffic controllers' vigilance and attention are evaluated. The results will be considered for the development of the MINIMA concept. The analysis ensures that it will be based on the state of the art. The concept will be described in the next Deliverable (D 1.2) and specify the task environment, possible adaptations of this environment and the set of psycho-physiological measures to be used and their interaction to be developed and evaluated in MINIMA.

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List of Acronyms

Abbreviation	Description
AA	Adaptive Automation
ANN	Artificial Neural Networks
ANS	Autonomic Nervous System
ASRS	Aviation Safety Reporting System
ATC	Air Traffic Control
ATCos	Air Traffic Controllers
ATM	Air Traffic Management
BCI	Brain Computer Interface
BOLD	Blood Oxygenation Level Dependent
EBR	Eye-Blink Rate
ECG	Electrocardiogram
EDA	Electrodermal Activity
EDRs	Electrodermal Responses
EEG	Electroencephalography
EI	Index of Engagement
ERPs	Event-Related Potentials
FF	Free Flight
fMRI	functional Magnetic Resonance Imaging
fNIRS	functional Near-Infrared Spectroscopy
FMS	Flight Management Systems

GPWS	Ground Proximity Warning System
GSR	Galvanic Skin Response
HbO	Oxygenated Hemoglobin
HbR	Deoxygenated Hemoglobin
HR	Heart Rate
HRV	Heart Rate Variability
ICAO	International Civil Aviation Organization
JPDO	Joint Planning and Development Office
LC	*Locus Coeruleus*
LOAs	Levels Of Automation
MABA-MABA	Men-Are-Better-At/Machines-Are-Better-At
MATB	Multi Attribute Task Battery
MINIMA	MItigating Negative Impacts of Monitoring high levels of Automation
NINA	Neurometrics Indicators for ATM
NTSB	National Transportation Safety Board
OOTL	Out-Of-The-Loop phenomenon
PCA	Principal Component Analysis
PERCLOS	PERcentage of eye CLOSure
PNS	Parasympathetic Nervous System
PSD	Power Spectrum Density
PVT	Psychomotor Vigilance Task
SA	Situation Awareness
SCL	Skin Conductance Level
SCRs	Skin Conductance Responses
SNS	Sympathetic Nervous System
SOA	Stimulus Onset Asynchronies
RTs	Reaction Times
RSA	Respiratory Sinus Arrhythmia
rMSSD	Root Mean Squared Successive Differences,
RTCA	Radio Technical Commission for Aeronautics

TMA	Terminal Manoeuvring Area

1 Executive Summary

Problem Area

Over the past few years the global air traffic growth has exhibited a fairly stable positive trend, even through economic immobility, financial crisis and increased security concerns. It is now clear that traffic flow patterns will become more complex, making conflicts and situations harder to identify for a human operator, putting immense pressure on the air traffic control system. In this context, several solutions have been proposed for modernizing air traffic control and meet the demands for enhanced capacity, efficiency, and safety. These different solutions rely on higher levels of automation as supported by both SESAR JU and HALA! Research Network.

On the one hand, implementing higher Levels of automation can improve the efficiency and capacity of a system. On the other hand, it can also have negative effects on the performance of human operators. For example it can reduce the vigilance and sensitivity to important signals [24], it can create unjustified, excessive trust in system ability [30], and it can lead to a loss of operator situation awareness [28]. These effects have been observed in domains in which the level of automation is already increased, for example in aviation [25], nuclear power plants [26], and the Stock Market [27]. Indeed, it is now well accepted that traditional automation can have negative consequences for performance and safety due to these difficulties [5, 6, 89]. This set of difficulties is called the Out-Of-The-Loop phenomenon (OOTL) [20, 22]. In the current context of a continued increase in automation, understanding the sources of difficulties in the interaction with automation and finding solutions to compensate such difficulties are crucial issues for both system designer and human factor society.

If this OOTL performance appears as a first concern in the human factors literature, it remains difficult to characterize and quantify, except for difficulties in takeover situation. Detecting the occurrence of this phenomenon, or even better detecting the dynamics toward this degraded state, is an important issue in order to develop tools for evaluation and monitoring.

The general objective of MINIMA project is to improve our comprehension of the Out-of-the-LOOP (OOTL) performance problem especially according to a future air traffic scenario. Further. MINIMA will develop tools to detect and compensate the negative impact of this phenomenon and a carefully selected distribution of tasks between the human agent and the automated system for the selected use case of a highly automated Terminal Manoeuvring Area (TMA).

Description of Work

The report is the result of an extensive literature review in order to provide a description of the state-of-the-art of the research relating to three main questions: (1) the characterization of the OOTL phenomenon, (2) the current solutions proposed to compensate this phenomenon, and (3) the identification of its physiological markers.

The aims of the review were to provide a basis for developing the MINIMA concept. The work started with a discussion regarding the increasing place of automation technology and the evolution of the human role in such system (Part 3). Then, we continued with an introduction to the OOTL concept and a review of the works dedicated to this phenomenon (Part 4). Particularly, we presented the performance consequences of the OOTL phenomenon and discussed how explain such degradation. Amongst other, vigilance decrement, system opacity and manual skills degradation were presented as potential causes for OOTL phenomenon. Together, these different inputs aim to clarify the OOTL characterization, a crucial step for the rest of the project.

The following part (Part 5) was dedicated to the current solutions proposed to mitigate OOTL phenomenon. In turn, we mentioned solutions based on training, operator selection and system design. We then focused on Adaptive Automation and discussed the type of Adaptation, the trigger mechanisms and the control framework to end by illustrations of such adaptive systems. This part is crucial to provide guidance regarding the adaptive solution we aim to propose in the MINIMA project.

In the last part (Part 6), we focused on the relation between OOTL and vigilance/attention decrement. Then, we assessed the possibility of attention monitoring using biopsychometrics. We discussed in turn the suitability of EEG, TCD, NIRS, Oculometric measures, ECG and GSR as relevant index of vigilance/attention decrement. In this part, we bring the necessary insight to develop tools for monitoring the internal state of the ATCos vis-à-vis of OOL phenomenon. This part is particularly critical to identify what should determine and “trigger” the adaptive change proposed.

Results & Conclusions

Based on literature review, we identify the vigilance/attention decrement as one of the main sources of the performance decrements observed in OOTL phenomenon. We conclude that current vigilance and attention levels of the human operator could be used as a measure of the OOTL phenomenon.

We also define the Adaptive Automation as the more relevant solution to compensate the OOTL phenomenon and delimit the way to use it.

Finally, we point several biopsychometrics sensitive to changes in vigilance/sustained attention suggesting them as potential candidates for triggering adaptive automation. The presented findings suggest that it is possible to obtain robust indices on vigilance/sustained attention state using physiological measures. EEG (power spectrum density), NIRS, oculometric measure and heart rate variability appear as the more promising sources of information.

2 Introduction

2.1 The Program and the Project

The Research and Innovation Action within the MINIMA project addresses the topic “ER-01-2015 – Automation in ATM” in “Work Area 1: ATM Excellent Science & Outreach” of the “Exploratory Research H2020 Call 1”.

Nowadays, many aspects of ATM require a high level of human intervention. Increasing the level of automation in ATM is seen as a measure to increase the performance of ATM to satisfy the predicted future demand. A challenge is to guarantee safety on the current level or even to improve it. Human cognitive abilities have proven to be a key enable for safe operations in particular in critical situations.

Increasing the automation of ATM will result in new roles for human operator. Human operators will often work in a supervisory or control mode rather than in a direct operating mode. Operators will mainly monitor highly automated system and intervene seldom. It can be expected, that human operators in such a role are affected by human performance issues like lack of attention, loss of situational awareness and de-skilling known as out-of-the-loop phenomenon. These problems are observed in other domains like flight-crew performance in the glass cockpit.

MINIMA will address these performance issues. Its aim is to identify thresholds in future ATM scenarios identifying out-of-the-loop behavior and to find solutions to minimize the negative impact of monitoring high levels of automation on the human operator’s performance.

2.2 Research Objectives

MINIMA’s main goal is to improve our comprehension of the Out-of-the-LOOP (OOTL) issue especially according to a future air traffic scenario. Further, MINIMA aims to develop tools to detect and compensate the negative impact of this phenomenon and a carefully selected distribution of tasks between the human agent and the automated system for the selected use case of a highly automated Terminal Manoeuvring Area (TMA).

In this sense, MINIMA will develop a dynamic adaptation of the task environment which is foreseen as a major requirement to keep the human ‘into the loop’, perfectly aware of the traffic situation. As a consequence of the developed concept, not all tasks potentially automated will be automated every time. Together with this adaptive task environment approach, the MINIMA project will identify the minimal information required to be provided to operators in order to support the coordination between human operators and automation. Finally, MNIMA will develop a real-time monitoring system that constantly measures the operators’ vigilance levels.

In particular, by the end of the project the following outcomes are expected:

- Identify the frequency of occurrence and the severity of the OOTL performance problems in the considered task environment. Particularly, MINIMA will analyse which of these problems affect the performance of operators of the highly automated TMA.
- Analyse the tasks environment, in order to define possible new task distributions and new procedures and develop new attentional guidance tools. This should result into a set of measures to engage the human operator “into the loop”, i.e. in the task.
- Develop a real time “Vigilance and Attentional Observer” to monitor the actual mental state of the human operator. This will be based on cutting edge technologies, such as electroencephalography, kinematic sensors and eye trackers.
- Develop specific adaptive automation solutions based on the output of the Vigilance and Attentional Observer.

2.3 Structure and Scope of the document

This document is D1.1 “State of the Art Report”. Here we have reported the state of the art of tasks environment design taking advantages of the benefits of high levels of automation. This Deliverable will present a description of the state of the art about:

- Operation concepts for monitoring high level of automation tasks;
- Concepts for tasks distribution including artificial tasks;
- Concepts for attention guidance support;
- Concepts for attention measurement using Brain Computer Interfaces Technologies.

This deliverable will provide direct inputs to accomplish Task 1.2 in view to specify the concept behind the MINIMA project. It has eight main sections. It starts with the Executive summary. Then, we introduce the topic of research in section 2 (this section). Section 3 introduces the concept of automation and discusses how automation has modified the human activity. In the following section (section 4) the OOTL phenomena are described in detail, with a specific focus on the origins of the performance decrements observed during these phenomena. Section 5 presents the different solutions currently used for OOTL issue mitigation. Finally, concepts for attention measurement are described in section 6. The references can be found in section 7.

3 Automation and society

Over the past 50 years, automation technology has profoundly changed our modern society. There is perhaps no facet of everyday life in which the influence of automation technology has not been felt. Whether at work nor at home, while travelling or while engaged in leisurely pursuits, human beings are becoming increasingly accustomed to using and interacting with sophisticated systems designed to assist them in their activities. Even more radical changes are expected in the future with increase in computers performance. How such developments will shape the future is not entirely clear, but the inexorable drive toward even more automation will continue and air traffic management should not appear as an exception. Crucially, whatever the advantages of using any particular automation technology, it is clear that it has profoundly changed human activity. Understanding the characteristics of this transformation is vital for successful design of new ATM systems.

3.1 What is automation?

Let us begin by defining automation, because the term has been used in many different ways. The Oxford English Dictionary defines automation as follows:

> “The action or process of introducing automatic equipment or devices into a manufacturing or other process or facility; (also) the fact of making something (as a system, device, etc.) automatic”.

The first use of the term automation is observed in the McGraw-Hill Encyclopedia of Science and Technology in 1948 (see also [1]) to describe the increased use of automatic devices and controls in mechanized production lines. Today use of the term has grown beyond product manufacturing and is applied to automatic control and instrumentation in a variety of domain (modern factories, chemical and power plants, airplanes and air traffic control, automobiles, ships to name only a few examples). In the fullest contemporary sense, the term automation refers to [2]:

a. the mechanization and integration of the sensing of environmental variables (by artificial sensors);

b. data processing and decision making (by computers);

c. mechanical action (by motors or devices that apply forces on the environment);

Because our main concern is about human performance in automated systems, we use a definition that emphasizes human-machine interaction and define automation as the process of entirely or partially allocating the activities constituting a task usually performed by a human, to a machine or a system. In such definition, automation refers to the full or partial substitution of a function initially performed by the human operator. In that sense, automation is not all or none but can vary across a continuum of levels, from the fully manual performance to the full automation and different scales of levels of automation (LOAs) involving automation of decision making and action have been proposed (see for example [3],[4]).

Further, automation also includes information gathering and analysis. For example, air traffic control involve (a) the acquisition of radar information on location, flight plans and identity of many aircraft, weather information, and so on; (b) the combination and analysis of the appropriate information, (c) a decision taking (which to speed, heading, and altitude for different aircraft to maintain safe separation and bring the aircraft safely though a sector of airspace or to land or take off) regarding the situation decisions be made as, and finally (d) a means to get the pilots (and aircraft) to cooperate and execute the instructions given. As a result, Parasuraman and colleagues [5] have suggested an extension of the LOA concept to four information-processing stages: (a) information acquisition, (b) information analysis, (c) decision making, and (d) action, with each stage having its own LOA scale (for similar scales, see [6]). At Stage 1, automation involves acquisition and preprocessing of multiple sources of information. It includes sensory processing and selective attention. At stage 2, automation involves manipulation of information in working memory. It includes cognitive operations such as integration, diagnosis, and inference, occurring prior to the point of decision. At stage 3, automation involves decisions based on previous cognitive processing. In Stage 4, automation involves action performing regarding the decision choice. In other words, automation is technology that actively selects data, analyzes information, produces decisions, or controls processes in place of the human operator.

