Concept for Human Performance Envelope

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Short abstract: Future Sky Safety is a Joint Research Programme (JRP) on Safety, initiated by EREA, the association of European Research Establishments in Aeronautics. The Programme contains two streams of activities: 1) coordination of the safety research programmes of the EREA institutes and 2) collaborative research projects on European safety priorities.

This deliverable is produced by the Project "Human Performance Envelope". The main objective of this document is to provide an extensive HF literature review in order to identify the factors that influence pilots performance and how. The final goal is definition of the Human Performance Envelope and its boundaries for the real time simulations.

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Acronyms

Acronym	Definition
ACARE	Advisory Council for Aviation Research and Innovation in Europe
ACARS	Aircraft Communications Addressing and Reporting System
ACROSS	Advanced Cockpit for Reduction Of StreSs and workload
ADS-B	Automatic Dependent Surveillance – Broadcast
ADVISE	Advanced Visual System for Situation Awareness Enhancement
AFMS	Advanced Flight Management System
AFRL	Air Force Research Lab
ALICIA	All Condition Operations and Innovative Cockpit Infrastructure
AMC	Acceptable Means of Compliance
A-SMGCS	Advanced Surface Movement Guidance and Control Systems
ATC	Air Traffic Control
ATCO	Air Traffic Controller
ATM	Air Traffic Management
AVRB	Amplitude-Velocity Ratio of Blinks
BOS	Behavioural Observation Scale
BR	Blink Rate
CATS	Cognitive Activation Theory of Stress
CDTI	Cockpit Displays of Traffic Information
CPDLC	Controller–Pilot Data Link Communications
CRM	Crew Resource Management
CS	Certification Specifications
EASA	European Aviation Safety Agency
EASp	European Aviation Safety Plan
ECG	Electrocardiography
EDA	Electro dermal activity
EEG	Electroencephalography
EFB	Electronic Flight Bag
EMG	Electromyography
EMMA2	European airport Movement Management by A-SMGCS, Part 2
EOG	Electrooculography

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EREA	European Research Establishments in Aeronautics
FAA	Federal Aviation Administration
fMRI	Functional Magnetic Resonance Imaging
FMS	Flight Management System
fNIR	Functional Near Infrared
FP	Framework Programme
FR	Fixation Rate
GIM	Global Implicit Measure
HEM	Horizontal Eye Movements
HF	Human Factors
HMI	Human Machine Interface
HP	Human Performance
HPE	Human Performance Envelope
HRV	Heart Rate Variability
HUMAN	Model-based Analysis of Human Errors during Aircraft Cockpit System
ICAO	International Civil Aviation Organisation
IFR	Instrument Flight Rules
KSS	Karolinska Sleepiness Scale
LOAT	Level of Automation Taxonomy
LOC-I	Loss of Control – In Flight
Man4Gen	Manual Flying Skills for 4th Generation Airliners
MOSES	More Operational Flight Security by increased Situation Awareness
OGFHA	Operator's Guide to Human Factors in Aviation
PERCLOS	PERcentage of eyelid CLOSure
PET	Positron Emission Tomography
PF	Pilot Flying
PNF	Pilot Not Flying
POMS	Profile of Mood States
PSF	Performance Shaping Factors
RSME	Rating Scale Mental Effort
SA	Situation Awareness
SAGAT	Situation Awareness Global Assessment Technique

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SALIANT	Situational Awareness Linked Indicators Adapted To Novel Tasks
SARS	Situation Awareness Rating Scale
SART	Situation Awareness Rating Technique
SAS	Supervisory Attentional System
SASHA	Situational Awareness for SHAPE
SEM	Slow Eye Movement
SESAR	Single European Sky ATM Research
SHAPE	Solutions for Human Automation Partnerships in European ATM
SOPs	Standard Operating Procedures
SPAM	Situation Preset Assessment Method
SRIA	Strategic Research and Innovation Agenda
TARGET	Targeted Acceptable Responses to Generated Events
TARMAC-AS	Taxi And Ramp Management And Control – Airborne System
TCD	Transcranial Doppler
TIS-B	Traffic Information Service – Broadcast
TOT	Time-on-task
TRL	Technology Readiness Level
VFR	Visual Flight Rules
WL	Workload

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EXECUTIVE SUMMARY

Problem Area

Aviation accidents inevitably involve the pilot and are almost always ascribed to 'human error'. Human Factors studies over decades have focused on a number of causes of 'pilot error', from communication to fatigue to situation awareness, in an attempt to stop pilot error and thus accidents. However, this 'single-shot' approach only gets us so far. To achieve a significant step change in avoiding or recovery from human error, we need to consider the full range of factors that can affect performance, and be able to detect when one or more are moving out of 'tolerance' zone.

In particular, to cope with the increased complexity in the cockpit, it's needed to reduce the pilot cognitive demand, e.g. through an appropriate use of HMI support. The focus should be put on the availability of resources (workload factor), with the design of HMI enabling pilots to be in a situation where they have sufficient cognitive resources to perform efficiently and safety their tasks. Another issue for aircraft manufacturer is certification. Although manufacturers consider it impossible to quantitatively measure human performance, they assumed that maximizing the flight crew performance (e.g. through design guidelines) should contribute to ensuring that the predicted human reliability is close to one. Finally, it would be in the interest of safety to know when the limits of the human performance are reached. Looking at a scenario with a risk probability of 10e-6, it is important to know whether the flight crew is able to perform the abnormal procedure properly. Does the abnormal situation lead to an accident because of its complexity? Does the pilot monitoring, reading the procedure, support the pilot flying properly in an abnormal situation? Where is the limit to all of the above? And whenever the safety of the flight is impaired, the knowledge from the experiment may be used to contact the manufacturer and justify a procedure change.

To answer these needs, the concept of Human Performance Envelope (HPE) has to be introduced and defined. The main goal of this report is to establish the Human Performance Envelope that forms the basis for the subsequent activities of the project.

Description of Work

The report is the result of two main activities:

1. On one side, the consortium performed an extensive <u>literature review</u> in order to provide a description of the state-of-the-art of the research on the factors that affect the human performance in the cockpit.

2. On the other side, the consortium identified a set of critical situations in the cockpit, i.e. situations in which the HP envelope is deeply stretched towards its boundaries, that can be used as starting points to develop the scenarios for the real-time simulations.

The aims of the review were to provide a basis on whether and how a set of identified factors impact on performance, and to identify and summarize previous research on relationships between the HPE components. On the basis of a previous work on human performance in Air Traffic Control, nine factors have been explored with respect to their interrelations and potential impact on pilots' performance too. For each factor, the consortium identified behavioural markers, including indicators of successful and degraded human performance, recovery measures and mitigation means currently envisaged, together with methods and techniques that can be used to measure factor variations. A workshop involving the majority of P6 partners was held to review the literature review preliminary results and to define the scope of the project, getting a shared understanding and basic representation of the HPE concept.

Finally, the consortium worked onto the situations that emerged as critical in stressing the HPE, i.e. all the situations that can reduce the safety margins between the level of pilot capability during the flight and the task requirements. Although there are many possible combinations of factors which will be HPE critical, some examples of HPE critical situations were provided, based on scenarios used in other research projects. The list of critical situations is not exhaustive, but they provide good examples of the elements to be taken into account to develop HPE critical scenarios and can be used as a preliminary source of inspiration for the scenarios design processes.

Results & Conclusions

HPE concept

The HPE is described as a construct combining a set of interdependent factors and represented with a spider web model. Depending on the value of each factor, the resulting HPE could evolve from fully acceptable (i.e. providing a nominal set of cognitive resources) to not acceptable (i.e. providing an error-prone cognitive and physical environment). Even though a single factor could have a non-acceptable value (e.g. low vigilance), it is assumed that the interaction should enable compensations among factors to be identified, and consequently overall acceptability of HPE to be proven. Influence of the demand of the tasks on the HPE has to be taken into account. Assuming that a HPE can be characterised for a given actor (e.g. pilot), there might actually be a set of acceptable HPEs for this same actor, each being dependent on the tasks. One way to address this task-related HPE could be to isolate specific tasks/situations, assess HPE factors in these situations and determine the feasibility of defining task-related HPE.

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For each factor, there is a “No Go” limit beyond which there should be a degradation leading to a negative impact on the human performance. For each factor, this “No Go” limit varies according to the situation (e.g. task, environment, context). There is a mutual influence of each factor level on their respective “No Go” limit, i.e. the limit for a given factor could be larger if another factor is far from its own limit (e.g. a high level of workload could be acceptable in a situation where stress is quite low and teamwork quite good –i.e. efficient).

<u>HPE Factors Cards</u>

Based on literature review, HPE Factors Cards were developed. The Cards are intended to be a living tool for P6 in which all the shared and consolidated information about the HPE components are structured and organised in a concise manner. The Cards will be refined and updated during the project to integrate new decisions and preliminary findings.

<u>P6 scope</u>

A selection of some of the 9 HP factors to be investigated through simulations was performed during the HPE Concept Workshop. It was agreed that the HPE should focus on three main aspects of human performance:

- Workload
- Stress
- Situational Awareness (also enabling indicators of attention and vigilance)

These factors were chosen as they appeared as the most prominent measures to consider. Although other factors such as fatigue and teamwork were also considered as important, the ability to obtain reliable indicators was a challenge which might hinder the validity of application of the resulting HPE model. Additionally, they were considered as the factors with the highest impact on the pilot performance, as well as those mostly likely to be investigated by using simulations. Potential measures for this factors to be used in the simulations and in the cockpit operations were also identified, together with the HPE performance markers.

<u>HPE critical situations</u>

A non-exhaustive list of HPE critical situations was defined, providing examples of how to stretch HP envelope towards its boundaries. Three ways to reduce the safety margin between task demand and crew capacity to a “critical” level were identified: (1) Increase in the taskload; (2) Decrease in crew capacity; (3) a combination of 1 and 2.

Applicability

This documents applies to the whole "Human Performance Envelope" project as it defines the scope of the research activities and put the basis for the real time simulations.

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INTRODUCTION

1.1. The Programme

The EC Flight Path 2050 vision aims to achieve the highest levels of safety to ensure that passengers and freight as well as the air transport system and its infrastructure are protected. Trends in safety performance over the last decade indicate that the ACARE Vision 2020 safety goal of an 80% reduction of the accident rate is not being achieved. A stronger focus on safety is required.

Future Sky Safety, established under coordination of EREA, is a Transport Research Programme built on European safety priorities that brings together 33 European partners to develop new tools and new approaches to aeronautics safety. The Programme links the EASp main pillars (operational issues, systemic issues, human performance and emerging issues) to the Flight Path 2050 safety challenges through four Themes:

- **Theme 1** (new solutions for today's accidents) aims for breakthrough research to address the current main accident categories in commercial air transport with the purpose of enabling a direct, specific, significant risk reduction in the medium term.
- **Theme 2** (strengthening the capability to manage risk) conducts research on processes and technologies to enable the aviation system actors to achieve near-total control over the safety risk in the air transport system.
- **Theme 3** (building ultra-resilient systems, organizations and operators) conducts research on the improvement of Systems, Organisations and the Human Operator with the specific aim to improve safety performance under unanticipated circumstances.
- **Theme 4** (building ultra-resilient vehicles) aims at reducing the effect of external hazards on vehicle integrity as well as reducing the number of fatalities in case of accidents.

Together, these Themes and the institutionally funded safety research intend to cover the safety priorities of Flight Path 2050 as well as the ACARE Strategic Research and Innovation Agenda (SRIA) (in particular the Challenges brought forward by ACARE Working Group 4 "Safety and Security").