Automation in aeronautical field has been recognized as an important topic [7] – new automated aircraft are in production, and air traffic control (ATC) is being transformed by the replacement of radar with satellite-based surveillance. But most safety-critical systems – power plants, intensive care units, and so on – include automation. The explosive growth of microprocessor technology (rapid improvements in performance, together with a decrease in size, cost, and power consumption) makes automation of many systems a reasonable alternative to traditional manual operation and sophisticated automation is becoming ubiquitous.

3.2 Why use automation?

People are accustomed to interact with automation technology. Indeed, modern automation has pervaded not just the workplace but also transportation, the home, and entertainment. We also use technology for communication, education, banking, purchasing and so on. But why use automation? What is the thrust behind system automation?

Wiener and Curry depicted the image of automation as follow:

> “*Quiet, unerring, efficient, totally dependable machines, the servant of man, eliminating all human error, and offering a safe and cost-effective alternative to human frailty and caprice. The traditional dream of traditional engineers has been to solve the problem of human error by eliminating its sourc*e.” [8]

As suggested here, the main reason to use systems of autonomous machines is both to improve safety and reduce cost.

The quest for ultra-safe system

As the International Civil Aviation Organization (ICAO) reported, air traffic increases annually by around 5% for several years. This rate demands to all partners to chase the never ending quest of safety. Starting effort was focused on decreasing systems failure – aircrafts are certified only if they have less than a probability of catastrophic failure of 10^{-9}. Nowadays, actors face a more difficult problem: human errors.

“Human error” is cited over and over as a major factor or “cause” of incidents. Surveys of anesthetic incidents in the operating room suggest that accidents were between 70 and 75 percent the fault of humans [9]. Similarly, over 70 percent of incidents in aviation domain have been attributed to crew error [10]. In general, incident surveys in a variety of industries attribute high percentages of critical events to the category “human error”.

One aviation organization concluded that to make progress on safety:

> *We must have a better understanding of the so-called human factors which control performance simply because it is these factors which predominate in accident reports.*
> *(Aviation Daily, November 6, 1992)*

Note here that we don’t completely agree this concept of human error. Particularly, it is interesting to observe that the same 70% rate is found when we look at how many accidents are avoided thanks to pilots [11]. In many cases, errors occurred in case of misunderstanding between the human operators and the machines, especially with strongly automatized environment. Therefore, “human error” may not be the best term and “interaction failure” would be more appropriate.

Whatever the doubt associated to this concept, the elimination of human error has been considered as a first concern in high-risk industries. Incidents attributed to human error then become indicators that the human element is unreliable. In this context, designers has been considered as custodians of already safe systems that need protection from unreliable, erratic human beings (who get tired, stressed, irritable, distracted, have all kinds of problems with perception, information processing, memory, recall, communication and much, much more). To overcome such perceived unreliability of human operators, it was claimed that we should reduce the human role in managing the potentially hazardous system. The typical belief is that we can create an autonomous system that required little if any human involvement and therefore reduced or eliminated the opportunity for human error. Aviation is a good example of this tendency. Indeed, in response to the fact that many aviation accidents can be attributed to human error, the aviation industry and federal aviation and safety industries have successfully pushed to increasingly automate flight systems. Autopilots, flight directors, and alerting and warning systems are examples of automatic systems that have had a beneficial effect on pilot work-load and/or safety margins. The ground proximity warning system (GPWS), for example, has dramatically reduced terrain strike accidents since its introduction by Congressional mandate in 1974.

It is now clear that such technology exhibits tremendous potential to extend human performance and improve safety. Flight management systems (FMS) are assuming greater control of flight tasks, such as calculating fuel-efficient paths, navigation, detecting system malfunctions and abnormalities, in addition to flying the plane. Because these aids are generally quite accurate, airplanes fly safely (overall accident rates have gone down). Such improvement in performance is observed in many other fields. For example, power plants run more efficiently with the use of automated decision aids and patient status is more accurately monitored in intensive care units. We can imagine that a similar justification will be used to introduce more and more automation in ATM system. If automation has been used as a suitable solution for functions that humans cannot achieve safely or reliably, it has been also considered as a potential tool to reduce the operational cost.

An economical concern

Whereas automation have been introduced into many work environments with the explicit goal of reducing human error, the utilization of sophisticated automation has also been justify by economical constraint. Economics benefits are both (1) benefits in terms of system operating, (2) benefits in terms of human operator.

In aviation domain, automation technology has undoubtedly brought about enormous savings through fuel conservation. Automation has both participated to the decrease in total flight time and the implementation of more fuel-efficient climb and descent patterns ([12],[13]). Automation also allows operation in inclement weather. As in other industries, a large component of airline operating costs is labor. While it is questionable whether automation can further reduce the number of persons in the cockpit, it is clear that automation has already reduced the number of persons required for operating a flight (e.g., there are no navigators or flight-engineers in modern cockpits anymore). It is also clear that automation may reduce direct labor costs by reducing flight times through more efficient lateral navigation, and may cut maintenance costs by more effective use of the equipment. Regarding these different facts, we can assume that automation has reduced cost associated to aircraft operation. A similar benefit is already expected for ATM. Particularly, it is imagined that automation should increase the number of airplanes per hour for each air traffic controllers (ATCo), in other words allow an increase of the traffic for a same amount of ATCos. For example, Vu and colleagues [14] found that when ATCos were given automation tools to use, they were able to manage higher traffic levels while reporting lower workload levels and making fewer safety violations (i.e., fewer losses of separation, LOS).

Even if one must also recognize that automation equipment does not come cheaply and that the industry is saddled with enormous costs for training and maintenance, it appears that automation has been a very good investment. It is also clear that the economic benefits that automation can provide, or is perceived to offer, have tended to focus public attention on the technical capabilities of automation.

What is clear at the moment is that automation makes some aspects of life safer, easier and faster. It leads to superior productivity and operativeness. When both safety and economical concerns have motivated the continuous increase in automation, we can predict a similar trend in air traffic management domain.

3.3 Automation in Air Traffic Control

Over the past few years the global air traffic growth has exhibited a fairly stable positive trend, even through economic immobility, financial crisis and increased security concerns. According to a prevailing opinion, this trend is unlikely to change in the future, although a number of contextual factors, such as political climate, economy, environmental issues, safety issues and security issues may affect its actual rate. Further, according to the ‘Free Flight’ and the ‘4D Trajectory Management’ concepts, different types of aircrafts, such as manned, unmanned and autonomous aircrafts, as well as all kinds of rotorcrafts, will operate simultaneously in a ‘structure-less’ and ‘time based’ environment allowing for much more direct and continuous trajectories to be used ([15];[16]). Also, brand new airspace designs, possibly dynamic, may be required.

Within this picture, traffic flow patterns will become more complex, making conflicts and situations harder to identify for a human operator, putting immense pressure on the air traffic control system. This increasing demand needs a change in the role of ATCo that reduces their per flight workload. Several solutions have been proposed for modernizing air traffic control and meet the demands for enhanced capacity, efficiency, and safety. As envisaged by both SESAR JU and HALA! Research Network, higher levels of automation will help ATCos to deal with increasingly complex airspace scenarios, enabling them to manage complex situations in a safe and efficient way. Together with this automation, proposals for air traffic management such as Free Flight call for a transfer of responsibility for separation between aircraft from ATCos to pilots. These different proposals have the potential to dramatically change the air traffic controllers’ role from active to passive control, with a policy of intervention by exception [17]. According to Sheridan’s classification [3], controller’s responsibility will move from “direct human control” to “computer-aided indirect control”.

However, the interposition of automated systems between ATCos and processes will dramatically transform the nature of their work [18]. Understanding the characteristics and the dynamics of this transformation is vital for successful design of new automated systems.

3.4 Automation: What does it change from a human operator perspective?

When a new automation solution is introduced into a system, or when there is an increase in the autonomy of automated systems, developers often assume that adding “automation” is a simple substitution of a machine activity for human activity (substitution myth, [19]). However, the fascination regarding the possibilities afforded by technology often obscures the fact that automation also produced new loads and difficulties for the humans responsible for operating, troubleshooting, and managing high-consequences systems. Whatever the merits of any particular automation technology, it is clear that automation does not merely supplant human activity but also transforms the nature of human work.

In future air traffic management systems, we assume that automatic devices will provide for the real-time, moment-to-moment control of the process. In such system, the main role for humans will be to undertake what is called supervisory control [3]. In other words, we expect that ATCos will be relegated to the role of monitor and decision-maker, keeping watch for deviations and failures, and taking over when necessary. This new form of interaction will differ dramatically from the traditional interaction of the ATCos with tools and devices that possess no intelligence, in which all sensing and control are done by the human operator.

Such change (from manual to supervisory control) is far from trivial. The role of passive information processor, much like that of supervisory controller, involves observing the actions of other operators or computer controllers and agreeing or disagreeing with them. The operator's task is to understand the actions of another system controller and thereby accept or reject its actions. The key difference between passive information processing and direct action on the process is that the former involves functions similar to those maintained during process monitoring (e.g., scanning information sources); whereas, the latter involves manual control functions including process planning, decision making, selecting responses and implementing strategies.

In this section, we have pointed the increasing place of automation in different domains and the different reasons for such trend. We have also assumed that a similar automation should be observed in ATM domain and described how this automation would dramatically transform the nature of the ATCos' work. Interestingly, empirical data on the relationship of people and technology suggest that traditional automation has many negative performance and safety consequences associated with it stemming from the human out-of-the-loop (OOTL) performance problem [20]. In the following section, we aim to detail how this change could impact ATCos' performance and bring a better understanding of this crucial phenomenon.

4 OOTL phenomenon characterization

The OOTL performance problem represents a key challenge for both systems designers and human factor society. After decades of research, this phenomenon remains difficult to grasp and treat and recent tragic accidents remind us the difficulty for human operator to interact with highly automated system. In the following part, we aim to review the current knowledge regarding this phenomenon and its potential impact on ATCos' performance. Because automation is more a (strong) possibility than a current concern in air traffic management domain, we will mainly refer to works and illustrations from other domains such as aviation or operator room to describe the future impact of automation on human operator performance, and particularly to understand the OOTL performance problem. By this way, we aim to illustrate how automation should impact ATCos performance.

4.1 Loop of control and out-of-the-loop phenomenon

4.1.1 Loop of control

The control theoretical perspective is a useful concept when considering human-machine systems, particularly for understanding when and how control can be lost, which is highly undesirable in safety critical systems. The concept of control can be seen in the light of Neisser's perceptual cycle [21] as a control loop. As humans we perceive through our senses, analyze and make decisions via cognitive functions and act using our limbs. Importantly, humans act upon feedback from previous events and perceptions and are thereby always part of several control loops simultaneously. More precisely, in the language of control theory, a system has a desired state, a means for adjusting the system toward that desired state, and then a feedback loop in which the actual state of the system is compared with the desired state, so that additional correction can be performed if there is a mismatch.

Let us take a simple illustration such as moving the hand to a target location. Even for this very simple task, there are an infinite number of possible paths that the hand could move along and for each of these paths there are an infinite number of velocity profiles (trajectories) the hand could follow. Motor planning can be considered as the computational process of selecting a single solution or pattern of behaviour at the levels in the motor hierarchy, from the many alternatives, which are consistent with the task. Using inverse model, the brain will specify and send a motor command to the arm. In parallel, the brain uses sensory feedback information about the state of the arm from vision and proprioception to generate or modify the motor commands sent to the arm based on error in the measured state and the desired trajectory (forward model). A same logic could be applied for ATCos' activity. When conflict is detected, ATCo has to select the relevant action amongst different alternatives. Then, he specifies and sends a command to the pilot. In parallel, he uses sensory feedback about the state of the traffic to perceive the evolution of the situation and assess the relevance of the action selected.

The combination of this control plus feedback is called the control loop, and when a human is operating the equipment manually, the human is an essential element of the control loop hence the saying, “the person is in the loop.”

4.1.2 Becoming out of the loop

The ”out-of-the-loop” concept describes a variety of situations where an individual is uninformed of information that is known by others: when an individual is a newcomer to a group, is ”in the dark” about a topic that others are discussing, or when information is actively shared with some people and specifically withheld from other individuals. Being out of the loop has been conceptualized as a form of partial ostracism—being ignored and excluded some of the time [22]. People may experience being out of the loop in a variety of contexts: from the micro level, including close relationships, social networks, and work settings to the macro level, including community, corporate, and government domains.

In the current research, we consider this phenomenon as it occurs in the context of human machine interaction. The human involvement and role in control of automatic systems depends on the level of automation. In manual control, the operator acts on the object, hence performing control on a lower level of aggregation. When a high level of automation is used, all of the control levels mentioned above are active and the operator acts as a supervisor on a high level where system and sub-system functionality is monitored rather than individual objects. The automation took care of the lower level actions and the human operators simply watched over the system, presumably ever-alert for deviations and problems. A same change is expected in future air traffic management system. In other words, ATCos should be relegated in a near future to passive information processor [23]: they will be “out of the loop”.

To summarize, the OOTL phenomenon corresponds to a **lack of control loop involvement** of the human operator. Automation technology should create an increasing distance between ATCos and the loop of control, making him disconnected from the automation system. Such a removal could lead to a decreased ability of the ATCos to intervene in system control loops and assume manual control when needed in overseeing automated systems (see following sections).

4.1.3 OOTL illustrations

As a major consequence, the OOTL performance problem leaves operators of automated systems unable to take over manual operations in the case of automation failure. Particularly, the OOTL performance problem causes a set of difficulties including a longer latency to determine what has failed, to decide if an intervention is necessary and to find the adequate course of action [24]. The three following incidents from aviation, nuclear plant and finance domains illustrate such difficulties.

- **Example 1: Aviation**

The first example concerns Flight 447 from Air France. On May 31, 2009, the Airbus A330 took off from Rio de Janeiro bound to Paris. Four hours after the departure and due to weather conditions, ice crystals obstructed the Pitot probes. Hence, speed indications were incorrect and lead to a disconnection of the autopilot. Likely following this disconnection, the crew was unable to diagnose the situation and apply the appropriate procedure. Alternating appearances and disappearances of some indicators and alarms coupled with high stress probably prevented the crew to correctly evaluate the state of the system and act appropriately (for the official report, see [25]).

- **Example 2: Nuclear Power Plant**

The second example concerns the incident of the nuclear plant of Three Miles Island (Pennsylvania, USA), in 1979. A valve used to regulate the water inlet in the nuclear core was stuck open, although a light on the control interface indicated that the valve position was closed. However, this light did not indicate real position of the valve but instead that the closure order was given. Because of ambiguous information provided by the control interface, the operators were unable to correctly diagnose the problem for several hours [26]. During this period, a sequence of different failures and inappropriate actions led to a partial meltdown of the nuclear core. Hopefully, the releases of radiations were not important enough to cause health and environmental damages. A major nuclear disaster was avoided.

- **Example 3: Stock Market**

In a completely different domain, we can mention one of the costliest computer bugs. Knight Capital is a firm specialized in high frequency trading (automated technic used to buy and sell stocks in fractions of a second). On August 1, 2012, the firm tested a new version of its trading algorithm. However, due to a bug, the algorithm started pushing erratic trades. Because supervisors were not up to date of the system behaviour, it took a long hour to understand that the problem came from the algorithm and cost to Knight Capital about 400 million dollars [27].

These previous cases highlight that when the automatic equipment fails, supervisors seem dramatically helpless for diagnosing the situation and determining the appropriate solution because they are not aware of the system state prior to the failure. Numerous experimental results confirm such difficulties. For example, Endsley and Kiris [28] provided evidence that performance during failure mode following a fully automated period were significantly degraded, as compared to a failure mode following a fully manual control. Merat and Jamson [29] reported similar conclusions. In a driving simulation task, they demonstrated that drivers' responses to critical events were slower in the automatic driving condition than in the manual condition.

We agree that none of these illustrations comes from ATC domain since as previously explained, automation technology remains marginal in current ATM in comparison to aviation, nuclear plant or finance domains. However, it is hard to imagine that ATCos would be preserved from the negative impact of automation. Because automation is not powerful enough to handle all abnormalities, this difficulty in takeover is a central problem in automation design.

Furthermore, the nature of the system in aeronautics domain makes worse these difficulties in take over situation. In this domain like in others (railroads or the nuclear industry for example), human operators have to monitor what we call ultra-safe systems, where risk of disaster is below one accident per 100 000 or even one million safety units. None of these systems has managed to achieve a global safety performance beyond one accident per 10 million safety units. They share common features. First, they are over-regulated, rigid and not adaptive. Second, accidents are different in nature from those occurring in safe systems. They usually occur in the absence of any serious breakdown or even of any serious error but result from a combination of factors, none of which can alone cause an accident, or even a serious incident. These combinations remain difficult to detect and to recover using traditional safety analysis logic.

The origins of these takeover difficulties have been largely debated. The following section will summarize and analyze the current knowledge regarding these origins.

4.2 Operator performance decrements: why?

As previously explained, the OOTL performance appears as a first concern in the human factors literature. Empirical data indeed suggest that automation is frequently accompanied by a decrease in operator’s performance, decrements in vigilance such as reduced sensitivity to important signals [24], complacent or excessive trust in system ability [30], and loss of operator situation awareness [28].

Cognitive engineering literature has discussed at length the origins of vigilance decrements (e.g., low signal rates, lack of operator sensitivity to signals), complacency (e.g., over trust in highly reliable computer control) and the decrease in situation awareness (use of more passive rather than active processing and the differences in the type of feedback provided) in automated system supervision. In the following sections, we will discuss these different issues.

4.2.1 A problem of Situation Awareness

The lack of operator involvement in supervisory modes and passive information processing contribute to critical human cognitive errors, specifically the loss of operator situation awareness (SA), to which many safety incidents have been attributed.

Situation awareness is defined as “the perception of elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future” ([31], p. 97). Situation awareness includes three processes:

- The perception of what is happening (Level 1)
- The understanding of what has been perceived (Level 2)
- The use of what is understood to think ahead (Level 3)

Nowadays, it is clear that a loss of situation awareness underlies a great deal of the out-of-the-loop performance problem [32] and that OOTL phenomenon is characterized by both a failure to detect and to understand the problem and by difficulties to find appropriate solutions.

- **Failure to detect (Level 1)**

Parasuraman et al. [5] defined their first state of information processing, sensory processing, as "the acquisition and registration of multiple sources of information" (p. 287). This refers to knowing where to look and when to look there. Such looking could be based on salient cues from the task itself or self-activation (activation by internal cues to reactivate the task) as suggested in the goal-activation model [33].

Several works indicate a lack of operator awareness of automation failures and a decrease in detection of critical system state changes when involving in automation supervision (for a review see [28]). Numerous incidents have been attributed to these difficulties in perception when operating in an automated mode. The near crash of Air China's Boeing 747 into the Pacific Ocean in 1989 illustrates this difficulty. In this case, the aircraft experienced a gradual engine failure that the human pilot was not aware of because of autopilot compensation (through rudder control) up until the point of failure of the autopilot, itself. Subsequently, the jet stalled and plummeted thousands of feet, being recovered within a few seconds of the ocean surface [34].

It is now clear that humans are less aware of changes in the environmental or system state when those changes are under the control of another agent (automation or human; [35];[36];[23]). Several studies have shown a decrease in failure detection performance with increase in system automation, including for ATCos. For example, Endsley et al. [37] found increased workload and increased in operational errors under conditions of reduced involvement. Endsley and Rodgers [38] found that ATCos showed poor performance in detecting conflicts in recorded traffic when they were passively monitoring the traffic. Galster et al. [39] found that passive monitoring with airborne control of aircraft separation, which would be the case under mature Free Flight, led to a marked decrease in conflict detection performance by ATCos under high traffic load (see also [23]). Willems and Truitt [40] found that under passive monitoring, response times to questions probing traffic awareness became longer and recall of data blocks poorer with increasing traffic load.

All these studies confirm that ATCos may be poor in detecting aircraft-to-aircraft conflicts when they are not actively controlling the airspace but nevertheless have to monitor for occasional anomalies. If human operators acting as monitors have problems in detecting system errors, they have also problems in understanding the system errors and find adequate solution to mitigate these errors.

- **Failure to understand (Level 2 and Level 3)**

In addition to delays in detecting that a problem has occurred necessitating intervention, operators may meet difficulties to develop sufficient understanding of the situation and to overcome the problem. Particularly, we observe a significant period of time to reorient themselves to the current state of the system after a failure. For example, Wickens and Kessel [41] demonstrate longer system recovery times and poor response accuracies for operators who had been removed from control loops in advance of critical events requiring intervention. This delay may prohibit operators from carrying out the very tasks they are required to perform or diminish the effectiveness of actions taken. Further, during failure modes, operators who have been removed from system control may not know what corrective actions need to be taken to stabilize the system and bring it into control. Several examples of incidents and accidents resulting from these system misunderstandings have been reported ([42],[43]).

"Automation surprises" are a direct instantiation of these difficulties in automation understanding and take-over situations [44]. Automation surprise is said to occur when the automation behaves in a manner different than its operator expects. When interaction with automated system, human operator will develop a mental model of the system's behaviour and use it to anticipate how the machine will behave in the near future. However, with increase in system complexity, it is sometimes difficult for the human operator to track the activities of their automated partners. The result can be situations where the operator is surprised by the behaviour of the automation asking questions like, what is it doing now, why did it do that, or what is it going to do next. These "automation surprises" are particularly well documented (e.g., [45],[46]) and have been listed as one of the major cause of incidents (see for example [47]).

These two types of SA problems (failure to detect and failure to understand the problem) have been hypothesized to occur through two major mechanisms:

(1) Changes in attention/vigilance mechanisms and;

(2) Changes in the information available to the human operator.

4.2.2 Changes in attention/vigilance

As previously explained, automation technology will profoundly change ATCOs' role. This new role will lead to an increasing demand on the ATCo to monitor systems for possible failures. Precisely, insufficient monitoring and checking of automated functions is one important behavioural aspect of the OOTL performance problem, (i.e. information on the status of the automated functions is sampled less often than necessary) (see for example [20],[24]). In the following sections, we would like to show how decrease in vigilance could explain operator failures to perceive the environment and understand the system.

As research on vigilance has shown, humans are poorly suited for monitoring role [48]. As illustration, reports of incidents in aviation domain have notably highlighted the role of vigilance decrement in human error. For example, Mosier and collaborators [49] examined NASA's Aviation Safety Reporting System (ASRS) database and found that 77% of the incidents in which over-reliance on automation was suspected involved a probable vigilance failure. Similarly, Gerbert and Kemmler [50] studied German aviators' anonymous responses to questionnaires about automation-related incidents and reported failures of vigilance as the largest contributor to human error.

Focusing on the Air Traffic Control domain, at the end of 90s the introduction of new concepts of automation, with the aim of enhancing the efficiency, capacity and safety of the whole ATM system, caused a great scientific interest in how such improvements could had also negative impacts, leading ATCos to make their performance worse. For instance, in the 1995 the Radio Technical Commission for Aeronautics (RTCA, [51]) proposed the concept of Free Flight (FF), as an operational concept emphasizing airborne self-separation with reduced ground-based control in the en route environment. Briefly, controllers would still be required to oversee separation assurance, intervene under emergency conditions and to monitor the transition of flights to managed airspace [52]. Nevertheless, following studies have shown that FF condition affected negatively the ATCo performance [[53],[54]. As already discussed before, there are many evidences about the negative impact of automation on the ATCos' situation awareness. In addition, Endsley and Rodgers [53] also found that ATCos, when involved in purely monitoring task, tended to commit more operational errors during those periods when they did not remember all the details of the aircrafts. In other words, such loss of memory could be seen as a consequence of inattention, induced by the high level of automation or, on the contrary, by long periods of high workload. In addition, in the same study came to light how sometimes ATCos committed operational errors because of an over-reliance in the system, i.e. a problem of complacency.

Kirwan in the 2001 [55] published an interesting review about the ATCos' role changing because of new automation concepts introduction in the ATM domain. Actually, he was not able to find an answer to the question if such automation would introduce more advantages or disadvantages. Anyway, it seemed very clear how vigilance would be one of the human cognitive processes more negatively affected by a purely monitoring approach to the work activities.

To summarize, two main sources could explain such decrease in vigilance: the inability to maintain a high level of vigilance in time and the complacency effect.

Difficulties to maintain high level of vigilance

One unintended consequence of automation for human operators is boredom. Indeed, highly automated environments require maintaining high levels of vigilance during a long period of time. In many phases of operation, operators are reduced to monitoring activities, waiting for the unlikely system anomaly. Resulting boredom increases the likelihood of operator distraction, which ultimately can affect system performance if operators miss or respond late to critical events.

Interestingly, several studies show that sustained attention over hours cannot be achieved [56]. Research on vigilance suggests that time on task decreases significantly the discrimination of infrequent and unpredictable signals from a noisy background of nonsignals ([57],[58]). For example, Thackray and Touchstone [59] showed an increase in detection times of about 50% after 1 h on task when students had to detect conflicts manually in a simplified version of an air traffic control task whereas Hitchcock and collaborators [60] illustrates this vigilance decrement in time using a 40-min simulated air traffic control task Moreover, there is some consensus for the existence of a decrease of human operator vigilance in case of interaction with highly automated system [61].Also, a study conducted by Rodgers and Nye [62] with a sample of American ATCOs found that a large percentage of system errors attributable to controller planning judgments or attention lapses occurred during conditions of low traffic complexity.

Warm et al. [63] noted that tasks requiring high levels of vigilance, rather than being understimulating, can be resource demanding and associated with high workload. Furthermore, if the nature of the ATCO role becomes too monotonous, controller motivation and/or vigilance may decline with concomitant effects on performance and error detection and correction. Straussberger and Schaefer [64] focused their research on the determining factors evoking and influencing monotony in ATC, founding that the controller's state of monotony is mainly caused by task repetitiveness and traffic load or traffic density. The authors claim that these task characteristics may interact with individual (e.g., age, experience, personality) and no-individual influences (e.g., characteristics of the work environment or organization) to influence or elicit monotony. This research can be considered as an initial step toward examining monotony in ATC from an individual differences perspective, thereby assisting in the personnel selection and training process of controllers as well as providing valuable insight into how these individual factors may lead to the long-term development of critical states. Analogous to the literature pertaining to conditions of task overload and ATCO performance, there is also evidence to suggest that task underload may result in controller performance problems [65].

In conclusion, both change in vigilance level and deterioration of the attentional mechanisms could cause degradation of the monitoring process involved in supervisory task and decrease performance of ATCos in failure detection and system understanding. However, the current scientific evidences about vigilance are mainly based on studies in strictly controlled laboratory environments [66]. The question of when vigilance decrements in operation environments occur and when not remains vital today [67], in part because there is the need of greater clarity if we hope to apply findings from the laboratory to modern tasks requiring sustained attention [68], and consequently develop Human-Machine Interaction –based systems able to support the Controller in his working activity, as MINIMA aims to do.

Over-trust / complacency

Together with this difficulty to maintain high level of vigilance in time, decrease in vigilance could result from an overreliance on automation, the so-called *Complacency phenomenon* [69]. Complacency defines the cognitive orientation toward high reliability automation, particularly prior to the first time it has failed in the user's experience. It illustrates the so-called automation misuse. This, together with their opacity and complexity, can lead operators to rely unquestioningly on automation ([35],[70]).