The Programme will also help coordinate the research and innovation agendas of several countries and institutions, as well as create synergies with other EU initiatives in the field (e.g. SESAR, Clean Sky 2). Future Sky Safety is set up with expected seven years duration, divided into two phases of which the first one of 4 years has been formally approved.

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1.2. Project context

Future Sky Safety P6 addresses Theme 3 (Building ultra-resilient systems and operators) focussed on strengthening the resilience to deal with current and new risks of the humans and the organizations operating the air transport system.

P6 builds on a concept previously proposed in the Air Traffic Management (ATM) domain, extending it to the Human Operators in the cockpit. The aim of the project is to define and apply the Human Performance Envelope for cockpit operations and design, and determining methods to recover crew's performance to the centre of the envelope, and consequently to augment this envelope.

The Human Performance Envelope is to some extent a new paradigm in Human Factors. Rather than focusing on one or two individual factors (e.g. fatigue, situation awareness, etc.), it considers a range of common factors in accidents and maps how they work alone or in combination to lead to a performance decrement that could affect safety. The safe region on the envelope is bordered by markers, which can be measured and signalled, allowing the pilots to detect and recover, or enabling external agencies to prompt recovery, or allowing automation to kick in and take over. The Human Performance Envelope will deal with the most crucial people in the accident chain, giving them back-up when they most need it, assuring performance when things get difficult. It will increase safety by focusing on the sharp end of accidents, and consign the term 'Pilot error' to the waste paper bin. The impact will primarily be through improved design and operational practices and is thus expected in the short to medium term.

1.3. Research objectives

The impact of "Human Performance Envelope" Project will primarily be through the improved design and operational practices in cockpit. The ultimate objective is to augment the Human Performance Envelope through HMI principles, innovative HMI design, automation concepts and flight crew monitoring solutions (with impact on procedures or training).

P6 is expected to produce/develop:

- Guideline for HMI development taking into account one dedicated concept of automation
- General guidelines for Augmenting the Envelope
- Demonstrator (i.e. prototype with limited functionalities in an example scenario) of HPE monitoring and regulation solutions implemented in full mission simulators

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1.4. Approach

To achieve its main objectives, the project is structured in four work packages. In the first one, the focus is on the development of the HPE concept, which forms the basis for the subsequent tasks. The aim of this work is to establish the boundaries of the envelope, and define the operational scope of the following activities. In the subsequent work package the HPE is established in the operational environment of a research flight simulator for evaluation and validation tests, together with assessment of the technology and methods that can be applied to Human Performance evaluation. Based on the results of the initial experimental evaluations and the limitations identified in the background analysis, the third work package aims to define the methods for recovering performance in an unexpected situation. This is done through the identification of markers to recognise when the HPE limitations are being approached, together with methods and principles to recover performance. Finally, the last work package takes these methods and translates them to safe system performance (in terms of HMI, training and procedures) into the operational environment of the cockpit.

1.5. Structure of the document

This document is the first one of the project and its main aim is to define the scope of the project. To do that, the document starts with a literature review on the factors that influence the Human Performance (Section 2), based on Tamsyn Edwards' work on Human Performance in Air Traffic Control. The literature review results in a state-of-the-art on Human Factors (Section 2.2) influencing the pilots' performance. Nine factors are presented in this document, each one described with its influence on human performance, methods and techniques to measure it, its behavioural markers, and recovery measures and mitigation means currently envisaged in aviation. Section 3 illustrates the results of the HPE Concept Workshop and defines the concept for Human Performance Envelope, providing also clarifications on the scope of the project. Last section of the document (Section 4) is dedicated to the identification of critical situations in the cockpit able to stress the HPE, which will be the basis for the development of scenarios for the real time simulations.

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2 STATE-OF-THE-ART ON HUMAN PERFORMANCE IN AVIATION

2.1. Human Performance Envelope in aviation

Aviation is a safety critical domain, where human performance and error are primary concerns as they may cause severe consequences and potential loss of life. The operators are the sharp end of the system, the ultimate responsible for ensuring the success and safety of the aviation industry. The other side of the coin is that the majority of accidents are attributed to some form of human error [86] and human factors stubbornly remain at the centre of most airline disasters. Knowledge of the impact of human factors on human performance and error is therefore critical in addressing safety incidents in aviation [45]. So far, most of the research has focussed on the impact of a single factor (such as workload or fatigue) on human performance. However, incidents often result from the interaction of multiple human factors and this interaction is still mostly underexplored. To achieve a significant step change in human performance and recovery, we need to consider the full range of factors that can affect performance, and be able to detect when one or more is moving out of 'tolerance'. We need to determine the key factors and their associated behavioural markers so that either the pilots themselves can recognise their performance is under threat and compensate accordingly, or external parties can detect a performance decrement and promptly recovery, or else there should be automated support to augment human performance or take over control.

The aim of this work is to identify and investigate the set of relevant related factors that affect the pilots' performance and play a role in the achievement of the intended goals, in order to determine the points at which they trigger a significant performance degradation that could affect system safety. The metaphor is a performance envelope, i.e. topography defined by the relevant factors and associated scales, which contains a region where performance will be tolerable, and where it starts to become hazardous. The basic concept is similar to the concept of an aircraft performance envelope:

- Within the envelope, the performance is good or within system tolerance.
- As human performance approaches edges of the envelope, the performance becomes at risk.

The idea is three dimensional, with the edges of the envelope curving downwards slightly to begin with, then with a sharper decline as the true performance edge is approached and a risky situation develops. This corresponds to what has been called 'graceful degradation' in Human Factors for the past fifty years, in contrast to the 'sudden catastrophic failures' associated with equipment malfunctions.

The definition of Human Performance adopted in this project is the one reported in "Human Performance in Air Traffic Management Safety White Paper" [53]:

"Human performance refers to the adequate performance of jobs, tasks and activities by operational personnel – individually and together".

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In this paper is highlighted that positive or negative variations of human performance depend on the Capability (person), Motivation (person), System support, Organisation and Environment (context of work), and according to the authors "all three need to be considered carefully. Even very high capability individuals will not perform well if motivation is low or if the systems, organisation or environment (e.g. training and procedures) are poor. Similarly, even the most motivated person, with good training and procedures, may not perform well if capabilities are poorly matched to the job requirements".

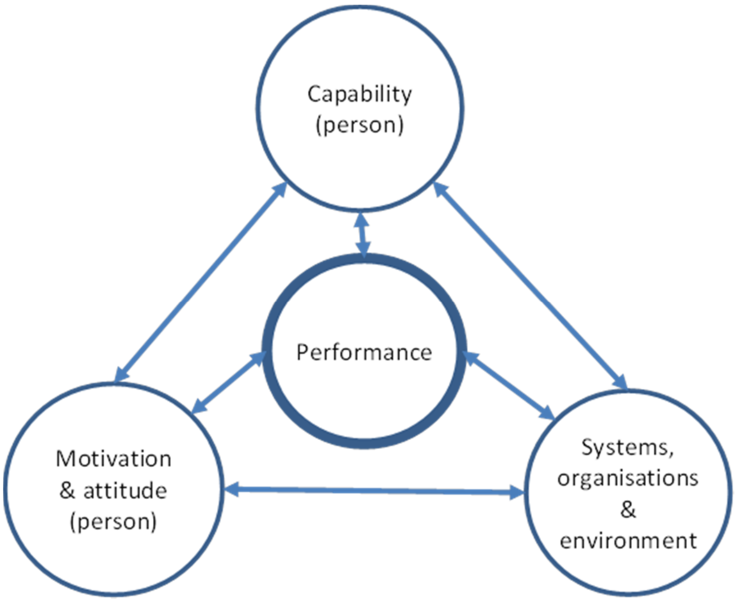

Figure 1: Determinants of Human Performance

The scope of the following sections is to is to provide an overview of the human performance issues faced by aviation operators and identify, on the basis of literature review, the (internal) factors that are considered associated to pilot's performance.

2.1.1. The ATM Perspective on Human Performance

The Human Factors aspects, including the automation-related issues, have long been a matter of concern in the aeronautical domain ([158], [160], [166]). ATM is a highly critical complex system. Beyond the stress involved by the system criticality, the system complexity introduces very high cognitive demands put on the actors involved (traffic managers, air traffic controllers, pilots) and leads to the extensive use of automation and support systems.

Modern technology allows more and more complex systems to ensure more and more critical functions. Even though automation could nowadays perform most of the control and navigation tasks, a significant role is still ensured by human operators in the aviation system. Whereas technical systems seem more reliable than human to perform routine and deterministic tasks, they reach their limit when facing unexpected situations and events. The human ability to react efficiently to such unexpected

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situations and to resolve what could be considered as "automation failures" (i.e. technical systems no longer able to fulfil their mission) still justifies the presence of both air traffic controllers and pilots in the overall ATM system. However, despite the recognition of their invaluable contribution, the human operators induce specific requirements to be considered when designing (or adapting) the overall ATM system. Human Factors issues in ATM have been regularly addressed and documented along the last 60 years ([57], [158], [52], [161], [40], [41]).

Controllers and pilots are expected to contribute both to the efficiency and to the safety of the ATM system. In this highly complex system numerous and varied information need to be processed (i.e. collected, analysed and understood) by the various technical and human actors involved, among which the tasks are split (e.g. controllers, pilots, information displays). The dynamic nature of the ATM system coupled to its impossibility to be stopped results in time pressure constraints put on the human decision making processes. To efficiently and safely operate in such a complex and time critical environment, both controllers and pilots rely on support introduced by their organisations (e.g. task description, training, working methods, procedures, automation, HMI and support tools). In addition, individual human factors also contribute and influence the controllers and pilots‘ performance (e.g. experience, skills, motivation, attention, fatigue, teamwork ability).

Literature review ([158], [82], [52], [133]) suggests that to ensure efficient and safe human performance, a set of critical issues need to be seriously tackled and taken into account when designing the ATM work settings (see Figure 1). As illustrated in the figure, those issues could be organised along the three dimensions of: capability; motivation and attitude; systems, organisations and environment.

Another grouping of human performance influencing factors is the internal/external nature of these factors, the external ones being essentially those put in place by the organisation to guarantee (as much as possible) the appropriate context for an efficient and safe performance. Most of the internal factors will be also discussed in details in Section 2.2.

Internal factors

- Motivation: Although skills, experience and working methods are essential for human operators to know how to perform their tasks, more individual factors such as motivation play an important role in the successful achievement of the tasks. Typically people's motivation (understood as what causes a person to want to repeat behaviour) influences their willingness to perform and the quality of their performance. Both intrinsic and extrinsic motivation need to be considered carefully to ensure their satisfaction and enable successful performance. Intrinsic motivation is driven by an interest or enjoyment in the task itself, and exists within the individual rather than relies on external pressures or a desire for reward. People are likely to be intrinsically motivated if they attribute their results to factors under their own control (autonomy or internal locus of control), believe they have the skills to be effective agents in reaching their desired goals (self-efficacy beliefs). To influence positively intrinsic motivation, one should encourage people self-desire to seek out new things and new challenges, to analyse one's capacity, to observe and to gain knowledge [125]. Extrinsic motivation refers to the performance of an activity in order to attain a desired outcome and it is the opposite of intrinsic motivation. It comes from influences outside of the individual upon which the organisation should act (e.g. rewards for showing the desired behaviour, and threat of punishment following misbehaviour). In ATM, one of the issue is how to maintain the controllers motivated while their roles are evolving, typically from active (execution) to passive (monitoring). Beyond the frustration of not being in control anymore of the system (but rather supervising the automation performance), they could be confronted to the pressure of not being able to recover from highly complex degraded situations, once the automation has reached its limits.