Several real cases illustrate this phenomenon. A first example is the case of the dramatic crash of Northwest Airlines at Detroit Airport in 1987. The McDonnell Douglas MD-80 crashed due to improper configuration of the flaps and slats of the aircraft. All persons were killed because an automated take-off configuration warning system, which the crew relied on, failed to function. They did not realize the aircraft was improperly configured for take-off and failed to check manually [70]. In another instance reported by the National Transportation Safety Board (NTSB), an automated navigation system malfunctioned and the crew failed to intervene, allowing the Royal Majesty cruise ship to drift off course for 24 hours before it ran aground [71]. A third example is reported by Sparaco [72] where pilots, trusting the ability of the autopilot, failed to intervene and take manual control even as the autopilot crashed the Airbus A320 they were flying.

In these different cases of automation error, when computer control facilities failed, operators, out of the direct control loop, were unaware of the state of the system and encounter difficulties to compensate for the failure mode before an accident occurred. As illustrated here, overreliance or complacency is created as operators form beliefs of the technical system as being more competent than it actually is [73]. This overreliance on automation represents an important aspect of misuse that can result from several forms of human error, including decision biases and failure of monitoring [35].

This phenomenon is directly linked to the concept of trust. The concept of trust in automation describes to what extent an operator relies on an automatic control system. The role of trust in human-automation interaction has been the focus of much research over the past decade (for a comprehensive review, see [73]). It has been proved that high levels of trust in automation that is not perfectly reliable lead to overreliance and failure to monitor the “raw” information sources providing input to automation – so-called complacency.

The first empirical evidence, in a controlled setting, of poor monitoring resulting from an overreliance on or excessive trust in automation was the study of Parasuraman and colleagues [69]. They tested non-pilot participants on a laboratory flight simulation task consisting of 2D compensatory tracking, probability monitoring of engine status, and fuel management. In the multiple-task condition, participants performed the tracking and fuel management tasks manually, and an automation routine detected and fixed engine malfunctions. In the single-task condition, participants had only to “back up” the automated engine status task. The automation routine would fail from time to time. Participants were responsible for detecting these failures and for making the appropriate response to fix the malfunction. Although participants normally had a detection rate of over 70% when performing the engine status task manually (a baseline condition), their detection rate substantially declined when performing the task with the automation routine in the multitask condition. Interestingly, the effect was absent when there were no other manual tasks, suggesting that complacency reflects attention allocation away from the automated task to other concurrent tasks ([75],[76]).

Furthermore, it is predicted that to resolve aircraft conflicts, ATCos will simply observe a conflict resolution display and select the most operationally suitable option [79]. However, operators make fewer eye movements to the raw information sources when using automation than under manual control reflecting allocation of attention to other concurrent tasks [80]. Further, when an explicit tool to uncover the raw data is provided to the operators, they use the tool less often under automation than under manual control [81].

In contrast to vigilance decrement with time, we found few experimental studies related to automation and complacency phenomenon in ATC domain. Hilburn and Flynn [77] examined 79 ATCos’ attitudes toward future automation needs, system development issues, and operational requirements and found that 18% of controllers sampled mistrusted technology, leading the operators to ignore the system entirely. Stedmon et al. [78] examined issues underpinning the potential move in aviation away from real-speech radiotelephony communications toward data-link communications involving text and synthetic speech communications. It was found that participants placed a greater level of trust in real (old) speech than in synthetic (new) speech. Moreover, the importance of trust in automation has been also underlined when considering the potential benefit of automation in ATM [82]. It is clear that the benefit of automation cannot be obtained if the ATCos do not trust and use the automation appropriately. Interestingly, benefit in terms of efficiency in air traffic management for students who were trained to trust automation has been proved ([83],[84]).

The previous section illustrates how the lack of ATCos involvement in automated systems control and the vigilance decrements induced would contribute to the loss of operator situation awareness. A second important factor explaining such degradation is the change/lack of system feedback.

4.2.3 Poor feedback

Until recently, we have considered that new technology could be introduced as a simple substitution of machines for people - preserving the basic system while improving it on some output measures. Unfortunately, such assumption corresponds to a vague and bleak reflection of the real impact of automation: automation technology transforms human practice and forces people to adapt their skills and routines. Whatever the merits of any particular automation technology, adding or expanding the machine's role changes the cooperative architecture, changing the human's role, often in profound ways. Creating partially autonomous machine agents is, in part, like adding a new team member. One result is the introduction of new coordination demands and the emergence of new classes of problems which are due to failures in the human-machine interaction.

Particularly, the role of passive information processor involves observing the actions of other operators or computer controllers and agreeing or disagreeing with them. The key difference between passive information processing and direct action on the process is that the former involves functions similar to those maintained during process monitoring (e.g., scanning information sources); whereas, the latter involves manual control functions including process planning, decision making, selecting responses and implementing strategies. To direct and manage the development of events and thereby stay in control in supervisory condition, a human operator has to engage in closed- and open-loop control. Closed-loop control means that corrective actions are taken based on information from the feedback received from the control system as the process is undergoing. This means that the operator has to have a notion of the desirable state at a given time. The desired state (from mental model or procedure) is compared with the actual state and the action to be performed is chosen as to minimize the difference between these states. The feedback-evaluation-action (or perception-decision-action in Neisser's terms) cycle is continuous over time.

In this condition, understanding the actions of the automated system is central for human operator. However, as previously discussed with the concept of "Automation Surprise", such understanding is difficult to obtain. The lack of system predictability is certainly a central point in understanding OOTL phenomenon and associated difficulties of takeover as underlined by several authors (see for example [84],[85]). With the progress of technology, current man-made complex systems tend to develop cascades and runaway chains of automatic reactions that decrease, or even eliminate predictability and cause outsized and unpredicted events. This is what we may call "system opacity": the difficulty for a human operator to have a clear idea of the system's intentions and to predict the sequence of events that will occur. In that sense, the main problem with automation is not the automation per se, but rather its inappropriate design within the human-computer interaction [85]. For example, previous studies have showed that ATCo performance can be compromised when ATCo do not have ready access to aircraft intent information ([86],[87]).

Although such difficulties have been identified for a long time, how to design more predictable systems remains a critical challenge.

4.2.4 Motor abilities

Together with the decrease in SA, a second factor is crucial to understand performance problem associated to OOTL phenomenon, and particularly problem of recovery in case of system failure. Indeed, out-of-the-loop performance problems are characterized by a decreased ability of the human operator to intervene in system control loops and assume manual control when needed. In a review of automation problems, Billings [88] noted six major aircraft accidents that could be traced directly to failures in monitoring automated systems. One of the most easily imagined consequences of automation is a loss of skills by the operator.

Loss of skills can be defined as the deterioration of manual and cognitive skills and knowledge due to the use of automatic control systems that reduce the possibility to practice manual tasks. It is now well accepted that the lack of control involvement contributes to the loss of human manual control skills for process or automated system error recovery (see for example [73]). Loss of skills and knowledge occurs as a result of operators not getting the chance of performing manually the tasks that have been automated. This leads to deterioration of the physical task performance skills. The operator's mental representation may also fade if it is not regularly used and maintained, thus loosing cognitive skills [89]. Many crew members report to have discovered this on their own and regularly turn-off the autopilot, in order to retain their manual flying skills.

If the use of automation will probably result in a decrease in the skill level for well learned manual tasks, there is also a concern that operators, who use an automatic control system from the beginning of their career, will never have the chance to acquire the skills and knowledge needed in case of automation failure where manual control becomes necessary.

Nowadays, such degradation is not currently observed for ATCo thanks to the relative few level of automation. However, as argued by several authors (see for example [90],[55]), we can assume that it will be the case in the next future.. Together with this performance decrement, another class of problem is associated with OOTL performance problem, namely the psychosocial aspect. Even though psychosocial aspects linked to automation have known few interests, we consider their impact as crucial for the future of the automation technology.

4.3 Psychosocial aspects of OOTL

Often neglected, the psychosocial aspects of automation may prove to be the most important of all, because they influence the basic attitudes of the operator toward his task, and, we would presume, his motivation, adaptability, and responsiveness. The significance of these questions lies not in the spectre of massive unemployment due to assembly line automation, but in the effects of automation on the changing role of the human operators.

4.3.1 Automation acceptability

Improving acceptance of new technology and system by human operators is an important area of concern to equipment suppliers [91]. To be acceptable, new technology must be reliable, efficient and useful. Although performance and preference are often positively correlated [92], high levels of performance do not guarantee the user acceptability. Further, it appears that users indeed tend to reject systems that enhance their performance in favour of systems that are less efficient but more acceptable. For instance, Inagaki et al. [93] showed that drivers preferred collision warnings than automated control, which tends to be misunderstood, even when automated control provided led to better performances.

As pointed by Shneiderman and Plaisant, [94], users “strongly desire the sense that they are in charge of the system and that the system responds to their actions”. Increase in automation has the potential to seriously threat this sense of control, as confirmed by Baron when he claimed:

> *“Perhaps the major human factors concern of pilots (or more generally, of human operator) in regard to introduction of automation is that, in some circumstances, operations with such aids may leave the critical question, who is in control now, the human or the machine?”* [95].

This is not a simple question, and it is certainly not merely a matter of human operators’ self-esteem being threatened by the advance of the machine age. “The question goes to the very heart of the nature of acting, the seemingly divided authority between human and machine, and mainly, what is the role of the human operator as minder of equipment that is not only increasingly sophisticated but increasingly autonomous” ([70], p.452).

Empirical evidence of such decrease in sense of control associated to increase in automation has been recently proposed by Berberian and collaborators [96]. By manipulating the level of automation in an aircraft separation task, they have found a decrease in agency (i.e., the feeling to be an intentional agent of the situation) concomitant to the increase in automation. They argued that the interposition of increasing automation between operators and automated systems tends to disrupt operators from action outcomes, decreasing their sense of control. Further, recent evidence shows a direct relation between this decrease in sense of control and system acceptability.

A major challenge in the Human Computer Interaction community with the next generations of highly automated systems is precisely to determine how to compensate this decrease in the sense of control and acceptability. If the operator does not trust the automation to perform what is needed in a sufficient manner, automation is likely to be abandoned and the advantages of the automatic system may be lost and economic benefits reduced. The lack of sense of control could cause such automation distrust [35].

4.3.2 Ethics

A second concern relates to ethical problems. The interposition of more and more automation between the ATCos and their system will distance human operators from many details of the operation. We can illustrate such evolution regarding the place of the pilot in modern aircraft. Todays, pilots are isolated from most of the physical structures of the system. In the same time, the automation tends to isolate the crew from the operations of the system. The automatic equipment monitors and controls it, providing little or no trace of its operations to the crew, isolating them from the moment-to-moment activities of the system and of the controls. This combination of relative physical and mental isolation tends to distance the human operator from the results of their action. At the extreme, some pilots argue that automation reduces the status of the human to a “button pusher” [97]. A same evolution should arise for ATCos.

Crucially, this form of disengagement regarding the result of the action has the potential to disturb the mechanism classically used to regulate human behaviour. Indeed, different works have proved that involvement in the consequence of your action is a necessary condition to act with ethics, to act with moral judgement ([98],[99]). Military robots are a perfect illustration of this ethical issue. Autonomy of this robot increases in same time than the technology progress. If the last decision remains to the operator at the moment, the distance (physically and cognitively) between human operator and its action clearly ask question, for the society in one part, but also for the operators themselves.

4.3.3 Penal Responsibility

A third concern relates to the penal responsibility of ATCos in case of incident. It is well accepted that we have to control our action, intentionally, to be judged as responsible. With the interaction with highly automated system, the notion of responsibility becomes less clear. If automation technology decreases human operator performance, what about the responsibility of ATCos in case of incident?

This is particularly important in safety critical systems and in semi-automated systems where a human supervising the task is held responsible for task failures. With the expected next generation of ATM system, this penal issue should become a major concern. These difficulties point to a paradoxical situation where the human operator is replaced by automation technology in the loop of control and the automated technology is designed in a way that complicates the transfer of control from the machine to the human in takeover situations. Nevertheless, system designers and safety authorities consider the human operator as the last barrier in case of system failure. For example, the federal aviation administration (FAA) clearly states in their general operating and flight rules that “the pilot in command of an aircraft is directly responsible for, and is the final authority as to, the operation of that aircraft” (14 CFR Part 91). A same approach is adopted in automobile sector (see Vienna Convention on Road Traffic). We can imagine a similar position of safety authority in ATM.

This paradoxical situation gives rise to a critical issue: what about in case of system failure, how guarantee the capacity of ATCos to take over the system? In this context, until automation becomes powerful enough to handle all abnormalities, enabling more efficient transfer of control from system to ATCos in case of system failure will become a major issue.

During this section, we have shown how the lack of operator involvement in process or automated systems control in supervisory modes and passive information processing will contribute to critical human cognitive errors (OOTL performance problem). We have also argued that the transformation induced by automation could change the way the ATCos will interact with their environment and create psychosocial issues. In the following section, we aim to present the different solutions currently proposed to mitigate the negative impact of the OOTL performance problem.

5 OOTL mitigation and current solutions

Solutions for solving the OOTL-Problem are diverse. Following the perspective of an "interaction Problem", a solution can either target at the system or target at human operators to make them less prone to OOTL-Problems.

One solution for OOTL-Problems targeting at human operators is Training. Human Operator can be explicitly trained for situations in which OOTL-Problems can occur. For example Bahner, Hüpner and Manzey [100] showed that a preventive training in which participants were exposed to rare automation failures could significantly decrease complacency in a laboratory experiment using a process control simulation (see also SESAR ER *AUTOPACE* project). Moreover, student ATCOs who were trained to trust the automation reported lower workload levels under some conditions [83] and benefit in terms of efficiency [82] compared to students who were not trained to trust the automation.

Another solution targeting at the Operator is a careful selection of Human Operators. Today, Air Traffic Controllers are carefully selected based on the key ability required in today's working environments. As operators will have to work with increased level of automation, the ability to monitor automated systems and to switching immediately form monitoring to decision making will become core competencies for ATCOs. This should be considered during the selection of future ATCos [101]. However, this solution would take some time to become effective and its effectiveness has to be proven. Another important aspect concerns the used of personality traits in ATCo selection. Personality traits have shown to predict ATCo performance ([102],[103]). Interestingly, Hoff and Bashir [104] have shown that people with high emotional stability and low neuroticism are more likely to rely on automated systems in general. A same trend is observed by Miramontes et al. for ATCo. Particularly, they found that people with high emotional stability reported higher levels of trust in automation.

As OOTL-Problems are caused by changing the system and introducing higher levels of automation, it seems likely that it can also be solved by properly designing the new system. As a guideline for this, MABA-MABA (Men Are Better At-Machines Are Better At) list have been developed (e.g. [1]). These lists consider all task and the capability of the agents (human and machine) individually. Tasks shall be assigned to agent who can better perform this type of task. However, Dekker and Woods [105] argue that MABA-MABA-like methods – they explicitly include the levels of automation proposed by Parasuraman, Sheridan & Wickens [5] as a design guideline – are misleading as automation often has unexpected effects. These include the OOTL-Problems discussed above. The reason is that introducing automation does not simply transfer the execution of functions from the human operator to the machine but creates completely new functions and transforms people practices. They conclude, that it is important that automation needs to support cooperation with their human operators – in standard and unexpected situations. This can be achieved if automation:

- makes their activities observable,

- is easy to direct,
- uses event-based representations that highlight changes,
- is future oriented and supports the operators for anticipating changes and,
- uses pattern-based representations so that difficult cognitive work is not required.

Also Rieth, Cool and Ngo [106] argued for better design of Human-Machine-Systems. They showed that the visual salience of standard indicators "generally do not draw attention to the information needed to identify emerging problems" and suggested other formats which better map the task-relevance of information to the visual salience of how it is displayed.

A holistic approach is to develop automation in such a way that it can be seen as a partner. Human operator and automation should form a team that works cooperatively together, in a highly adaptive way to achieve its objectives. They have to adapt to each other and to the context in order to guarantee fluent and cooperative task achievement. Klein and collaborators [107] defined ten challenges that have to be solved in order to make automation a team player. According to them, an automation that can be considered as a team player must have a basic compact, model the others' intentions, be delectable, make their status and intentions obvious and be able to interpret the status and intention of others, be able to engage in goal negotiations and enable a collaborative approach, be able to participate in managing attention and help control the costs of coordinated activity.

A technical solution for some of these challenges is the concept of adaptive systems which is introduced in the following.

5.1 Introduction to Adaptive Systems

A system that can be considered as cooperative must be able to adapt to the needs and the state of the user in real time. It is able to meet the changing needs of operators often without requiring the human operator to explicitly state his needs or trigger the adaptations. Making a system adaptive enables it to behave like a good human assistant.

The concept of Adaptive Automation concentrates on the dynamic allocation of function between operators and systems. This means, in that the Level of Automation of such system is not fixed but is adapted during the runtime according to the current needs of the operator.

Adaptive and Adaptable Automation can be distinguished based on the authority to change to allocation of functions [108]. In Adaptable Automation, the user is in charge of changing the allocation of function. In Adaptive Automation, the system triggers changes. From the perspective of the framework of Adaptive System, these two approaches differ in the applied trigger mechanisms. While Adaptive System uses the measured operator state as a trigger mechanism, adaptable systems use explicitly operator actions as trigger mechanism.

Newer characterizations of Adaptive Systems extend this view and do not only consider adaptations of the function allocation and but also include many more types of adaptations like the adaptation of the detail or the modality in which information is presented. Feigh, Dorneich and Hayes [109] developed a two-part framework for the two main components of Adaptive Systems – adaptations and triggers. Adaptations describe what aspect of the system is actually adapted and how the behavior is changed. Triggers used by the system determine if and when it should adapt its behavior.

Very similar to the concept of adaptive systems is the concept of augmented cognition. It aims at a tight coupling between user and computer via physiological and neurophysiological sensing of user's cognitive state to take advantage of knowledge about cognitive state to adapt user-system interaction. In their overview, Stanney et al. [110] describe cognitive state sensors (which can be considered as operator-based trigger mechanisms) and adaptation strategies used in augmented cognition approaches.

A further similar concept is the concept of adaptive interface. Rothrock et al. [111] developed a classification of adaptability types and variables calling for adaptation (from the perspective of adaptive systems: triggers) for this concept.

In the following different kind of trigger mechanisms and different kind of adaptation strategies that haven been used for adaptive systems are presented. The term adaptive systems will be used as a general term in the following. Augmented Cognition systems, adaptive interfaces and other approaches will be considered as specific kinds of adaptive systems. Types of Adaptation describe ways a systems behavior and interface can be changed. Trigger mechanisms define when these adaptations should occur. Additionally a control framework is necessary that defines how to connect the trigger with the adaptations.

5.2 Types of Adaptation

Function Allocation: As the OOTL-Problems arose as a result of automation, one obvious solution would be to reduce the Level of Automation again. As in most of the cases the benefits of automation would be lost, this is not a reasonable solution. In adaptive systems however, the allocation of function between human operator and automation can be adapted dynamically. In some situations tasks are executed automatically, in other situations the same tasks is executed manually by the human operator. In other words, the Level of Automation of these systems is not fixed but changeable during operation. Such system can give the human operator the most appropriate level of control for a given situation.

Many names have been used to refer to systems that can adapt the allocation of functions dynamically, for example Adaptive Automation [112], Adaptive Function Allocation [113] and Adaptive Aiding [114].

The dynamic allocation of Functions allows to profit from the benefits of higher levels of automation and also to reduce OOTL-Problems. As the operator takes over some tasks from time to time and executes them manually, skill degradation can be reduced. For example in some airlines, pilots are encouraged to switch of the FMS during approach if possible in the current situation and to fly the approach manually to maintain their skills. A lot of Research was carried out to analyze the effects of adaptive function allocation. For example it was shown that adaptive system can improve situation awareness and workload [115] and it was demonstrated that an adaptive system can prevent a decrement of vigilance [116].

Task Scheduling: Adaptive system can support human operators in multi-task environments by regulate the timing and prioritization of tasks. The timing of tasks refers to the time when tasks are initiated. To find the best timing for tasks is a difficult challenge for human working in complex environments [117]. An adaptive system can support here by internally generating an optimal schedule for task performance and giving information about task to the operator just in time.

The system could also assess the priority of tasks, which varies depending on the given situation. The priority of tasks can not only be used for the scheduling of tasked as described above but also to decide if a task should be executed at all.

It should be noted that task scheduling will only withhold information about tasks and cannot manipulate the overall task load. Thus, a backlog can develop. If this backlog cannot be reduced, it will eventually overload the operator and a successful execution of all tasks becomes improbable.

Strategy: Humans can adapt their working strategies to scope with the characteristics of the current set of tasks. In an early work by Spearandio [118] conducted in the context of Air Traffic Control it was demonstrated that human operators select their operative methods based on the tasks to be carried out so that they are efficient from the point of view of performance and are economical from the point of view of workload. When the load is high, they switch to more economical methods and when the load is low, they switch to methods aiming at a better refinement of the solution or aiming to maintain a level of activity. Although, ensuring safe operations is the main goal of air traffic control, safety was not explicitly mentioned.

More recently, Kallus et al. [119] also analyzed the strategies of air Traffic Controllers. They included the aspect of safety and defined the Task load-Efficiency-Safety-Buffer Triangle. In this context, “safety buffers are additional risk-reducing factors… to increase safety beyond tolerable risk”. They observed that in most cases an increase of workload was accepted to stabilize safety buffers (44% of all cases) and efficiency (50% of all cases). On the other hand also strategies accepting a decrease of efficiency (5% of all cases) or a decrease of safety-buffers (4% of all cases) to stabilize workload were observed.

When designing an adaptive system it should be consider that human operators do not always apply the same strategy but adapt them. Thus, it is necessary that the adaptive system is able to handle a change of the strategy initiated by the human operator. Moreover, in order to apply the strategy that best fits to the current situation the adaptive system could suggest this strategy and encourage the operator to accept it.

The adaptation of the strategy is a way to influence the workload without changing the level of automation. Only if free capacity is available, a strategy aiming at a higher efficiency or safety should be selected and if the workload is low, a strategy with requires more effort can be selected.

Presentation of Information: In order to amplify human capabilities an Adaptive System can change the presentation of information. This type of adaptations changes the way how information is presented, but it does not change the information itself. To change the presentation of information, an Adaptive System can change the layout of information, the modality or the interaction style.

Presented information can be grouped or the spatial separation between relevant and irrelevant items can be increased, which has been shown to increase performance [120]. Also the position of important information can be changed to reduce search time. However, this behavior must be clear to the operator so that he knows when and where information will be located.

According to Wickens's multiple resource theory separate resources are used for visual and auditory modalities and for focal and ambient visual channels [121]. By presenting information at the most readily available modality and visual channel or using more than one modality for the same information (modality redundancy) the resources can be utilized in the best way.

An adaptive system may also change the interaction style and change whether information is presented in any case or if it has to be requested by the operator. This can be used to display just the most relevant information in high workload information, but this comes with the risk to hide information the operator needed. Thus this method would even increase his workload.

Guidance of Operator Attention – An adaptive system can also augment the show information in order to guide the attention of the human operator. For example the system can apply cues to guide the operators' attention [122] and increase the salience of information (e.g. by highlighting them). Cues can be applied very flexible as their modality, form and intrusiveness can be selected according to the requirements of a given situation [110]. One benefit of cues is that they do not alter the original information. As cues interrupt operators and make them to refocus their attention, the timing of cues has to be selected very carefully. Operators should ideally be interrupted between to tasks or when their workload is low [123].

Content - While the adaptation of the interaction and presentation just describes different ways to transfer the same information, a modification of the content would actually change the information transferred exchanged in the interaction. Changes of the content can refer to changes of the quantity, changes of the Quality or Abstraction of the information. The quantity of information results from the decision whether to show information at all. For example, by showing only selected information may help the operator to focus on the important tasks. However, this adaptation comes with the high risk of hiding relevant information and making it more difficult or even impossible for the operator to complete a task. If only a limited band-width is available for transferring information to the user interface, the quality of the information can be reduced to ensure that the information is shown in time. Examples are the color-resolution of figures, sampling rate of audio-messages or the bandwidth of videos. Furthermore, the abstraction of information can be modified or information can be aggregated with the intention to reduce the time the human operator needs to process it.

System Autonomy - Autonomy is about the responsibility for the assignment of task. It's is about who can give orders and who has to accept them. The Autonomy of the system is not changing if the human operator decides to hand over some tasks to Automation. In contrast, the Level of Automation is increasing in this case. The Autonomy in Human-Machine-Systems has to extremes: The human operator has the full authority or the system has the full authority. Three points on the continuous scale between the two extremes are called "management by delegation", "management by consent" and "management by exception". Following the principle of "management by delegation", automation is carrying out some tasks related to tactical decision of the operator when instructed to do so by the operator. The principle of "management by consent" refers to automation that is provided with goals and that will perform the actions to achieve these goals but asks for consent before starting specific tasks. This principle shall keep pilots involved and aware of systems intent. Finally, the principle of "management by exception" describes automation that is able to perform all tasks and will execute them unless the operator intervenes [124]. There are various types of "management by exception" giving the operator more or less time to intervene or requiring more or less effort to intervene.

5.3 Trigger mechanisms

Operator Initiated: The simplest method for triggering an adaptation is direct operator input. If only this trigger mechanism is applied, all adaptations of the system are under human control. The operator remains in charge and is responsible to adapt the system during system operation according to his/her current needs. Thus, the system is adaptable as opposed to adaptive according to the definition of Scerbo [108]. This method requires input, time and attention which may not be available, especially in high workload situations in which assistance might be most necessary. Additionally, the operator might not select a suitable task sharing to avoid the OOTL problem, for example due to overtrust in the system. To apply this mechanism, the delegation interface has to be carefully designed. It determines how easy and flexible the automation can be used. For example Miller and Parasuraman [125] suggest designing such an interface based on a shared hierarchical task model in order to mirror delegation to an intelligent assistant.

Operator Measurement: As the aim of adapting the system is to control and stabilize the state of the operator, adaptations can be triggered based on the measured cognitive state, for example on workload, vigilance, fatigue or stress. It is essential to reliably measure the cognitive state of the operator, but it cannot be measured directly. However, changes in cognitive state are related to physiological and neural activations that can be measured with sensors. Sensors that can be used for this purpose have a wide variety of characteristics: physiological or neural activation that can be observed, temporal resolution, spatial resolution, accuracy and level of intrusion. For example, EEG (Electroencephalography) can be used to measure electrical neuronal activities. Based on this, event-related potentials (ERPs) can be derived. Further, functional near-infrared spectroscopy (fNIRS) can be used to measure brain activity through hemodynamic responses. Moreover, peripheral sensors can be used to measure continuous variation in the electrical characteristics of the skin (electrodermal sensors) and the eye activity (oculomotor sensors). Furthermore, cardiovascular parameters like the heart rate and the blood pressure can be measured. These sensors and their suitability to measure the cognitive states considered in MINIMA, namely vigilance and attention, are discussed in detail in chapter 6.

Operator Modelling: Operator modelling can be applied if the measurement of the operator state is not possible or feasible, for example because it is too intrusive or costly. However, operator modelling also aims to infer about the information processing state of the human operator, e.g.

about intentions and situation awareness. Thus it can provide information that cannot be obtained by operator measurement.