- <u>Experience and skills</u>: those need to be considered at two levels, first the definition of the initial expectations (to select the appropriate candidates) and second their continuous evaluation, both to ensure that the skills are maintained, and to assess how new skills are developed through experience (potentially leading to e.g. an adaptation of the task definition, and of the associated training, working methods, support tools). In particular, in ATM, the introduction of support tools and automation potentially induces changes in the controllers' roles, evolving from active to more passive. This could possibly impact on the one hand their skills and competencies (i.e. due to reduced opportunities to execute some procedures) and on the other hand reduce their motivation and satisfaction (e.g. due to a feeling of being less in control of the situation and possibly less capable to recover a degraded situation which they might no longer understand).
- <u>Perceived Workload</u>: successful human performance relies on adequate task and working methods definition, on the correct selection of actors, and on appropriate task allocation among the various "systems" (human and technical). It is essential to ensure at this stage that the demand (essentially cognitive) put on the actors is adapted to their capabilities, considering both tasks in isolation and when interacting. It is also important to assess continuously the level of workload to ensure that an unexpected increase is detecting early enough to provide the actors additional support (human or technical) enabling them to remain efficient, ahead of the situation, i.e. able not only to understand the current state of the system but also to anticipate its evolution and the impact on their performance. Although excessive workload is detrimental to human performance, underload, which could be as dangerous (e.g. risk of reduced vigilance) should also be avoided [80].
- <u>Attention and vigilance</u>: in ATM, a large part of both the controllers' tasks consist in monitoring the situation through various complex information display. Controllers continuously assess the characteristics of the current traffic (e.g. aircraft position, attitude, speed, planned trajectory, airspace constraints) to determine how to provide the best service in terms of efficiency and safety. . In addition to the skills, motivation, working methods discussed above, they need to maintain a correct level of attention and vigilance to be able to detect unexpected events.

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Whereas operators could be trained on how to best pay attention, or to remain vigilant, to detect decrease in own performance, support systems could be introduced to alert them. Those should be designed carefully to ensure that the information they convey supports the operators rather than increase the complexity of their task. Typically, as discussed above, a disruption in the operators cognitive state should be aimed at, but visual overload should be avoided. In addition, auditory signals should be well designed to ensure that they match as much as possible the criticality of the situation, again avoiding any overload.

- Situation awareness: Providing the controllers with the means to efficiently maintain his/her awareness of the situation and to anticipate its evolution is another core Human factors issue. The continuous monitoring performed by controllers and pilots is essentially oriented towards 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", which corresponds to Endsley's definition of Situation Awareness (SA, [48]). Support from the (human and technical) environment is needed to ensure that the three levels of SA are properly achieved. The first level of SA (perception), which involves the processes of monitoring, cue detection, and basic recognition of multiple situational elements (objects, events, people, systems, environmental factors) and their current states (locations, conditions, modes, actions) is largely supported by information displays. The second level (comprehension) involves an analysis of those elements through the processes of pattern recognition, interpretation, and evaluation to understand how it will impact upon the individual's goals and objectives. Although it is based on operators’ skills and experience, external support could be provided through automated information analysis and intelligent information display. The third level (projection) involves the ability to anticipate how these elements will evolve and is achieved through knowledge of the status and dynamics of the elements and comprehension of the situation. Similarly to the previous level, in addition to operators’ experience and skills, expert systems could contribute to the identification of projected states and provide inputs to the human operators. Lundberg [100] brings together various strands of SA research into a holistic framework, and illustrates its applicability to air traffic control tower situations.
- Teamwork ability: Despite the increasing role played by technology in critical functions handling, in most critical systems a significant part is still ensured by human operators, and especially teams of operators. In many work settings, humans have to maintain continuously a precise knowledge, related to the state of the technical system and of the environment on the one hand, and to the actions, intentions and knowledge of their colleagues on the other hand. This is the key for their ability to handle appropriately the unexpected events: detection of errors (due to human or technical components), diagnosis and selection of an appropriate sequence of actions. Up to a large extent, the global dependability of many socio-technical systems thus depends on the efficiency of teamwork [122]. There are many studies on teamwork and crew resources management, both for air and ground ([158], [40]) to document the task distribution between the actors involved (executive / planning controllers, flying/non flying pilot). The teamwork ability should actually be extended across air and ground. Not only

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should controllers and pilots exchange information and instructions, but they also need to rely on each other. Typically, following an instruction to a pilot, a controller could use the pilots' read back not only to confirm the correct reception of the instruction, but also to assess additional elements (e.g. stress, fatigue) through more implicit indicators (tone or pace of the voice).

External factors

- Task definition: the first step when setting the scene for human performance is to clearly define what is expected from the human (individually and collectively), in terms of objectives, means and context of the task to identify the associated requirements (e.g. actors skills, required information, tools) and later validate that those are fulfilled.
- Training: to ensure that the selected operators acquire the knowledge specific to the tasks (i.e. that on top of their individual expertise and skills they develop the knowledge required for the efficient performance of the task according to the organisation expectations and rules). In addition to the initial training, the organisation needs to support a continuous one, taking into consideration both changes in the work itself (e.g. new procedures, lessons learnt and experience feedback) and in the individual (e.g. skills acquisition, experience, rules of thumb, heuristics).
- Task repartition, working methods and procedures: Intelligence, flexibility and ability to adapt to changes are essential qualities of the human actors. Those should be employed as a framework to clearly specify situations, for which expected task repartition (among human actors, but also between human and systems), working methods and procedures have been defined. Such prescribed organisation enable the various actors to share a common understanding of the common goals, to expect other to follow same rules and working methods and consequently to facilitate the recognition of others' current objectives and possibly expectations.
- HMI, automation and support tools: the time criticality of the complex systems handled makes it nearly impossible for the human to collect, analyse, understand and work upon such a large quantity and heterogeneity of information. The human resources (both physical and cognitive) reach their limits so that to perform efficiently and safely in such complex work settings, the human performance could no longer take place without tools that support the various stages of the human cognitive performance: information collection and filtering, information processing and analysis, decision making and execution. Automation is considered as "a device or system that accomplishes (partially or fully) a function that was previously carried out (partially or fully) by a human operator" [159]. "Automation should assist human operators to undertake their responsibilities in the most efficient, effective, economical and safe manner" [82]. To ensure an effective and efficient support, these "tools" (information display, HMI and automation) need to be designed with and around the final users, on the basis of understanding their needs in the various contexts. The system design, and more specifically the

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automation design, evolved from an engineer driven approach (based on technical feasibility) to a human user centred approach (based on the user requirements and on the need to reduce accidents/incidents and costs). Automation was even the focus of a European Commission project (Role of the Human in the Evolution of ATM Systems –RHEA, 1998), investigating in particular the roles of the controller in future ATM systems [28]. The automation surprises observed in the cockpit ([127], [10]) could also be experienced in the Air Traffic Control (ATC) systems with the introduction of support systems. As Wiener [161] stated, to perform efficiently, operators need to understand what the automation (or any support system) is doing, why it is doing so and what it will do next. To tackle these issues, designers need to ensure that automation, HMI and support systems are as simple and intuitive as possible, once again involving the final users in their design. It should be mentioned that whereas automation and support systems are initially introduced to help the operators in their performance, there might be needs for other types of intervention: in problem solving situations, people happen to suffer from attentional tunnelling [157] when over focus on an initial diagnosis of the situation and fail to consider new information and question this initial diagnosis. In such situations, automation and support systems could be envisaged as “disruptors” (or cognitive countermeasures) in the sense that they could remove the sources of information to create an attentional disengagement and oblige the operators to reconsider the situation [32].

2.1.2. The Manufacturers perspective on Human Performance

2.1.2.1. Boeing Research and Technology perspective

To certify an airplane, manufacturers have to guarantee that flight events with different severity effects are below a certain probability per flight hour, defined by the green zone in the Risk Map in Figure 2. Based in this figure we can observe that minor flight events can be probable (probability below 10-3), Major flight events have to be remote (probability below 10-5), flight events with hazardous outcomes have to be extremely remote (probability below 10-7), and flight events with catastrophic outcomes have to be extremely improbable (probability below 10-9). These severity levels are defined as follows (FAA AC 25.1309-1A1 and EASA AMC 25.1309 - System Design and Analysis):

[1] FAA is releasing an updated Advisory Circular (AC) (Subject: System Design and Analysis) that describes acceptable means for showing compliance with the airworthiness requirements of § 25.1309 of the Federal Aviation Regulations. The present unreleased but working draft of AC 25.1309–1 is the Aviation Rulemaking Advisory Committee recommended revision B-Arsenal Draft (2002), and can be found at http://www.faa.gov/regulations_policies/rulemaking/committees/documents/media/TAEsdaT2-052496.pdf

- No Requirement: Failure Conditions that would have no effect on safety; for example, Failure Conditions that would not affect the operational capability of the airplane or increase crew workload.
- Minor: Failure Conditions which would not significantly reduce airplane safety, and which involve crew actions that are well within their capabilities. Minor Failure Conditions may include, for example, a slight reduction in safety margins or functional capabilities, a slight increase in crew workload, such as routine flight plan changes, or some physical discomfort to passengers or cabin crew.
- Major: Failure Conditions which would reduce the capability of the airplane or the ability of the crew to cope with adverse operating conditions to the extent that there would be, for example, a significant reduction in safety margins or functional capabilities, a significant increase in crew workload or in conditions impairing crew efficiency, or discomfort to the flight crew, or physical distress to passengers or cabin crew, possibly including injuries.
- Hazardous: Failure Conditions which would reduce the capability of the airplane or the ability of the crew to cope with adverse operating conditions to the extent that there would be:
  - A large reduction in safety margins or functional capabilities;
  - Physical distress or excessive workload such that the flight crew cannot be relied upon to perform their tasks accurately or completely; or
  - Serious or fatal injury to a relatively small number of the occupants other than the flight crew.
- Catastrophic: Failure conditions which would result in multiple fatalities, usually with the loss of the airplane. (Note: A "Catastrophic" Failure Condition was defined in previous versions of the rule and the advisory material as a Failure Condition which would prevent continued safe flight and landing).

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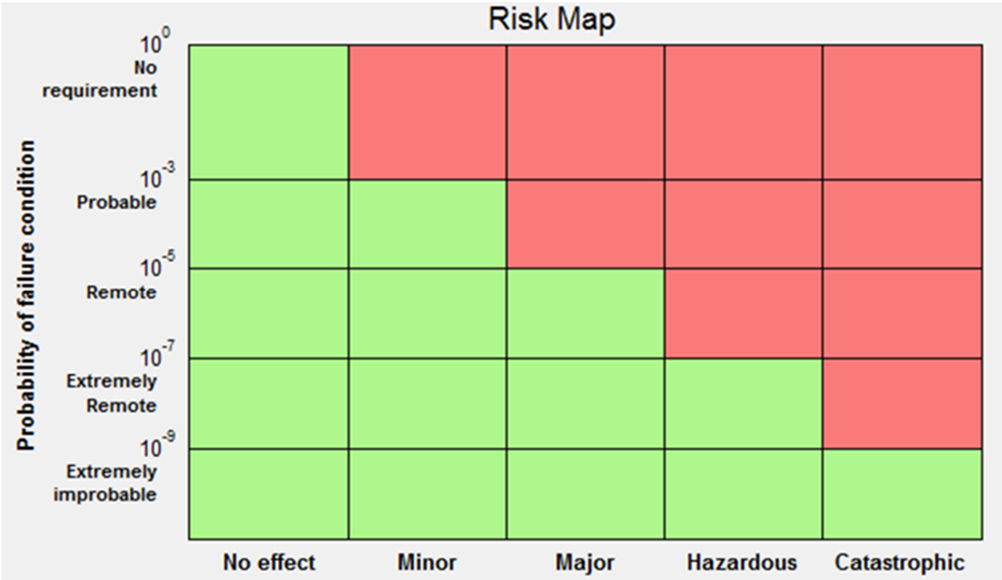

Figure 2: Risk map for flight events.