Performance models that can be used to evaluate present goals, present and future behavior, situation awareness and workload can be based on data bases and rule bases. For example, a data base of a set of tasks can be combined with a rule base to assess the workload in different task configurations. Such a model was recently developed within A-PiMod project as part of adaptive cockpit to improve pilot-cockpit cooperation [126].

Models can also be based on theories of human performance like signal detection theory, queuing theory, sampling theory and control theory.

Also Wickens's multiple resource theory can be applied to operator modeling. According to this theory separate resources are used for visual and auditory modalities and for focal and ambient visual channels [121]. For example, this theory can be combined with a data base of a set of tasks as described above. Such a model will predict a performance reduction if two or more tasks require the same information processing resources.

System and Environment: Adaptive Systems can also apply trigger mechanisms based on the state of the system. For example, adaptations can be triggered if the state of the system reaches predefined thresholds or if the system enters a specific mode. Further, if a model of the system is developed, adaptations can also be triggered based on anticipated changes of the system's state or mode. In a similar way, adaptations can be triggered by environmental states or events.

Task and Mission: The progress of a specific task or of the complete mission can also be used as a trigger mechanism. For example, adaptations can be activated if a task is initialized or completed or if the mission reaches an intermediate goal. The challenge when implementing this kind of trigger mechanism is to detect the status of tasks and mission.

Spatiotemporal Triggers: Spatiotemporal triggers are relatively simple trigger mechanisms. For example, adaptations can be engaged and disengaged with a fixed frequency. Hilburn et al. [127] analyzed the benefits of high versus low frequencies. Further, adaptations can be triggered by absolute positions of the system (for example GPS location of an aircraft) or relative positions (for example distance between two aircraft).

5.4 Control Framework

To activate and deactivate adaptations often thresholds are defined. If a value considered as a trigger exceeds the threshold, the adaptation is activated. If it falls below the threshold, it is deactivated. However, using thresholds has some drawbacks.

When applying trigger mechanisms based on the state of the operator, the operators' state influences the adaptation of the system. An adaptation of the system in turn affects the operators' state. Thus, a loop is closed. To ensure these systems are robust and stable a control framework is necessary. In other word, noise related to the measurement of operators' states should not trigger adaptations. Further, fast oscillations of an adaptation should not occur. This effect can appear if simple thresholds are used to activate and deactivate adaptations. For example, a physiological indicator exceeds the threshold, an adaptation is triggered which brings the physiological indicator below the threshold and the adaptation is immediately turned off. This in turn will result into the physiological indicator to increase again. Finally, the adaptation will be engaged and disengaged with a high frequency.

However, as pointed out by Stanney et al. [110], most adaptive systems today apply simple threshold-based control frameworks and there is a need for the development of sophisticated control frameworks. Such a control framework could be based on engineering control system theory. This theory provides tools for analyzing and designing the properties of closed-loop systems. Most of these tools require a model of controlled loop system. Thus, to apply this theory, it must be understood in detail how adapting the system influences the cognitive state of the operator and the measured physiological indicators.

5.5 Examples for Adaptive Systems

An example for an Adaptive System is the system developed within the Aviator 2 project [128]. In this project, assistance functionalities for ATCOs were switched on and off depending on the ATCO's current workload. Two display functionalities have been used: Turn-to-base countdown of approaching aircraft and an aircraft distance control mileage for a runway centerline. The self-assessed workload on a traffic-light scale was the basis for adaptive functions with three different levels. Level 1 did not foresee any additional controller support. Level 2 activated the mileage display. In level 3, the turn advisory at the aircraft radar label was switched on. This system used an operator initiated trigger and adapted the content of the interaction, specifically the abstraction (in Level 2 the distance between aircraft shown on the mileage display is an abstract way the distance already available on the main radar screen), respectively quantity (in Level 3 the turn advisories are shown additionally).

Also the attention assistants known from the automotive domain are adaptive systems even though the adaptation is very limited. In a system developed by Daimler (2016) various parameters such as time of day, duration of travelling, speed, steering wheel movements, vehicle accelerations or use of technical devices are taken into account to detect fatigue of the driver. This profile is compared to the drivers' profile of the first quarter hour of his journey. After showing certain signs of fatigue, the driver may get a visual or acoustic warning. This system used an operator model to infer about the fatigue based on the observable behavior and adapts the content of interaction by issuing a warning.

6 Measuring: focus on attention/vigilance

One of the main goals of the MNIMA project is to provide solution to compensate the negative impact of the OOTL performance problem and improve human performance in monitoring task. Particularly, we aim to design a module, called the adaptive task activation module, able to modify both the level of automation and the feedback sent by the automation technology in order to maintain the ATCos in the loop of control and improve their performance in monitoring task. This kind of adaptive automation (AA) has recently been proposed as an alternative approach to static, or traditional, automation.

Given the problems associated with automation noted above, researchers and developers have begun to turn their attention to alternative methods for implementing automated systems. Amongst other, *Adaptive Automation* has been proposed to address some of the shortcomings of traditional automation. In adaptive automation, the level of automation or the number of systems operating under automation can be modified in real time. However, a critical challenge remains: how changes among modes or levels of automation will be triggered. In other words, what should determine and "trigger" allocation of functions between the operator and the automation system. Four major invocation techniques have been proposed [112]. (1) Changes among modes could be engaged regarding the presence of specific tactical events that occur in the task environment. (2) Another approach would consist to estimate operator performance in real time and use deviations from acceptable ranges to invoke the automation. Specifically, changes among modes or levels of automation are triggered by a set of criteria or external events. Thus, the system might invoke the automatic mode only during specific tasks or when if it detects an emergency situation. (3) Alternatively, models of operator performance or workload could be used to drive the adaptive logic. For example, a system could estimate current and future states of an operator's activities, intentions, resources, and performance. Information about the operator, the system, and the outside world could then be interpreted with respect to the operator's goals and current actions to determine the need for adaptive aiding. (4) The last method for implementing adaptive automation described by Parasuraman et al. [112] uses psychophysiological measures to trigger changes among the modes of automation. Under this method (i.e. biopsychometrics), physiological signals that reflect central nervous system activity would serve as a trigger for shifting among modes or levels of automation.

In MINIMA project, we propose to focus on biopsychometrics for several reasons. First, the measures can be obtained continuously with little intrusion. Second, it is difficult to measure resource capacity with performance indices because behaviour is often at a low level when humans interact with automated systems. Finally, these measures have been found to be diagnostic of multiple levels of arousal, attention, and workload. Even if there are still many critical conceptual and technical issues (e.g., making the recording equipment less obtrusive and obtaining reliable signals in noisy environments), numerous works have proved that it is indeed possible to obtain indices of one's brain activity and use that information to drive an adaptive automation system to improve performance and moderate workload in complex environment (see for example [129],[130])

In this context and regarding the fact that the vigilance decrement is a first concern in OOTL phenomenon (see part 4), we propose to develop a real time “Vigilance and Attention Observer” using biopsychometrics to monitor the state of the human operator and drive our adaptive automation. Why and how will be developed in the following sections.

6.1 Attention/Vigilance: A major issue in OOTL phenomenon

6.1.1 Some definitions

Let us begin by defining the following concepts: Vigilance, Arousal and Attention

The term *vigilance* has been used in different ways. Psychologists and cognitive neuroscientists use the term to describe an ability to sustain attention over a lengthy period of time under monotonous stimulus ([131],[132])**.** Psychiatric clinicians use the term vigilance similarly but with specific focus to attention to potential threats or dangers. Hypervigilance is for example considered as a common feature of various anxiety disorders, including post-traumatic stress disorder. Clinical neurophysiologists use the term vigilance level to refer more specifically to arousal level on the sleep–wake spectrum without any mention of cognition or behavioural responsiveness.

Arousal refers to non-specific activation of cerebral cortex in relation to sleep–wake states. While vigilance as we have defined it is conceptually distinct from arousal, most research on vigilance has, in fact, studied alterations in arousal through the use of subjects who are sleep deprived, have sleep disorders, or are taking sedative medications. Alertness is another term that overlaps with arousal but more specifically includes some cognitive processing. Some researchers use the terms phasic and tonic alertness ([133],[134]). Phasic alertness relates to the orienting response and tonic alertness will be used synonymously to vigilance and sustained attention.

Attention usually refers to a more focused activation of cerebral cortex that enhances information processing [134]. If attention is more generally perceived as the appropriate allocation of processing resources to relevant stimuli [135], one aspect, sustained attention, is used synonymously with the most common usage of vigilance [132]. Particularly, the process of sustained attention refers to an individual’s ability to maintain their focus of attention and to remain alert to stimuli over prolonged periods of time [136], a definition closed to vigilance.

For our purpose, *vigilance or sustained attention* will be defined as the ability of organisms to maintain their focus of attention and to remain alert to stimuli over prolonged periods of time [137].

6.1.2 Vigilance decrement

There are numerous occupations in today’s society that require focused attention. Particularly, the need to remain alert and to detect infrequent but critical signals is crucial in many job activities, including air traffic control, nuclear power plant operation, or radar and sonar operation. A vigilance failure in any of these settings could have dramatic impacts.

If the ability to maintain the focus of cognitive activity on a given stimulation source or task is a crucial determinant of cognitive performance, fifty years of research on this problem reveals that vigilance performance is fragile. The most notable finding is that detection performance declines over time [131]. This decline has been called the vigilance decrement and is one of the most ubiquitous findings in vigilance research.

The neurologist Norman Mackworth [138] brought the first empirical evidence of this vigilance decrement. He began the systematic study of vigilance to determine why airborne radar and sonar operators on antisubmarine patrol missed weak signals on their displays signifying the presence of enemy submarines in the sea below, particularly toward the end of a watch. To study the problem, Mackworth developed a simulated radar display in which a black pointer made small jumps around the circumference of a blank-faced clock devoid of any scale markings to serve as reference points. Occasional larger jumps were the critical signals for detection in experiments lasting continuously for 2 hours. Using this display, Mackworth confirmed field-generated suspicions that vigilance wanes quickly. He found that the accuracy of signal detections declined by about 10% to 15% after only about 30 min and then showed a more gradual decline over the remainder of the watch period.

Subsequently, Mackworth's results have been largely replicated by both basic experimental psychologists and human factors researchers. If most of the decrement typically appears within the first 15 min of watch, it can also appear as rapidly as in the first 5 min when task demand conditions are high (see for example [139]). The vigilance decrement is found with experienced as well as naive operators and, counter to the claim that it may simply be an artificial laboratory phenomenon occurs in operational as well as laboratory settings [140].

The importance of vigilance decrement for understanding human performance in a variety of industrial and military systems is now largely accepted. Several studies have shown that accidents ranging in scale from major to minor are often the result of vigilance failures [141]. Hawley [142], for example, described the role of vigilance and situation awareness in fratricide incidents in the Iraq war involving the highly automated Patriot missile system.

Interestingly, vigilance decrement is also considered as one the major index of OOTL phenomenon (see part 4.2.2). In Minima project, we assume that both change in vigilance level and deterioration of the attentional mechanisms could cause degradation of the monitoring process involved in supervisory task. In this context, the aim of the operator vigilance and attention level observer is to measure both the current vigilance and attention levels of the human operator in view to quantify the OOTL phenomenon. In the following sections, we assess the possibility of attention monitoring using biopsychometrics.

6.2 Attention/Vigilance quantification

Monitoring vigilance/attention is a hot field since it is extremely useful to prevent some accident in performing attention-demanding and monotonous tasks. Several approaches have been proposed, from the analysis of system parameter [143] to physiological signal ([144],[145]). We will here focus on psychophysiological measure for different reasons (see previously).

Using psychophysiological measures in adaptive automation necessitate identifying relevant index of alertness and sustained attention. Several biopsychometrics have been shown to be sensitive to changes in vigilance suggesting them as potential candidates for adaptive automation such as electroencephalographic (EEG), near-infrared spectroscopy (NIRS), transcranial Doppler sonography (TCD), oculometrics, electrocardiogram (ECG) or skin electric potential (GSR). In the following sections, we will review each in turn.

6.2.1 Electroencephalography (EEG)

The rapid development of neuroimaging techniques offers multiple ways to measure the neural processes underlying attentional performance. Amongst these techniques, EEG is regarded as a “gold standard” of vigilance detection.

Electroencephalography (or EEG) is the recording of electrical activity produced by the firing of neurons within the brain. Electricity is the language of the brain: neurons communicate with one another via electrical impulses that regulate neurotransmitter release at chemical synapses. The coordinated activity of large neuronal ensembles creates electric currents large enough to be measured at the scalp surface with EEG.

Several studies have demonstrated the suitability of EEG for real-world monitoring of mental states and for brain-computer-interface (BCI) applications. For example, in the course of the project NINA (NINA homepage, 2016) a mental state classifier was developed to evaluate controller workload and learning progress based on, amongst others, EEG data ([146],[147]). The resulting workload classification index was used to adapt the automation very simply every 30 seconds.

Interestingly, EEG is assumed as one of the most reliable indicators of vigilance [148] and a number of EEG markers have been specifically correlated with vigilance based on two different methods: power density spectrum analysis and evoked potential technique.

Power spectrum & global level of arousal

The conventional methods employed to analyze the EEG generally involve computation of the power spectral densities (PSD) within the classically defined frequency bands (alpha, beta, theta, delta, and gamma) or ratios between these frequency bands. The EEG consists of a spectrum of frequencies between 0.5 Hz to 35 Hz (Surwillo, 1990). Delta waves are large amplitude, low frequency waveforms that typically range between 0.5 and 3.5 Hz in frequency, in the range of 20 to 200 *u*V. Theta waves are a relatively uncommon type of brain rhythm that occurs between 4 and 7 Hz at amplitude ranging from 20 to 100 *u*V. Alpha waves occur between 8 and 13 Hz at a magnitude of 20 to 60 *u*V. Finally, beta waves are an irregular waveform at a frequency of 14 to 30 Hz at amplitude of about 2 to 20 *u*V.

Interestingly, studies show that the changes in EEG spectrum are related to the vigilance state and a number of methods have been proposed to make accurate judgments of vigilance levels ([149],[150],[151]). Using multivariate EEG, Makeig and Jung [149] showed that a single principle component of EEG spectral variance was predictive of reaction time on a test of alertness. Of the several frequencies that load onto this component, it has been suggested that decreased beta activity is most strongly associated with vigilance changes. Later, Jung and collaborators [144] reported that full-spectrum EEG power was a marginally better predictor of reaction times than the single principle component, or any of its constituent frequencies. They proposed a model of estimating alertness based on EEG power spectrum principal component analysis (PCA) for EEG feature extraction, and artificial neural networks (ANN) for alertness modelization. Particularly, during maximal attention, some awake frequencies, e.g. alpha, are attenuated whereas beta activity increases. Similar results were obtained by Lin and collaborators [150]. The authors explore many experimental results to verify the relationship between EEG power spectrum density (PSD) and drowsiness. They observed that the power of alpha and beta rhythm in an alert state was greater than in a drowsy state (see also [152],[153]).

Nowadays, there is a very large literature concerning the relationship of oscillatory activity and attention/vigilance and brain dynamics associated to vigilance are well known (for in-depth reviews see [154]). Overall there is increased slow frequency activity (alpha and theta bands) on the EEG with decreasing vigilance whereas increasing vigilance induces an increase in beta activity. Several BCI systems have been designed based on this idea (see [155],[156]). For example, Brookhuis and De Waard [157] described how in driving simulator research, analysis of EEG by means of power density spectra might indicate driver vigilance state, with particular interest in drowsiness and loss of sleep. Interestingly, these studies show that mental (de)activation may be monitored by changing balance between brain activity regions. Beta activity (12-30 Hz) is predominant when the participant in the study is generally awake and alert, while the activity dropping to Alpha activity (8-12 Hz) indicates developing drowsiness, and going further down into the theta region (5-8 Hz) may even lead to falling asleep.

Recently, several investigators have reported that EEG power band ratios may be better at distinguishing among different levels of attention than is any single power band. Pope, Bogart, and Bartolome [158] described a system in which changes between modes of automation were triggered by an index of engagement (EI) based on ratios of EEG power bands (alpha, beta, theta, etc.). The rationale for the EI is that increases in arousal and attention are reflected in the beta-bandwidth while decreases are reflected in the alpha and theta bandwidths. They studied several different engagement indices from a variety of sites. The engagement indices were computed using a 40-s moving window that was updated every 2 s. Their participants performed the Multi-Attribute Task (MAT) battery (Comstock & Arnegard, 1991), a PC-based suite of activities that includes compensatory tracking, monitoring, and resource management tasks. Using such index, Pope et al. [158] showed that it is possible to moderate an operator’s task load with a psycho-physiologically based adaptive system using a ratio of EEG power bands. Such result was replicated and extended by several works [159].

A similar approach has been used for detecting or monitoring driver drowsiness level. For example, Lin et al. [145] demonstrated the feasibility of detecting or monitoring driver drowsiness level using a wearable and wireless dry-electrode EEG system. In a case study involving 15 study participants assigned a 90 min sustained-attention driving task in an immersive virtual driving environment, these authors demonstrates the reliability of the proposed system. Consistent with previous studies, power spectral analysis results confirm that the EEG activities correlate well with the variations in vigilance. Furthermore, the proposed system demonstrated the feasibility of predicting the driver's vigilance in real time (see also [160] to [164]).

Taken together, these different works show that continuous, accurate, non-invasive, and nearly real-time estimation of vigilance levels using EEG is feasible based on power spectrum analysis. In addition to examining global levels of arousal, it is possible to use electrophysiology to characterize discrete cognitive processes, namely the event potential related technique.

Event Related Potential and attention

Event-related potentials (ERPs) are derived from continuous EEG recording and represent the response of the brain to a discrete stimulus event. Unlike the EEG, which reflects brain activity in the frequency domain, the ERP represents an averaging of the EEG that is time-locked to the occurrence of a particular event. The resultant waveform is a sequence of separate components which reflect neuronal activity linked to specific sensory and cognitive processing. There are several components of the ERP waveform that have been identified. ERP components can be characterized in several ways, but they are typically described by their polarity and order of occurrence (P1, N1, P2, N2, P3, etc.) or mean latency in milliseconds from event onset (e.g., N170, P360). While there are not any distinct ERP components explicitly elicited by attention, several components can be modulated by attention, such that their amplitude increases to stimuli which are attended compared to stimuli which are not. For example, attention modulated components that have already been elicited by visual stimuli (P100 and N100), auditory stimuli (N100), infrequent stimuli (P300) or semantic stimuli (N400).

N100/P100

The N100 was first explored by Hillyard and collaborators [165] in an auditory selective attention paradigm. Subjects heard a series of tones presented independently to either ear (higher frequency tines in one ear than the other). Subjects were asked to attend to one of these streams (i.e., either left or right ear) and to detect tones, occurring once every ten stimuli or so, which were of a slightly higher frequency than the tones to which they were attending. In the attended ear, the N100 component of the ERP waveform was enhanced compared to the unattended ear. In the visual domain, unattended visuo-spatial stimuli are associated with attenuation in the amplitude of both N100 and P100 components [166]. In conclusion, waveforms elicited by attended and unattended stimuli in either visuo-spatial or auditory modalities differ as early as 50-100ms post-stimulus.

Functionally, the P1 component is usually interpreted as a neurophysiological indicator of preferential attention to sensory inputs (suppression of unattended information) and is thought to reflect the general level of arousal. The amplitude of P1 generally varies with the amount of attention ([167],[168]). Further, the amplitude of P1 increased when speed of response emphasized, suggesting that this peak may also reflect the level of arousal [169]. Similarly, the N1 component is assumed to reflect selective attention to basic stimulus characteristics. Its amplitude is enhanced by increased attention to the stimuli [170].

P300

The P300 is the most commonly researched component of the ERP waveforms. It was first identified by Sutton and colleagues [171] in a cuing paradigm as a pronounced positivity over parietal areas that occurred in response to an unexpected stimulus type approximatively 300 ms after stimulus onset. The amplitude of the P300 is larger, the more infrequent the stimuli.

Interestingly, it can also be used as an index of attentional function [172] because, as with the N100/P100 effects described above, the amplitude of the P300 can be modulated by attention [173]. Larger amplitudes are evoked by attention-demanding conditions. For example, O'Connell et al [174] observed a modulation of the P3 amplitude four to five seconds before a lapse of attention in a temporal expectancy task. Martel and collaborators [175] observed a same pattern of results. Subjective, behavioural and encephalographic (EEG) data of 12 participants performing a modified Mackworth Clock task were obtained and analysed offline. The stimulus consisted of a pointer performing regular ticks in a clockwise sequence across 42 dots arranged in a circle. Participants were requested to covertly attend to the pointer and press a response button as quickly as possible in the event of a jump, a rare and random event. Significant increases in response latencies and decreases in the detection rates were found as a function of time-on-task, a characteristic effect of sustained attention tasks known as the vigilance decrement. Interestingly, a significant gradual attenuation of the P3 event-related component was found to precede misses by 5 s.

Further, the P300 component, which reflects the availability and distribution of processing resources, has been found to vary reliably with changes in task load. For example, Isreal, and colleagues [176] examined the ERP in response to primary and secondary task demands. The use of a secondary task technique is predicated on the assumption that any processing resources not used on the primary task will be devoted to the secondary task. Therefore as primary task demands increase, fewer resources are available to be directed toward the secondary task, resulting in smaller P300 amplitude [177].

N400

The N400 was first described by Kutas and Hillyard [178]. This negative component occurs approximatively 400 ms after stimulus onset and is elicited in response to semantically deviant stimuli. The more unrelated the target word is to the context, the larger the amplitude of the N400. The N400 can also be modulated by attention, such that its amplitude increases to attended but not unattended words. For example, McCarthy and Nobre [179] found that spatial selective attention can modulate N400, such that words in an attended visual hemifield increase the amplitude of the N400 but ords in an unattended hemifield produce very little by way of an N400 component. The authors conclude that the N400 is not produced automatically to word presentation, but instead is modulated by attention.

To summarize, EEG has the potential to measure fast electrical signals from the surface of the scalp and is considered as one of the most reliable indicators of vigilance/attention. Several studies have demonstrated the suitability of EEG for real-world monitoring of mental states and for brain-computer-interface (BCI) applications. While artefacts attributed to movement, eye blinks, and physiological interference accompany EEG data, several algorithms have been developed to allow for the removal of noise in the EEG signal in real time or during post processing of the data (Jung et al., 2000). Recent developments in making “field-friendly” EEG systems include “dry” electrode caps, which do not need extensive participant preparation time, as well as wireless systems that do not require the participant to be tethered to cables. These technical developments have enhanced the relevance and value of EEG for mobile applications.

6.2.2 Other technics for brain activity index

A different approach would be to use blood flow–based neuroimaging methods, such as functional magnetic resonance imaging (fMRI), positron emission tomography (PET), Transcranial Doppler sonography (TCD) or functional Near-infrared spectroscopy (fNIRS).

It has been recently suggested that metrics of brain oxygenation could be considered as a quantitative measure of attentional resources. Brain imaging studies using PET and fMRI techniques have demonstrated that changes in cerebral blood flow and glucose metabolism could be used as correlates of attention/vigilance [180]. While PET uses injected radioactive tracers to measure the blood flow in response to stimuli, based on their respective magnetic characteristics fMRI focuses on the resulting contrast between oxygenated and deoxygenated blood called the Blood Oxygenation Level Dependent or BOLD signal. Numerous studies have demonstrated in BOLD signals as measured with fMRI, ranging from sensory regions to parietal and prefrontal cortex [181]. Even if several studies have used fMRI for real world monitoring of mental states (see for example [182],[183]), some major limitations exist in the use of PET and fMRI for our purpose. First, such equipment is extremely expensive to purchase and use. Second, PET and fMRI procedures feature restrictive environments in which observers need to remain almost motionless throughout the scanning procedure so as not to compromise the quality of the brain images, and fMRI acquisition is accompanied by loud noise. To meet our needs, we propose to focus in this review only on the TCD and fNIRS techniques.

Transcranial Doppler sonography (TCD)

Recent studies using a less expensive and less restrictive imaging system, known a transcranial Doppler sonography (TCD), have provided strong independent evidence for resource changes linked to performance decrement in vigilance tasks.

TCD is a non-invasive neuroimaging technique that employs ultrasound signals to monitor cerebral blood flow velocity or hemovelocity in the main stem intracranial arteries. TCD measures the difference in frequency between outgoing and reflected energy as it strikes moving erythrocytes. When a particular area of the brain becomes active, by-products of this activity, such as carbon dioxide (CO2), increase. The increase in CO2 generates dilation of blood vessels serving that area, and by extension an increase in blood flow to that region. Consequently, TCD offers the possibility of measuring changes in metabolic activity during task performance [184].

In studies by Warm and colleagues, blood flow velocity was measured in the medial cerebral artery, which carries about 80% of the blood flow within each cerebral hemisphere. Interestingly for our purpose, Hitchcock and collaborators [185] have shown that cerebral blood flow provides a metabolic index of the utilization of information-processing resources during sustained attention in a simulated air traffic control task. As described in recent review [186], these studies provide dramatic support for a resource model of vigilance. They show that the vigilance decrement is paralleled by a temporal decline in blood flow velocity but only when observers actively engage with the vigilance task. When observers were asked to view the vigilance display passively without a work imperative for an amount of time equal to that in the active conditions – what might be considered the case of maximum under stimulation – blood flow velocity remained stable throughout the course of the session.

TCD offers good temporal resolution and can track rapid changes in blood flow dynamics that can be followed in real time. It offers less restrictive and invasive conditions compared to PET and fMRI. Further, TCD technique provides a very economical way to assess cerebral flow. However, TCD does not provide information on oxygen utilization in the brain, which would be useful to assess as another indicator of the activation of neuronal populations recruited in the service of cognitive processes.

Near-infrared spectroscopy (NIRS)

Another potentially suitable technique for measuring vigilance in natural settings is the near-infrared spectroscopy (NIRS). NIRS is an optical imaging that can be used in the assessment of cerebral oximetry. Similar to fMRI, NIRS measures the blood oxygenation level of the superficial layers from the surface of the human brain and can distinguish between concentration changes of oxygenated and deoxygenated hemoglobin (HbO and HbR). Thereby, it measures an effect comparable to the blood oxygenation level dependent (BOLD) effect in fMRI. While concentration of HbO is expected to increase after focal activation of the cortex due to higher blood flow, HbR is washed out and decreases.

NIRS has been successfully used to investigate the neural signatures of performing vigilance tasks, typically by contrasting a task with a resting or control condition ([187],[187]). For example, Bogler, Mehnert, Steinbrink & Haynes [189] demonstrate that non-invasive NIRS signals correlate with vigilance. These signals carry enough information to decode subjects' reaction times at a single trial level. Interestingly NIRS has also been used in ecologically valid environments to investigate vigilance [190].

Near-infrared spectroscopy (NIRS) enables accessible non-invasive monitoring of operator brain functions in a variety of tasks and appears suitable for attention monitoring. NIRS has the substantial benefits of low-costs, easiness to handle and, and mobility. Even if it suffers from depth sensitivity (limited to the upper layer of the cortex) and spatial limitations as compared to fMRI, it remains a good candidate to complete EEG technique, particularly for source localization.

6.2.3 Oculometric changes

The vigilance decrement could be associated with a number of physiologic changes besides the direct measure of brain activity. Amongst other, various eye activity measures have been associated with change in vigilance and attentional processes. Two major changes have been identified: change in pupil diameter and change in blink properties.