To ensure that, for example, flight events with catastrophic outcomes do not occur (e.g., loss of pitch control), airplane systems have to be very reliable and manufacturers have to guarantee that vital airplane functionalities are not lost due to single (or multiple) component failures. Therefore, system design is done based in the component failure statistics. However, in some cases one needs to consider the flight crew intervention in the system design and its contribution to the calculation of the probability of a certain flight event.

The current regulation (AC 25.1309-1A and AMC 25.1309 - System Design and Analysis) states that "quantitative assessments of the probabilities of crew or maintenance errors are not currently considered feasible". Therefore, designers cannot directly calculate a probability representative of how many flight crews would handle the event in a successful way. Instead, system designers have to assume that all flight crews would handle the event in an expected way (e.g., following the correct procedure). Due to this, there are design guidelines for flight deck features like alerting, system and flight controls, among others, to ensure that flight crews follow the correct actions. Consequently, the impact of the flight crew on total system reliability is done by assessing:

- The information provided to the crew;
- The complexity of the required actions;
- Other concurrent safety related crew tasks.

According to AC 25.1309-1A regulation "If the failure indications are considered to be recognisable and the required actions do not cause an excessive workload, then for the purposes of the analysis, the probability that the corrective action will be accomplished, can be considered to be one. If the

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necessary actions cannot be satisfactorily accomplished, the tasks and/or the systems need to be modified". Therefore, to be compliant with current regulation, research on the Human Performance Envelope would ideally support the design guidelines that maximize flight crew performance such that human reliability is close to one. An example would be the creation of a flight event database, similar to the one already used for Functional Hazard Assessment (ARP 4761 - Guidelines and methods for conducting the safety assessment process on civil airborne systems and equipment), that contains design guidelines based on the necessary crew actions to successfully handle those events.

Beyond technical reliability, it should be noted that the European regulation contains a specific section related to "Installed systems and equipment for use by the flight crew" (EASA CS & AMC 25.1302). This section is specifically dedicated to the human factors issues to be addressed for the certification of cockpit equipment and how the certification process should be built. In particular, it provides recommendations for the design and evaluation of controls, displays, system behaviour (automation), and system integration, as well as design guidance for error management. This regulation document recognises that even well trained and alert flight crews make errors and that the design of the flight deck and associated systems can influence flight crew performance and the occurrence and effects of flight crew errors. Thus it proposes guidance on how the certification applicant may address potential crew limitations and errors.

2.1.2.2. Thales Avionics perspective

One can only witness that, still today, "non-defective aircraft" monitored by "perfectly trained crews" are involved in fatal accidents. One explanation is that we have reached, at the crew level, a system complexity that, while acceptable in normal conditions, is hardly compatible with human cognitive abilities in degraded conditions. It appears that the efficiency of the glass cockpit paradigm has faded away with the evolution of the aeronautical environment (traffic increase & permanence of service). Though the glass cockpit fulfils its promises in normal and lightly degraded situations, it can fail to deliver when crews are confronted to those emerging extremely rare (off-normal) situations that are the potential consequence of failures of highly complex systems with ever variable humans in that increasingly complex environment.

As of today (ICAO Montreal, 2014), the current mitigation of such risk still relies mostly on the enforcement, through intensive training, of an ability to manage those extremely rare situations. But there is a cost and a limit to the efficiency of training for such rare events.

As an avionics manufacturer, Thales Avionics is looking back into the limits and strengths of operators, and has selected key knowledge on human cognitive strategies that enabled our engineers to revisit and review our design principles to give back to pilots the ability to stay in the loop: not through the management of more and more complex systems, but by helping them doing what they do best, manage their own resources to make adequate decisions [9].

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First, four basic ground rules regarding human factors are followed as key references to designers and planners:

1. There is no such thing as a system without a Human being because that system only makes sense because there is a human use behind it. The first ground rule: *“No design can ever be performed without the human use in mind”*
2. There is no such thing as a constant average Human. Engineers should not trust their opinion on who the end user is. Only the confrontation to reality will enable design progress by testing it against a rough environment and variable human being . this will promote the use of cyclic design (design, try, analyse fault, design, etc…). The second ground rule: *“Knowledge about the end user is crucial to the understanding of their need”*
3. Catachresis: deviation in use. People do that all the time. Even with complex systems, usually when those refuse to do what the operator wants to achieve. They find a way around, a simplification, a short cut, any way to use it that would require less investment (or fatigue) for an acceptable result. Such catachreses are a wealth of information about how to enhance the system you designed. Always look for them when talking/observing the end users of technologies. Collect and analyse them because they reveal the true need that is not satisfied by the design. The third ground rule: *“End user creativity is to be expected and thoroughly analysed for design enhancement”*
4. The efficiency of the brain for understanding perception (visual, aural, tactile, olfactory, …) is unmatched by technology, so efficient with so little resources. Let’s not fool ourselves; we never willingly do more than expected. The principle of “good enough” for the minimal investment defines our daily objectives. We are governed by that need to spare ourselves for maximum efficiency… The fourth ground rule: *“Design must integrate & respect end user limits & resources”.*

Second, the paradigm of Cognitive Resources Management guides us for HMI design. Cognitive strategies that are “naturally” followed by operators to spare their resources are systematically facilitated in AV2020’s HMI.

- We facilitate routinization of behaviours by easing the training through highly intuitive HMI that rely on pre-existing stereotypes (developed on today’s touch technology) so pilots can easily rely on instinctive responses;
- We facilitate delegation of work to available agents (human or not) by proposing clear and unambiguous feedback from agents on their state and efficiency;
- We systematically rely on schematized information that is contextualized to simplify the presentation of information to the pilot, thus easing information management and decision making;

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- We facilitate anticipation and planning through the systematic use of time referenced data on a time line. Pilots can thus easily refresh their working memory and prepare themselves for upcoming events.

AV2020 generation HMIs thus observe an “ecological” design paradigm to preserve crew cognitive resources and favour pilots’ core abilities: i.e. decision making and application of airmanship.

2.1.3. The Pilots perspectives on Human Performance

As emphasized in the previous sections, the pilots are like air traffic controllers at the sharp end of the Air Traffic System (ATS). They are, and will continue to hold the ultimate responsibility for flight safety. As key actors of a complex socio-technical system, they have obviously to cope with the evolution of this system along the years.

Indeed, in a context of increased competition, airlines have to continuously adapt their operations models and new concepts of operation have thus been introduced, including hubs, shuttles and low cost flights. These concepts together with a growing passenger demand have resulted in increased pressure put on the aircrews. As a matter of fact, the issue of fatigue indeed emerged quite recently, not only for long haul flights but also for commuter flights. Regulation has been put in place for instance at the European level in order to impose limitations in working times and flight cycles. However, studies are still under way to better understand the relationships between fatigue, human performance and the resulting overall safety. While controllers basically use the same tools till some decades while facing a regular increase in traffic load and congestion at major airports, pilots have seen considerable changes in their work environment. Among these changes, the shift from three to two crewmembers has come together with increased support of automation, flight management systems and generalization of fly-by-wire and glass-cockpit aircraft.

All these changes have clearly an influence on the human performance envelope of pilots.

On ground, airlines have structured their operation in processes. The vast majority of the processes work faultless, without any occurrences. But whenever something goes wrong and not according plan, the flight and cabin crew has a painstaking job to do to take corrective action within and during that efficiently designed system. With little ground time and as many things need an exertion of influence, the convalescence for the flight crew on ground is cut short. Workload and stress on ground do have an influence on pilot’s performance during the subsequent flight legs.

In flight, the situation has also changed tremendously for pilots. The level of automation of today’s airplanes is constantly increasing. This does not only apply to the airplane systems itself, but also to the many other technologies which have been implemented additionally by airlines to increase the

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efficiency of its operation. This includes for example a more sophisticated Aircraft Communications Addressing and Reporting System (ACARS), a better Controller-Pilot Data-Link Communication (CPDLC) and the usage of an Electronic Flight Bag (EFB), using a notebook as an electronic library, making the cockpit a paperless workplace. The level of automation is helpful during normal operation. In case of an abnormal situation, pilots have to deal with a demanding gradual reduction of automation. This can be challenging because it is rarely practised and may lead to automation surprises. Additionally it needs excellent teamwork among the flight crew.

In flight, during an abnormal situation, the flight crew is confronted with another challenge. Today's manufacturers must be careful to fulfil legal requirements. Liability costs have risen and became unpredictable. Even for major companies like Boeing or Airbus, a liability law suit, due to an accident, may become existential for the company. Those legal circumstances have not made procedures easier. For some emergency situations, procedures become more complex and longer which makes their application in a stressful situation even more difficult for the flight crew. During abnormal situations, dealing with a demanding procedure, the collaboration between the pilot flying and the pilot monitoring becomes more and more important. As an example, simply calculating an actual landing distances on a wet or contaminated runway needs three different steps of calculation which have to be done by the pilot monitoring (pilot not flying). Thus, abnormal situations became prone to errors just because of their complexity and due to their longer procedures. In addition to the challenging handling of automation as mentioned above, complex procedures could increase workload and may lead to additional stress. The need for simplicity in abnormal situations is not sufficiently accounted for.

With the development of information technologies, further changes are underway towards more automation, changing the role of flight crews to “hands-off manager” or “strategic supervisors” [42]. In particular, the SESAR and NextGen initiatives will introduce new technologies which potentially could deeply impact the flight crew role and tasks. Examples of such technologies include information sharing through data-links and automatic broadcast (ADS-B), and cockpit displays of traffic information (CDTI) allowing for the delegation of tasks from Air Traffic Controller (ATCO) to flight crews under certain conditions.

Many simulator studies have already been performed. The correlations between pilot’s performance and the HPE-components are well known and have widely been analysed. Dozens of research projects have been carried out by airlines and universities and the influence of increased workload, stress and fatigue on pilot’s performance have been well documented. The same is valid for the correlation of pilot’s performance, attention and vigilance. The Universities of Munich and Berlin together with Lufthansa have conducted 2 flight simulator studies called SaMSys, including up to 120 pilots. The first SaMSys study was about the evaluation of manual flying skills under the influence of performance shaping factors [72]. The second study was about the Pilot’s performance in abnormal flight situations,

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using procedures and checklists [70]. In the course of both studies - further described below - 23 articles were published about the human performance and its envelope.

The first study addressed manual flying skills, which is one particular aspect of pilots' performance. The study was motivated by the hypothesis that manual flying skills degrade with low level of practice and training, and furthermore with the use of automation ([72], [71]). Another goal was to investigate other Performance Shaping Factors (PSF) such as fatigue. An experiment was thus designed, involving 57 randomly selected pilots divided in two groups: young short-haul co-pilots vs elder long-haul captains. Each participant flew an approach and landing scenario where a missed approach was followed by manual landing without assistance of automation. The performance was measured objectively by deviation from the prescribed landing trajectory. Significant difference in performance was found between the two groups. The results of this study indeed confirmed the hypothesis and support the conclusion that manual flying skills are associated by recent flight practice resulting from frequent flight operations, rather than by operational experience (i.e. number of flight hours).

The second study [70] aims to address another aspect of performance, related to the management of unknown and time critical abnormal situations, and whether checklists and standard procedures adequately support pilots in these situations. The study also addresses the fact that pilots normally have to adhere to Standard Operating Procedures (SOPs) although they can deviate from these SOPs in case it may result in safer consequences, hence addressing decision quality in critical situations. Eye tracking, audio recording and objective performance were recorded. As in the previous study, two groups (long-haul captains and short-haul first officers) for a total of 60 participants were involved. They had to perform a non-precision approach in full mission simulators. The scenario consist of a rather complex sequence of events (hydraulic system malfunction resulting in unsafe landing gear deployment, go around, high fuel consumption due to landing gear down, emergency landing on a new wet runway and second malfunction affecting slat movements). Communication was also used as an indicator of efficient crew resource management. The results of this study are not published yet. However, the hypotheses and experimental settings highlight the variety of factors (e.g. level of practice and training, support provided by automation, checklists and procedures, known vs unknown situations, time pressure, communication) which potentially may affect the pilots' performance.

By the current state of scientific knowledge and as most of the correlations and its impact on human performance are already well known. From the pilots' point of view, there seems to be no need for further HP research outside the cockpit environment. Simply quantifying the correlations among human performance will not help to enforce safety procedures. But it would be in the interest of safety to know when the limits of the human performance envelope are reached. Looking at a scenario with a risk probability of 10e-6, it is important to know whether the flight crew is able to perform the abnormal procedure properly. Does the abnormal situation lead to an accident because of its complexity? Does the pilot monitoring, reading the procedure, support the pilot flying properly in an abnormal situation?

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Where is the limit to all of the above? And whenever the safety of the flight is impaired, the knowledge from the experiment may be used to contact the manufacturer and justify a procedure change.

A proper simulator scenario is the key to success. EASA has set a European safety limit of 10e-7. Every airline operator must be better or safer than those 10e-7. Within a realistic and representative simulator scenario, every pilot must succeed in dealing with any abnormal which has a probability of less than those 10e-7. Within that given safety level, all appropriate abnormals must be handled correctly, not impairing the safety of the flight.

2.1.4. Lessons learned from previous research

Several EC and national research projects have been performed so far to study the impact of human factors on aviation safety. In particular, the human factors issues hit the headlines when new operational concepts are proposed and investigated. According to the scope of this project, we selected a set of research projects that investigated the introduction of new operational concepts to address specific HF issues or that assess the impact of these concepts on pilots' performance. The projects analysed are:

- ACROSS (Advanced Cockpit for Reduction Of StreSs and workload) – FP7 European project;
- EMMA2 (European airport Movement Management by A-SMGCS, Part 2)– FP6 European project;
- HUMAN (Model-based Analysis of Human Errors during Aircraft Cockpit System Design) – FP7 European project;
- Man4Gen (Manual Flying Skills for 4th Generation Airliners) - FP7 European project;
- MOSES (More Operational Flight Security by increased Situation Awareness)– DLR internal project.
- Military studies on Human Factors.

It has to be noted that all the projects focus on a specific sub-set of factors (i.e. Situation Awareness, Workload, and Fatigue) while less attention is payed to others (such as teamwork and trust). Also, the factors are investigated in isolation, i.e. the interaction between multiple factors is not taken into account. Anyway this approach had a proven value for a better understanding of how humans can most safely and efficiently integrate with technology to support cockpit equipment design and certification, and most of the projects' approaches and findings can be exploited by P6.

2.1.4.1. ACROSS review

The ACROSS project aims to design automation that reduces pilots' peak workload in current two-pilot operations and support them in dealing with difficult situations, thus enhancing safety and performance. In particular, ACROSS establishes an integrates research approach to develop, combine and test new cockpit-based technologies to facilitate the management of the peak workload situations

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(including increased stress) and allow a reduced crew to operate safely in a limited number of well-defined conditions. The design of the cockpit automation in ACROSS is inspired by the Level of Automation Taxonomy (LOAT) developed within the SESAR programme to classify and compare different kinds of automation in Air Traffic Management. The taxonomy supports the automation designer in selecting the most adequate level of automation for a specific task, i.e. it helps to balance the involvement of humans and technology, so that the latter is properly designed to support the most relevant mental activities (information acquisition, information analysis, decision and execution) of the operators - which of course ultimately increases Situation Awareness. The review of the project is summarised in Table 1.

Lessons learnt in P6 and relevant project results: the project is still ongoing and will close in one year time. For the time being most of the results are not publicly available to be used as lessons learnt by other projects. With ACROSS conclusion and release of the final report(s), P6 can benefit from the scenarios developed, from the set of new avionics proposed to improve crew task, the results of human factors evaluations (in particular workload and stress) and recommendations for management of reduced crew operations, and from the cockpit solutions proposed to better support crews in the current two-pilot configuration during situations of high stress. P6 can also benefit from the ALICIA (All Condition Operations and Innovative Cockpit Infrastructure) HMI philosophy that was further developed by ACROSS as an intermediate means of providing guidance to address the HMI design issues throughout a project life-cycle.

Table 1: ACROSS project review

Project Name	**ACROSS - Advanced Cockpit for Reduction Of StreSs and workload**
Framework	FP7
Duration, conclusion	3 years, ongoing (Jan 2013 – June 2016)
Project abstract	ACROSS will develop new applications and HMI in a cockpit concept for all crew duties from gate to gate. Human factors, safety and certification will drive this approach. The new system will balance the crew capacity and the demand on crew resource. ACROSS workload gains will be assessed by pilots and experts. A Crew Monitoring environment will monitor physiological and behavioural parameters to assess workload and stress levels of pilots. A new indicator will consolidate flight situation and aircraft status into an indicator of the need for crew resource. If this need becomes higher than available crew resource, cockpit applications and systems will adapt to the new situation: • Decision support: cockpit interfaces will adapt to focus crew on needed actions, • Prioritisation: non-critical applications/information will be muted in favour of critical elements, • Progressive automation: crew actions not directly relevant with the

	situation will be automated, • Decision sharing: in case of persistent crisis situation, an automatic information link with the ground will be established to further assist the crew. In extreme situation where both pilots are incapacitated, further steps will be: • Full automation: measures to maintain the aircraft on a safe trajectory, then reroute to nearest airport and auto land. • b) Decision handling: mechanisms allowing ground crew to remotely fly the aircraft.
Scope	ACROSS develops new cockpit applications and human-machine interfaces covering all safety related crew duties, with the overall goal of reducing crew workload and improving the safety level in two-pilot operations. The project assess workload volume and stress of pilots in different operational conditions including peak workload situations and reduced crew operations. A Crew Monitoring Environment is being studied in order to monitor physiological and behavioural parameters of the crew and a new indicator will be developed to assess crew resource availability. Cockpit applications and technologies are being developed and tested for situations in which the need is higher than the available crew resources.

Operational concept(s) studied	ACROSS addresses two different operational conditions and produces specific operational concept for each of them.
	• Peak Workload – Today, pilots routinely fly in ever more demanding conditions (such as higher traffic densities, more demanding operational constraints and lower visibility conditions). The ACROSS project will contribute to a cockpit environment that mitigates the impact of crew workload peaks in the flight deck and ensures that pilots have the opportunity to address all relevant issues in a timely and effective manner. This is achieved through new avionics functionality, cockpit displays, flight deck and air-ground communication solutions. The project aims to provide, for example:
	  ○ Increased automation in those conditions where this is contributing to increase the safety level of the operation
	  ○ Improved human machine interaction
	  ○ Improved support in the case of abnormal conditions (failures, emergencies, etc.)
	• Reduced Crew Operations – ACROSS develops new cockpit-base technologies that allow one remaining pilot to safely manage the flight. Different situations are addressed:
	  ○ **Intentionally reduced crew in long haul flight**, for a limited period of time during cruise: the need is to support the remaining flight crew in the cockpit while the other one is at rest, and to prevent fatigue by allowing him/her to rest efficiently.
	  ○ **Partial flight crew incapacitation**: ACROSS analyses solutions to help the remaining pilot to perform safe completion of the flight to the nearest suitable airport
	  ○ **Full flight crew incapacitation**, from cruise to landing until

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	aircraft stops (no taxiing).
Technologies:	ACROSS develops and tests solutions for all the main functions of the aircraft: aviate, navigate, manage mission and communicate. In addition, technologies are also developed for crew monitoring and total incapacitation.
TRL - technology readiness level- of the solutions	Solutions addressing peak workload situations are developed and tested up to TRL 5 (technology validated in relevant environment), while solutions for reduced crew operations are developed and tested up to TRL 3 (experimental proof of concept)
Human Factors	Workload and stress, situational awareness, impact on roles and working methods, impact on communication, impact on training requirements.
Scenarios of application	Both Nominal and non-nominal scenarios are taken into account. When analysing peak workload situations the following specific scenarios are also considered: high density traffic, bad weather and emergencies.
Main conclusions/outputs	Tools, technologies and guidelines produced by ACROSS are listed hereafter: • A set of technology solutions for crew monitoring. • A set of new avionics functions with the demonstration of global performance improvement for each crew task, (Aviate, Navigate, Communicate and Manage) specifically during peak workload situations. • A supplementary step in the technical capability for continued safe flight and landing in case of crew incapacitation. • Following initial human factors evaluations, recommendations for management of reduced crew operations, training aspects and evolutions on functions developed. While achieving these goals, ACROSS will also define short-term solutions with short implementation time for immediate use in the cockpit, in order to better support crews in the current two-pilots configuration during situations of high stress.

2.1.4.2. EMMA2 review

The goal of EMMA2 was to develop and validate an operational concept for higher levels of Advanced Surface Movement Guidance and Control Systems (A-SMGCS). It aimed at increasing capacity and throughput at airports which are the major bottleneck in ATM. Its predecessor EMMA consolidated the surveillance and conflict alert functions (also known as Level 1 resp. Level 2), and EMMA2 focused on advanced on-board guidance support for pilots and planning support for controllers and the use of Taxi-CPDLC. The overall A-SMGCS concept is an integrated air-ground system, seamlessly embedded in the overall ATM system.

In order to meet the mentioned objectives, EMMA2 built upon previous work - especially from the ICAO Doc. 9830 on A-SMGCS and from EUROCONTROL. The harmonised concepts of operations were applied and validated by functional and operational testing under real operational conditions with active participation of licensed controllers and pilots from different countries. At first the concept was tested

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in real time simulations for the Prague, Milan Malpensa and Toulouse airport environment and finally in field and flight tests at the airports. Finally the Integrated Project EMMA2 led to comprehensive results which supported the regulation and standardisation bodies.

Within the scope of EMMA2 was the effect of higher levels of A-SMGCS levels on Workload and Situation Awareness. It could be shown that situation awareness increased for both flight crews and ATCOs. Furthermore workload decreased for the operator who used higher level of A-SMGCS.

The review of the project is summarised in Table 2.

<u>Lessons learnt in P6 and relevant project results:</u> P6 can benefit from the approach how scenarios were developed. Secondly the results of human factors evaluations (in particular workload and situation awareness) can be taken into account. Finally P6 might benefit from EMMA2's cockpit solutions for better support of the flight crews during taxiing.