Pupil dilation amplitude

Pupillary response is a physiological response that varies the size of the pupil, via the optic and oculomotor cranial nerve. Normally, when the fight or flight response is functioning properly, it should only activate during periods of intense fear – i.e., times when you will need to fight or run away. During those times, your body needs to have the best vision possible. That is why your pupils dilate. When they dilate, your eyes are letting in more light and your vision temporarily improves.

Interestingly, the size of the human eye pupil could be used as a measure of mental effort because it is assumed that the pupil size is related to the amount of cognitive control [191], attention [192], and cognitive processing [193] required by a given task. More specifically, pupil size variation has been associated with *locus coeruleus* (LC) activity [194], mainly through the noerepinephrine circuit. Neural activity in the noradrenergic *locus coeruleus* correlates with periods of wakefulness and arousal. It has also been shown that electrotonic coupling in noradrenergic LC neurons may play an important role in attentional modulation, and the regulation of goal-directed vs. exploratory behaviors [195]. Few decades ago, it has been shown the pupil size also decreases during drowsiness ([196],[197]) and with decreased performance on a sustained attention task [198]. Later, it has been assumed that the extent of pupil dilation recorded during a cognitive task could be a psychophysiological measure of task processing load and resource allocation, with larger pupil dilation reflecting greater processing load or mental effort.

Since, several studies converge to a similar relationship between pupillary tonic response and task difficulty, mental effort, and the state of arousal or vigilance of the participants. Sustained processing yields an increase in the pupil tonic response. Indeed, it is observed that gradual increase in arousal occurs with large increases in pupillary baseline (see for example [192],[199],[200]). For instance, such relation has been observed by Verney and collaborators [201]. They recorded pupil dilation responses in college students while performing a visual backward masking task. 5 different stimulus onset asynchronies (SOA) between the target and mask stimuli and a no-mask condition were tested (33, 50, 67, 117, and 317 ms). They observed that pupil dilation was significantly greater during task performance (cognitive load) relative to a condition where participants passively viewed the stimuli (cognitive no-load), and there were no significant differences between SOA conditions during passive viewing of the stimuli (no-load). They concluded that pupil dilation is a relevant index of cognitive resource allocation. A more recent illustration is brought by Binda and Murray [202]. They measured pupil size in adult human subjects while we manipulated both the luminance of the visual scene and the location of attention. They found that, with central fixation maintained, pupillary constrictions and dilations evoked by peripheral luminance increments and decrements are larger when spatial attention is covertly (i.e., with no eye movements) directed to the stimulus region versus when it is directed to the opposite hemifield. Conversely, when the tonic state is low, as in a person who is fatigued after sustained attention or is sleepy, the pupil begins to fluctuate considerably while its average diameter gradually decreases [203]. These different results indicate that pupillometry is not only an index of retinal and brainstem function, but also an objective measure of attentional allocation [202].

Because the pupillary response is slow—pupil size increases slowly in response to a relevant event and peaks after approximately 1 s— measuring effort by assessing pupil dilation traditionally has been thought to be reserved for slow tasks or tasks in which meaningful events are well separated in time. However, Wierda and collaborators [204] have recently showed that high-temporal-resolution (10 Hz) tracking of attention and cognitive processes can be obtained from the slow pupillary response (1 Hz). Using automated dilation deconvolution, based on the quantitative analysis of the pupillary response, they show that dilation deconvolution can track and isolate attentional processing of multiple events at close temporal proximity, thus revealing the temporal dynamics of the mind's eye at a surprisingly high resolution. As shown empirically in this study, dilation deconvolution can provide valuable information regarding the occurrence and timing of attentional processes that underlie human cognition.

Eye blink: Blink duration and frequency

Blinking is a semi-autonomic rapid closing of the eyelid. Blinking cleans the ocular surface of debris (cellular, dried tears, and the junk that blows in with the wind) and flushes fresh tears over the ocular surface. Interestingly, blink amplitudes also varied and amplitude and rate showed correlations of possible functional significance.

Research has shown that disappearance of blinks, mini-blinks and relative quiescence in eye movement are the earliest reliable signs of drowsiness, preceding slow eye movement and EEG alpha frequency and amplitude changes [205]. Blinks duration and frequency increase during fatigue [206] and are correlated with decreased performance [207]. Two measures could be derived from this statement.

The PERcentage of eye CLOSure (PERCLOS) measures the percentage of time during which a driver has his eyes closed over a window of several minutes (usually 1 to 3 minutes). An eye closure is usually characterised by an 80% (sometimes 70%) closure of the eye compared to its nominal size. Fast blinks are removed (time < 0.25s) from the computation of the PERCLOS. Driver hypovigilance is then detected using a maximal eye closure threshold [208].

The spontaneous eye-blink rate (EBR) measures the blink frequency. EBR is a well-validated indicator of visual attention; it is reduced during periods when attention is oriented toward significant external stimuli, and this reduction is proportional to the required attention [209]. . Decreased blink rate has been proved to be correlated with decreased performance on a sustained attention task [211]. For example, Campagne and collaborators [210] use such a measure to assess driver attention and vigilance level during a prolonged simulated driving task. Thirty six subjects drove for two hours.

Blinking activity and eye movements associated with glances to the speedometer were recorded during the entire driving task and particularly during specific road events. During significant events, blinking and ocular activity decreased, attesting a higher attention of the driver. With increased duration of driving, the reduction in blinking [212] and ocular activity was progressively smaller for the less significant events, indicating a reduction in attention.

This influence of vigilance on blink frequency has been also proved in Mind Wandering. Mind wandering is a spontaneous mental state during which our attention momentarily drifts away from our on-going task and perceptual milieu [213]. It is considered as an altered state of vigilance. Interestingly, Smilek and collaborators [214] demonstrate that during an extended period of reading, episodes of mind wandering, compared with on-task periods, contain more eye closures (blinks) and fewer fixations on the text even as subjects continue to scan the text.

These different findings show that eye activity (both *pupillary response* and *blinking*) can be used as a relevant index of cognitive resource allocation and vigilance. Moreover, it could be followed using systems based on cameras, systems unobtrusive and easily implemented in different ecological environment.

6.2.4 Heart-Rate Variability

Another underlying mechanism associates with the understanding of attentional processes is activity in the cardiovascular system. A particular attention has been directed to the fluctuation in the inter-beat-interval between normal heartbeats. This has been referred to as heart rate variability (HRV).

Spectral analysis of variations in heart rhythm provides an index of the relative contributions of the underlying components: the sympathetic and the parasympathetic branch of the autonomic nervous system (ANS). The ANS is subdivided in two anatomically and functionally distinct systems: the sympathetic nervous system (SNS) and the parasympathetic nervous system (PNS). Whereas the sympathetic branch can be viewed as the “activating” side of the ANS, responsible for example for the fight-or-flight response when confronted with danger, the parasympathetic branch can be viewed as the “relaxing” side, lowering spontaneous heart rate for example.

Spectral analysis of heart rhythm is typically segmented into three distinct bandwidths: 1) low frequency (0.02-0.06Hz), which is associated with temperature regulation; 2) mid-frequency (0.07-0.14Hz), which is affected by blood pressure regulation and cognitive effort; 3) hi-frequency (0.15-0.50Hz) which is associated with the effects of respiration on heart rate, the respiratory sinus arrhythmia (RSA). The mid-frequency bandwidth is associated with the combined activity of the parasympathetic and sympathetic systems, while the RSA is influenced by parasympathetic activity.

Several studies show that HRV is modulated by memory performance and mental workload (. For example, using a continuous memory task, Backs and Seljos [215] found that as memory load increased, good performers had a small heart rate (HR) period variability decrease (i.e. higher root mean squared successive differences, rMSSD), and poor performers had a large heart period variability decrease (i.e. lower rMSSD). In addition, Mulder and collaborators [216] show that suppression of the mid-frequency bandwidth is “very diagnostic” of the mental workload.

More interestingly, relation between HRV and attention has been demonstrated. First empirical evidence has been brought by Porges and Raskin [217] who demonstrated that HRV was significantly reduced during sustained attention. Similarly, Backs and Ryan [218] found decreased HRV as attention demands increased from focused to divided attention. In that experiment, they manipulated the difficulty of a continuous memory task by manipulating both the temporal demand (i.e., varying the inter-stimulus interval) and the memory load (i.e., increasing the number of target items to be counted). They found impact of the task difficulty on HRV and concluded that vagally mediated cardiac tone could be viewed as sensitive to cognitive tasks and acting as a measure of reactivity. Furthermore, Middelton et al. [219] found lower values of HRV during attentional tasks that involved small aspects of working memory compared to executive and planning tasks.

Nowadays, the heart rate variability (HRV) is used as a robust metrics for vigilance measurement ([220],[221],[222]). For example, Chua and collaborators [220] found that RR-interval power density in the 0.02- to 0.08-Hz frequency range correlates strongly with lapses on the Psychomotor Vigilance Task (PVT) and can be used to estimate decrements in PVT performance caused by sleepiness. In the same vein, Henelius and collaborators [221] investigated the use of spectral HRV metrics in the measurement of sleepiness in chronic partial sleep restriction. They examined computationally the association between spectral HRV metrics and neurobehavioral metrics of vigilant attention (PVT) and subjective sleepiness measures (KSS). Their findings suggest that HRV spectral power reflects vigilant attention in subjects exposed to partial chronic sleep restriction. Finally, Pattyn and collaborators [223] underlined the relation between ECG and vigilance decrement too. They applied a cued (valid vs invalid) conjunction search task, and ECG and respiration recordings were used to compute sympathetic (normalized low frequency power) and parasympathetic tone (respiratory sinus arrhythmia, RSA). Behavioural results showed a dual effect of time-on-task: the usually described vigilance decrement, expressed as increased reaction times (RTs) after 30 min for both conditions; and a higher cost in RTs after invalid cues for the endogenous condition only, appearing after 60 min. Interestingly, the vigilance decrement comes with an increase in heart period.

It is clear that the ECG carries information about a person's vigilance state. It is a relatively unobtrusive physiological measure and it appears to be readily accepted by subjects in an operational environment. In a recent review of applied physiological measurement techniques, Fahrenberg and Wientjes [224] ranked cardiovascular measurement as the most suitable for field studies due to its reliability, unobtrusiveness and ease of recording. Hence, HRV measures could potentially be used to predict when an individual is at increased risk of attentional failure.

6.2.5 Galvanic Skin Response

Electrodermal responses (EDRs) have also been used as an index of cognitive resource allocation and vigilance, and particularly the Galvanic Skin Response. The Galvanic Skin Response (GSR) is one of several electrodermal responses. EDRs are changes in the electrical properties of a person’s skin caused by an interaction between environmental events and the individual’s psychological state.

Human skin is a good conductor of electricity and when a weak electrical current is delivered to the skin, changes in the skin's conduction of that signal can be measured. The variable that is measured is either skin resistance or its reciprocal, skin conductance.

Two types of skin conductance are characterized, tonic and phasic. Tonic skin conductance is the baseline level of skin conductance, in the absence of any particular discrete environmental event, and is generally referred to as Skin Conductance Level (SCL). Tonic skin conductance levels vary over time in individuals depending on his or her psychological state and autonomic nervous system regulation. Phasic skin conductance is the type that changes when events take place. For example, we observe time related changes in skin conductance in presence of discrete environmental stimuli (sights, sounds, smells, etc.). These are generally referred to as Skin Conductance Responses (SCRs). SCRs are increases in the conductance of the skin which may last 10-20 seconds followed by a return to the tonic or baseline level of skin conductance (SCL). These phasic changes are often simply called GSRs.

The parameters of event-related GSRs that can be quantified are: amplitude, in microSiemens; and latency, rise time, and half-recovery time, in seconds. The amplitude of an event-related GSR is the difference between the tonic skin conductance level, at the time the response was evoked, and the skin conductance at the peak of the response. Latency is the time between the stimulus and the onset of the event-related GSR. Rise time is the time between the onset of the event-related GSR and the peak of the response. Half-recovery time is the time between the peak of the response and the point after the peak when the conductance returns to amplitude that is one-half the amplitude of the peak.

Interestingly, GSR is frequently used as an indirect measure of attention, cognitive effort, or emotional arousal. It correlates positively with the novelty, intensity, emotional content, and significance of the stimulus. An increase in tonic EDA indicates readiness for action and an increase of phasic EDA indicates that one's attention is directed toward a stimulus ([225],[225]). Because skin potential level and skin potential fluctuations are related to EEG alertness levels and the amount of spontaneous skin potentials prior to stimulus presentation may be correlated with performance on a vigilance task, GSR is therefore expected to decrease during monotonous tasks [212] and could be used as an index of vigilance decrement.

6.3 Conclusive remarks

In MINIMA, we intend to build "a Vigilance and Attention Observer" using sensors and combining measures of the brain's electrical activity (neurometrics) with other neurophysiologic measures to monitor vigilance and attentive state of an ATM operator and identifies and studies appropriate actions to support his/her activity. Therefore, it seemed reasonable to determine the efficacy of using psychophysiological measures to quantify change in attention/vigilance.

In this section, we have pointed that several biopsychometrics have been shown to be sensitive to changes in vigilance suggesting them as potential candidates for adaptive automation. These include: electroencephalographic data, blood flow–based neuroimaging methods (TDC and NIRS), eye activity (blinking and pupil dilation), electrocardiographic data and skin electric potential.

Taken together, the presented findings suggest that it is indeed possible to obtain indices on vigilance state using physiological measures and use that information to drive an adaptive automation system to improve human automation interaction. There are, however, still many critical conceptual and technical issues (e.g., making the recording equipment less obtrusive and obtaining reliable signals in noisy environments) that must be overcome before.

7 References

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