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Table 2: EMMA project review

Project Name	**EMMA2 - European airport Movement Management by A-SMGCS, Part 2**
Framework	FP6
Duration, conclusion	3 years, 2006-2008
Project abstract	The main objectives of EMMA2 were the consolidation of higher A-SMGCS functions in the operational environment. Building upon the harmonised level 1 & 2 ground movement assistance tools and procedures further functions were realised and validated. The higher services of A-SMGCS cover: • Planning (Planning of Runway Operations, Departure Management, Taxiway Planning, Integrated HMI), • Guidance (Airport Navigation Means on-board; On-board HMI; Guidance of the aircraft by data-link (CPDLC) Co-ordination with existing ground based guidance means), • Information Management (Co-ordination of Plans with adjacent centres (Approach, ACC); Handling assistance for hand over the responsibility between Approach and Tower). Within EMMA2 these functions were developed at least as prototypes, the adequate operational procedures were worked out and as far as possible the modular system were validated in an operational environment. Stepping ahead from current Level 1&2 A-SMGCS towards these higher levels, further constraints were taken into account and further applications became possible to get the full A-SMGCS benefit. The project results fed the relevant documents of international organisations involved in the specification of A-SMGCS (ICAO, EUROCAE, EUROCONTROL).
Scope	A main extension of the A-SMGCS concept by EMMA is the holistic, integrated air-ground approach, considering advanced aircraft with pilot assistance systems in a context of tower and apron controllers supported by A-SMGCS ground systems. A mature technical & operational concept as developed through EMMA ensures consistency of traffic information given to controllers and pilots. This is the basis for a common situation awareness and safe ground operations. The associated operational concept defines the roles and tasks of the on-board and ground stakeholders and the procedures from an overall, holistic point of view. The development from reactive conflict detection and resolution towards pro-active conflict prevention will not only increase safety but also efficiency, as small plan deviations will be reduced instead of corrected. EMMA2 was organised in six different sub-projects: four vertical development sub-projects, three dedicated to the development of ground systems for the three test sites and the fourth one dedicated to on-board systems. These four sub-projects were autonomous and independent. This organisation was used to minimise frictional losses to give the partners involved the chance to use their own existing systems. However, these four sub-projects were inter-linked with the sub-projects 'concept' and 'validation' to guarantee that different systems are based on a common A-SMGCS interoperable air-ground co-operation concept and validated with the same criteria. This structure was

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	surrounded by the overall management and a user forum, which was used as a 'speakers' corner' or as an interface to the project for additional users or other interested stakeholders.
Operational concept(s) studied	The operational concept for all A-SMGCS levels for ATCOs and pilots (= mainly taxiing, but also approach and landing)
Technologies	Departure Management, Taxi-CPDLC, ADS-B, TIS-B
TRL - technology readiness level- of the solutions	TRL 7 (system prototype demonstration in operational environment)
Human Factors	Workload, situational awareness, impact on communication. Furthermore impact on roles and working methods, impact on training requirements.
Scenarios of application	Both nominal and non-nominal scenarios were taken into account. Peak workload situations consisted of high density traffic and low visibility.
Main conclusions/outputs	• The derivation of the necessary performance requirements, • A-SMGCS integration in simulators at three airports and in several aircraft • Verification of performance requirements, • Validation of operations, • Guidelines and recommendations to common technical and operational system performance, safety requirements, certification aspects, and procedures for the transition phase.

2.1.4.3. HUMAN review

The objective of the HUMAN project was to develop a methodology with techniques and prototypical tools supporting the prediction of human errors in ways that are usable and practical for human-centred design of systems operating in complex cockpit environments.

The former approach of analysing systems was error prone as well as costly and time-consuming (based on engineering judgement, operational feedback from similar aircraft, and simulator-based experiments). The HUMAN methodology allows to detect potential pilot errors more accurately and earlier (in the design) and with reduced effort.

<u>Lessons learnt in P6 and relevant project results:</u> P6 can benefit from the human errors which were provoked in the simulator trials. Secondly the approach to create scenarios might be interesting for P6. Finally the results of eye-point of regard measurements and the Talk Through sessions (= debriefing) can be taken into account.

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Table 3: HUMAN project review

Project Name	**HUMAN - Model-based Analysis of Human Errors during Aircraft Cockpit System Design**
Framework	FP7
Duration, conclusion	3 years, 2008-2011
Project abstract	A methodology with techniques and tools enabling to considerably improve human centred design of cockpit systems was developed. The methodology integrates (1) a cognitive crew model able to predict design relevant pilot errors, (2) a high-fidelity Virtual Simulation Platform enabling execution of the cognitive crew model, (3) a prototypical tool based on the virtual simulation platform supporting usability of the platform and cognitive model, (4) formal techniques and prototypical tools for analysis of simulator data, (5) a detailed knowledge base about cognitive processes leading to pilot errors and derived guidelines for cockpit system design with a Usability Advisor tool for automatically checking a design against usability guidelines.
Scope	The human errors were studied in relation to a target (cockpit) system, the AFMS (Advanced Flight Management System), with which the crew interacts for navigation activities. The target system based on a future ATM system in the cockpit, with flight management functions and crew interface functionality compatible with 4D flight planning and guidance and trajectory negotiation by means of a data link connection. The interaction with the target system took place during many phases of the flight, where crew activities have to conform to previously specified normative activities (e.g., SOPs). Because of simplification and execution errors, crews tend to deviate from normative activities. A main research goal of the HUMAN project was to develop and validate a cognitive model that predicts these deviations. Two simulation platforms were in use to achieve this objective: a physical simulation platform, comprising a full scale simulator usable for human-in-the-loop experimental simulations and a virtual simulation platform, comprising an aircraft model, a scenario model (e.g. ATC), an environment model (meteorological conditions), and a model of the target system and of its symbolic HMI or user interface, and a cognitive crew model. The virtual simulation platform was used to produce predicted crew activities (with a special focus on human errors) on the dedicated experimental flight scenarios also used on the physical platform to gather actual crew activities. The results on both platforms were compared and the cognitive model improved, based on the discrepancies observed between actual and predicted activities.
Operational concept(s) studied	Operational concept of AFMS during en route cruise
Technologies	AFMS (Advanced Flight Management System)
TRL - technology readiness level- of the solutions	TRL 5 (technology validated in relevant environment)
Human Factors	Human Errors (learned carelessness, cognitive lock-up)

Scenarios of application	Nominal scenarios in real time simulations. Deviations from normative activities were provoked and flight crews tended to simplification and execution errors.
Main conclusions/outputs	Contribution to enhancing safety: • contribution to the objective to reduce the accident rate • reducing the design effort of active and passive safety measures • reducing the effort of flight simulator tests for active and passive safety measures Research dimensions: • Cognitive modelling: an integrated cognitive crew model to predict relevant pilot behaviours (including errors) • Virtual simulation platform: a high-fidelity virtual simulation platform to execute the cognitive crew model in realistic flight scenarios • Knowledge base on human performance: to build up a detailed knowledge base about cognitive processes and to develop formal techniques and prototypical tools to validate and further develop the cognitive model. Improve human centred design of cockpit systems: • a cognitive crew model able to predict design relevant pilot errors, • a high-fidelity virtual simulation platform enabling execution of the cognitive model, • a prototypical tool based on the virtual simulation platform supporting usability of the platform and cognitive model, • formal techniques and prototypical tools for analysis of simulator data, • a detailed knowledge base about cognitive processes leading to pilot errors and derived guidelines for cockpit system design, • a methodology that integrates all the techniques and tools for their application during system design.

2.1.4.4. Man4Gen review

A steady rise in the number of accidents of modern highly automated aircraft (4th Generation airliners) was attributed to the ability of the flight crew to assess and understand an unexpected situation, and consequently respond appropriately to handle the situation, and eventually in some cases limited manual handling skills by pilots. One main objective of Man4Gen is to identify the factors that affect the ability of the flight crew and aircraft to handle unexpected events and gradually deteriorating conditions to maintain effective control of the aircraft. In addition to that, methods were identified to prepare flight crew to deal with unexpected events, using the training, procedures and systems available to operators of highly automated aircraft today.

<u>Lessons learnt in P6 and relevant project results:</u> In Man4Gen's initial phase the background of the problem was established from an academic and an operational perspective. In the next step the

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challenges faced by flight crews were reproduced in an experimental setting to study pilots' behaviour and their responses.

Table 4: Man4Gen project review

Project Name	**Man4Gen - Manual Flying Skills for 4th Generation Airliners**
Framework	FP7
Duration, conclusion	3 years, end of August 2015
Project abstract	While aviation is an extremely safe mode of transport, there has recently been a steady rise in the number of accidents that are attributed to limited manual handling skills by pilots. From the accident data gathered over the past decade, the majority of these accidents and incidents occurred in a phase of flight where the automatic systems were disengaged. Modern, 4th generation, aircraft are extremely safe, and there is a particularly low chance of an accident when operating these aircraft. Automation clearly plays a very positive role in enhancing aviation safety and preventing accidents. However, without a set of skills that also include the ability to manually control an aircraft, to manage the automation systems effectively, always maintain an acceptable level of situational awareness, and remain in control of the aircraft, these accidents will continue to occur. The single largest cause of fatalities in commercial aviation is Loss of Control – In Flight (LOC-I). Invariably, during the chain of events that leads to the accident in a LOC-I situation, the pilot is unable to maintain control of the aircraft by applying manual operation skills to prevent or recover from the situation that lead to the LOC-I. Such instances have occurred in the highly augmented 4th generation aircraft, as well as conventional aircraft, and with experienced pilots fully trained to current standards. These accidents are often due to a combination of the crew not managing the aircraft systems effectively after an unexpected event, and being unable to apply appropriate manual handling skills. Man4Gen aims to identify the common thread behind the events that lead to these accidents, and to recommend short-term changes to operational procedures, training and aircraft systems technology in order to mitigate this threat to aviation safety. By engaging the key members from the industry, research and academia, and applying the two leading facilities for such research, the deliverables of Man4Gen will lead to a much deeper understanding of the root causes of losing situational awareness in highly augmented and automated aircraft, and how this can be improved through both design and procedures.
Scope	Solutions to enable a high level of Situation Awareness supporting robust decision-making in challenging, unexpected situations on modern airliner flight decks, especially when a rapid transition from a monitoring to an authoritative decision-making role is required.

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Operational concept(s) studied:	Training (e.g., Competency-based), procedures (e.g., mnemonics), flight deck displays (PFD and systems)
Technologies	Standardised, objective flight crew performance evaluation, measurement of competency level, display solutions representing impact of failures
TRL - technology readiness level- of the solutions	Training: up to 7 Procedures: up to 5 Flight deck: 3
Human Factors	Situation Awareness and decision-making
Scenarios of application	Mostly non-normal
Main conclusions/outputs	The project is still running. Preliminary results of this project showed that flight crews successfully handling challenging and unexpected flight events exhibited good qualities in several pilot core competencies like leadership and teamwork, problem solving and decision making, communication, and workload management. On the other hand, poor-performing crews had difficulties during low-workload flight events and revealed poor manual flight skills. Good performance in the pilot core competencies seems to be correlated with a resilient flight crew. Therefore, moving from event-based training to competency-based training could be an effective way to train resilient flight crews since it does not allow for the development of memorized skills. The second part of the project is testing whether these core competencies transfer between different scenarios and if they can be measured with a generic desktop exercise. These results will then support the project outputs in the form of training, procedural, and flight-deck-design recommendations.

2.1.4.5. MOSES review

The DLR internal project focussed on measuring situation awareness of pilots. Therefore a multi-metrological approach to record the phenomena was used and proved in tests with more than 80 pilots in the DLR-Institute of Flight Guidance simulator cockpit.

<u>Lessons learnt in P6 and relevant project results:</u> Within MOSES no measurement techniques for SA that directly grab information (SAGAT, SPAM) have been used as one assumed that these techniques disturb the flow of the procedure of the simulation too much and therefore diminish the explorative power of the results. Instead the project followed an approach that is called “implicit measurement” [38] that starts with the design of the simulation scenarios. Finally the results of eye-point of regard measurements and the electroencephalography (EEG), electrocardiography (ECG) data can be taken into account.

Table 5: MOSES project review

Project Name	**MOSES - More Operational Flight Security by increased Situation Awareness**
Framework	DLR internal project
Duration, conclusion	3,5 years; 2001-2005
Project abstract	Inputs by the operator are increasingly restricted in a highly automated environment like the cockpit. In contrast the monitoring task is becoming predominant. Therefore the way pilots gather their information was studied. i.e. their eye movement behaviour as well as their physiological state parameters. Furthermore psychological data of self and objective assessment were used and set into context to the specific conditions of the scenario, the requirements of the system and the system state. Basically simulations were designed in a way that during the simulation events occurred that asked for unambiguous and highly trained reactions from the pilot. In case these reactions did not come up, one could assume a loss of situation awareness. If there was i.e. an object on the runway and the pilot was not cancelling the landing procedure to avoid a collision or was not breaking then this behaviour can be rated as an indicator for insufficient SA, which means that critical occurrences have not or to late been remarked by the pilot.
Scope	Measuring Situation Awareness (mainly level 1) with eye-point-of-regard measurements
Operational concept(s) studied	Approach, landing, taxiing. En route
Technologies	DLR's pilot assistance systems • A-HMI (Airborne Human Machine Interface): interactive navigation display • ADVISE (Advanced Visual System for Situation Awareness Enhancement): the enhanced and synthetic vision head-up display • TARMAC-AS (Taxi And Ramp Management And Control – Airborne System): Taxi-Guidance system
TRL - technology readiness level- of the solutions	TRL 5 (technology validated in relevant environment)
Human Factors	Situation Awareness, Workload, Fatigue
Scenarios of application	Cooperative, uncooperative obstacles whilst taxiing (aircraft/ further vehicles like fuelling vehicles.
Main conclusions/outputs	Use of eye-point-of regard measurement to give insight in loss of situation awareness

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2.1.4.6. Military studies review

Flight psychophysiology was the subject of a special issue of the Int. Journal of Aviation Psychology (vol. 12(1), 2002) which presents several studies in the field of military aviation with an emphasis on inflight measurements.

Wilson [163] presents an analysis of mental workload during flight performed at the US Air Force Research Lab (AFRL) and using multiple psychophysiological measures. Heart rate, heart rate variability (ECG), eye blinks (EOG), electrodermal activity (EDA), electrical brain activity (EEG), and subjective estimates of mental workload were recorded. Interestingly, electromyography (EMG) was also recorded in order to examine the possible effects of muscular activity over EDA. Ninety (90) minutes flights were performed on a single engine trainer aircraft (Piper Arrow) including VFR and IFR flight. The study in fact involved ten general aviation pilots instead of military pilots. Two flights were performed by each pilot at intervals of several days, with the aim to investigate the variability of the measures over long periods. The results showed no significant differences between the data from the two flights, thus confirming the consistency of the measures over a long period. They also showed significant changes of the psychophysiological measures depending on the flight segments, with take-offs and landings producing the greatest number of changes. Heart rate, EDA and EEG alpha and delta band were found as the most sensitive markers of the cognitive load during these flight phases, while HRV was not as sensitive. High correlation was found between heart rate and EDA. Discrepancies were reported between the heart rate and subjective rating, suggesting that the mechanisms underlying these responses are different. In particular familiar procedures produced low workload estimate, while heart rate may be more sensitive to actual demands placed on the pilot, No interference of the muscular activity (EMG) was found with EDA. In summary, the study confirm the value of multiple psychophysiological measures, each providing complementary information beyond that available from subjective measures alone.

Caldwell et al. [21] present an investigation of the US Aeromedical Laboratory regarding the use of EEG to detect fatigue resulting from flight deprivation. The measurements were collected from UH-60 helicopter pilots during actual training flights and laboratory tests over one full night. Mood evaluation was also performed using the Profile of Mood States (POMS). The study showed EEG effects both in the laboratory and in flight. They suggest that it is possible to monitor increase of fatigue via acquisition of EEG activity from inflight environment.

Veltman [150] evaluated psychophysiological measures in a flight simulator and in a real aircraft. Heart rate, HRV, respiration (frequency and amplitude), blood pressure, eye blinks and saliva cortisol were recorded with the aim to measure workload (mental effort). The participants were 24 selection candidates of the Netherlands Air Force. They had to perform basic manoeuvres both in the simulator and in a small dual-seat aircraft. Mental effort was also rated subjectively by use of a Rating Scale Mental Effort (RSME). Blood pressure was difficult to measure in flight and thus was finally not discussed. While the participants rated their effort higher in the simulator than in real flight, no

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difference was found on HR, HRV and respiration frequency. Respiration amplitude was slightly higher during real flight. Eye blinks significantly differed in real flight, which may be partly explained by the limitations of the simulation environment, providing instrument only without outside view. A relatively large increase in cortisol values was found during the real flight. In short, this experiment shows that cardiovascular, respiration and eye activity can be measured quite easily in real-flight situations and reflect the effort investment. However, robust data were obtained only with averaged data over long time periods and with a substantial number of participants. The conclusion states that more research is required before physiological data can be used to measure mental effort of one individual within small time windows.

Magnusson [102] reports a study regarding the psychophysiological reactions of fighter pilots from the Swedish Air Force in simulated and real flight. Heart rate, HRV and eye movements were continuously recorded both in the simulator and in the actual aircraft - a single-seat SAAB 37 Viggen combat aircraft. Each pilots performed six attack missions including weapon delivery, the first three in the simulator and then three in real flight. The physiological data were standardized in order to cancel the inter individual differences. As in the previous study, the results suggest that there is very little difference in the reaction patterns between simulated and real flight, although the activity levels significantly differ. HR, HRV and eye activity were found sensitive to the actual flight conditions and associated mental workload. An effect was also found of the flight replication, with higher levels for the first flight than the next two, as shown for instance on Figure 3 that illustrates the differences in heart rate among the three times the mission was flown.

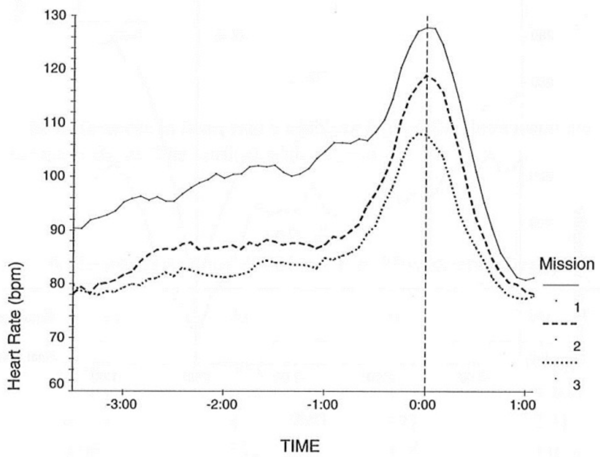

Figure 3: Effect of flight replication and time before weapon delivery on averaged heart rates [102].

Skinner & Simpson [137] discuss the workload issues of modern 2 pilots military airlift (Hercule C-130) operated by the Australian Air Force and propose a workload assessment strategy based on aircrew and mission performance, subjective assessment and psychophysiological index (HR). The tactical environment of the airlift missions imposes high demands on the flight crew for navigation, timing, systems and automation management. The study focused on the radar navigator during a low level ingress mission at night. The HR show a high sensitivity to mission events, consistent with subjective ratings.

Svensson & Wilson [145] analyse the effects of mission task complexity on mental workload, situation awareness and performance. A first study used subjective ratings collected at the end of 144 missions involving 20 military pilots of the Netherlands Air Force, flying the SAAB 37 Viggen aircraft. A second part of the study involved 15 fighter pilots of the US Air Force in simulated flights. HR, Fixation Rate (FR) and Blink Rate (BR) were recorded. The same statistics were used in both parts of the study. HR was found to have a high correlation with the perceived mental capacity. HR, FR and BR show similar patterns in simulated and real flight and were sensitive to the changes in taskload. Both parts of the study also supported a model for relationships between workload, SA and performance, where workload is seen as impacting SA which itself impacts performance.

<u>Lessons learnt in P6 and relevant project results</u>: A conclusion of this set of military studies is that psychophysiological measures used in combination of subjective ratings and performance criteria can actually support the analysis of crew activity, even in the case of demanding missions. Cardiovascular and ocular activities were found sensitive to task demands. Furthermore, they can quite easily be applied in real flights for research purpose, they show similar trends between simulated and real flights and they proved to be robust over long time periods.

It should also be noted that these measures are now likely to be more easily deployed because of new technologies for mobility. On the other hand, military aviation currently sees a trend similar to civil aviation towards more automation and shared information, thus changing the role of humans to managers and making the pilots' task less observable.

2.2. HPE Components review

Once discussed the Human Performance concept in aviation and analysed the results of previous research projects, we move on the review of the Human Performance Envelope Concept looking for a shared definition of the concept and its boundaries. The definition of the HPE Concept passes through the review of aviation human factors studies and cognitive science literature, which results in the identification of the HPE components affecting the performance and their interdependencies.

The starting point of this literature review is Tamsyn Edwards PhD thesis [43] and supporting papers ([44], [45]). Edwards thesis introduced the Human Performance Envelope concept and applied it to the

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ATC context. While previous research was focused on the effects of single factors on performance, the objective of the thesis was to investigate the relationships between multiple, co-occurring factors and their association with human performance.

A literature review, an incident report analysis and a survey of air traffic controllers confirm that factors co-occur in ATC and may interact to negatively affect performance. A first set of nine factors (Figure 4) and their relationships were identified through the literature review [45]. The number of research articles addressing each factor is also shown on Figure 4 by the size of each factor's bubble.

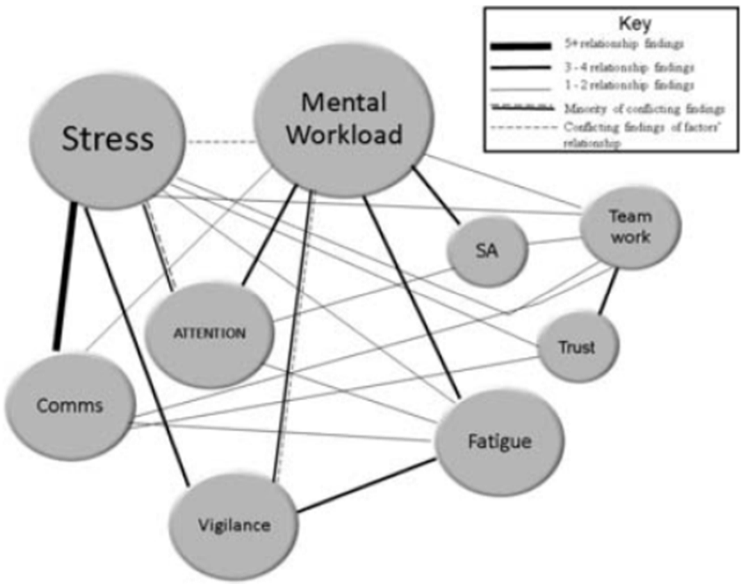

Figure 4: Frequencies of research articles relating to factor interactions according to literature review performed in Edwards thesis [45]

Some comments regarding these factors have a peculiar importance when considering their extension and application to other domains:

- Most of these factors (e.g. Stress, Workload, Vigilance,..) relate to psychophysiological constructs which may be experienced by the controller or crew member during his/her activity. These can be considered as primary factors which indeed are recognised to possibly affect human performance.
- Some of these factors may be considered as closely related (e.g. Vigilance, Attention and Situation Awareness) and thus may require a clarification effort to avoid possible ambiguities, especially when discussing the factors with operational experts.
- Last, some factors (Communications, Teamwork) are of a different nature as they relate to the quality of a specific practical dimension of ATC or flight crew work. These two factors thus may be considered as secondary factors although their quality may indeed affect the performance of the individual crew member.

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- Trust was seldom addressed and other factors (e.g. memory, perception, motivation, engagement, skills and expertise) were also identified as possibly affecting performance under certain conditions –although they may be considered as pre determinant of the performance of a crew rather than rapidly evolving factors on the timeframe of one day of operation.

Some dyadic relationships were also identified, in particular between Workload and SA, Fatigue and Vigilance, Vigilance and Stress. No research was found addressing the relationships between more than two factors. A conclusion of this work was that further research was needed to investigate the nature of dyadic and triadic relationships, and the impact of factors interactions on performance.

The ATC incident report analysis revealed that Attention, SA and Communication contribute to more than one third (33%) of the reported incidents. Perception and Memory were also often reported as contributing factors to incidents. Dyadic relationships were found between Attention/Vigilance and Communication, Situation Awareness and Memory.

The ATC survey was conducted to investigate the understanding of seven factors and their effects within the ATC community. While Workload was addressed by two distinct factors (high workload and under load), Vigilance and Attention were considered under the general notion of SA and Trust was not specifically addressed, as closely related to Teamwork. Dyadic relationships were again pointed out between high Workload and Teamwork, SA and Communications. An hypothesis was raised that the level of Workload may be a determinant of the impact of other factors on performance, which calls for further investigation. As a synthesis, Figure 5 shows the dyadic relationships identified in the course of T. Edwards studies.

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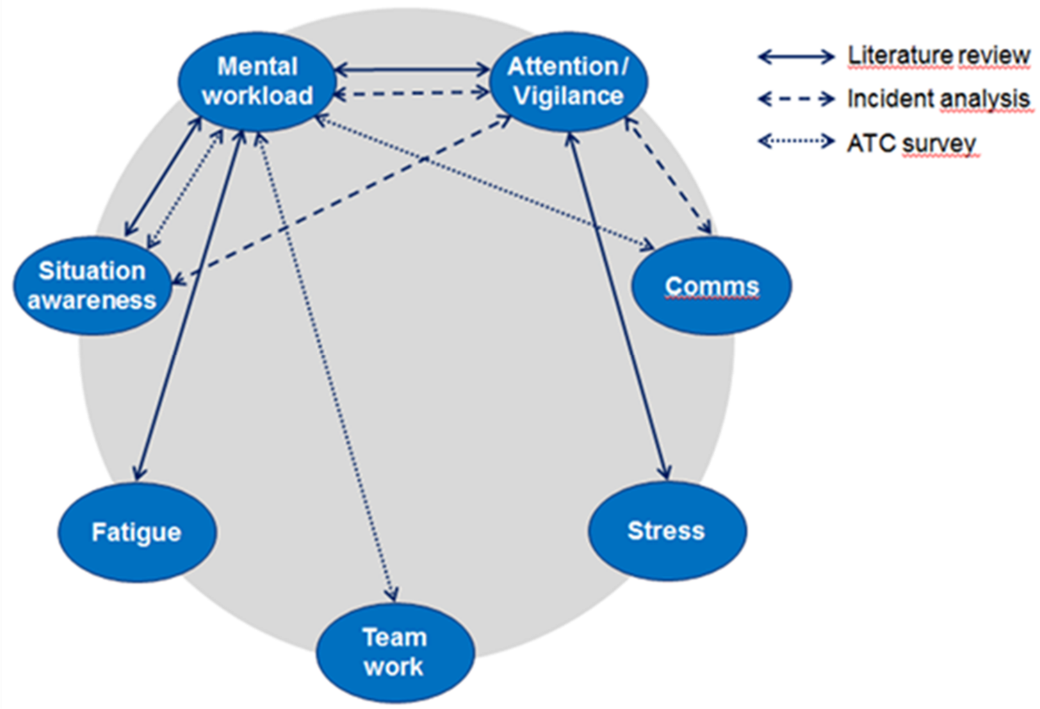

Figure 5: Dyadic relationships identified in Edwards's work

Using Edwards thesis as a starting point for the state-of-the-art, P6 focuses on the same nine factors, i.e. Mental Workload, Stress, Fatigue, Situations Awareness, Attention, Vigilance, Teamwork, Communication, and Trust. The goal here is to integrate Edwards literature review for each factor and investigate the factors with respect to their influence on pilot's performance. With respect to Edwards' findings, the HPE concept for pilots can be reduced or integrated with other factors that might be relevant for pilots activities.

The results of literature review are illustrated in the following sections. For each component of the HPE we provided a shared definition(s) as it is reported in previous research, the behavioural markers, including indicators of successful and degraded human performance, and the recovery measures and mitigation means currently envisaged (if not used yet) in the aeronautical domain. Mitigation is considered as steps taken to control or prevent a hazard from causing harm and reduce risk to a tolerable or acceptable level, while recovery as the actions put in place in real-time to handle the hazard (i.e. to restore the system to its nominal - pre-failure - state or at least to limit the consequences of the failure).

An extensive list of measures/techniques for each factor was also extracted from literature review. In particular, two kinds of measures were taken into account:

- Task-related measures: refer to subjective assessment and measures related to the execution of the task (i.e. accuracy, duration etc.);

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- Psychophysiological measures: refer for instance to brain, cardiac respiratory, eye, blood flow, muscle and electrodermal activity, from whose variation it can be detected a neurophysiological change in the operator state (e.g. Electrocardiography, Electrooculography etc.).

To improve the document readability, the full list of measures for each factor is directly illustrated in the HPE Factors Cards in Appendix A. The cards also contain all the other data coming from literature review and consolidated during the HPE Concept workshop (see Section 3), and illustrate in a synthetic and structured way the HPE components, as they are shared and intended to be used in P6.

Table 6 summarises the studies included in the literature review for each factor. A quick overview of the table shows that Workload and Stress have been the most investigated factors in the aviation research, while few studies were conducted on Fatigue. Most of the literature review on Fatigue was thus performed through cognitive studies together with some research activities on car drivers. Situation Awareness is another relevant topic in aviation and several studies were found on this topic. However the distinction between Situation Awareness, Attention and Vigilance was often unclear and the concepts seem to overlap in most of the cases. It also emerged that the impact of Communication, Teamwork and Trust on aviation operators performance is mostly unexplored.

Table 6: Literature review summary

HPE factors	Pilots references	ATC references	Generic
Mental workload	Roscoe, 1992, 1993; Veltman & Gaillard, 1996, 1998; Caldwell et al., 1994; Jorna, 1993; Comstock & Arnegard, 1992; Wilson, 2002; Hart & Staveland, 1988; Hankins & Wilson, 1998; Wison et al., 1994; Borghini et al., 2012;; Callan, 1998; ACROSS/WP1, 2013	Brookings et al., 1996; Costa, 1993	Hockey, 1997; Eggemeier & Damos, 1991; Gopher & Donchin, 1986; Fairclough et al., 2005; Aasman et al., 1987; East, 2000; De Waard, 1996; Jorna, 1992; Klimesch, 1999; Wilson et al., 1999; Gevins & Smith, 2003; Van Orden et al., 2001
Stress	; ACROSS/WP1, 2013; Stroks & Kite, 1994; Martinussen & Hunter, 2010		McEwen & Sapolsky, 1995; Frankenhaeuser, 1986; Ursin & Eriksen, 2004; Lundberg, 1995; SENSATION/WP1.1; McEwen & Seeman, 1999

HPE factors	Pilots references	ATC references	Generic
Mental fatigue – drowsiness	Muzet, 2003		Hargutt & Krüger, 2000; Schleicher et al., 2008; SENSATION/WP1.1; SENSATION/WP4.4; Slater, 2008; Åhsberg et al., 1997; Marcora et al. 2009; Grandjean, 1970; Picot et al., 2012; Hargutt, 2003; Santamaria and Chiappa, 1987
Situation Awareness	Harris, 2011; Endsley, 1995;; ACROSS/WP1, 2013; Boy & Ferro, 2004; Harris, 2011; Bell & Lyon, 2000; Borghini et al., 2012; Lundberg, 1999; Nählinder, 2004, 2009; Endsley and Garland, 2000		Smith & Hancock, 1995; Parasuraman et al., 2008
Attention		Hitchcock et al., 2003	SENSATION/WP1.1; Eysenck, 2001; Zomeren & Brouwer, 1994; Shallice, 2002; Klimesch, 1999; Warm et al., 2009; Hollander et al., 2002
Vigilance		Hitchcock et al., 2003	Smit et al. 2004, 2005; Mackworth, 1957; Warm et al., 2008; Davies & Parasuraman, 1982; Parasuraman, 1998; Kamzanova et al., 2014; Warm et al., 2009; Hollander et al., 2002
Teamwork		Edwards, 2013; Bailey, L. L. & Thompson, 2000; Seamster et al., 1993	Erdem & Ozen, 2003; Rasmussen & Jeppesen, 2006
Communication	Huttunen et al., 2011; Kanki et al., 1991	Edwards, 2013; Rognin and Blanquart, 2001	Hogg & Vaughan, 2002; Gibson et al., 2006
Trust		Edwards, 2013; Bonini, 2001; Bonini et al., 2001; Wickens et al., 1997	Costa et al., 2001; Kiffin-Petersen & Cordery, 2003; Mishra, 1996; Muir & Moray, 1996; Erdem & Ozen, 2003; Wickens, 2002

2.2.1. Workload

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Workload, or more precisely Mental Workload, refers to the portion of operator information processing capacity or resources that is actually required to meet system demands [46]. This hypothetical construct describes the extent to which the cognitive resources required to perform a task have been actively engaged by the operator [63]. Workload is not an inherent property, but rather it emerges from the interaction between the requirements of a task, the circumstances under which it is performed, and the skills, behaviours, and perceptions of the operator [69].

Workload on the flight deck is, on a normal day, predictably cyclical for every flight and fluctuations between low and high workload are common both for crews and ATCO teams. Variations in traffic-load, although adverse weather, degraded equipment, loss of aircraft and other non-normal situations that can trigger abnormal or emergency procedures, may cause workload peaks[2]. Other situations that can cause high workload conditions are: last minute changes during take-off, approach and landing stages that can overload the pilots, low visibility, and incapacitated crew.

High workload states have an impact on operator's performance. However, understimulation could be risky as well. Situations of low taskload can easily lead to the experience of low workload (or underload) that can result in boredom and a reduced level of alertness [158]. Many studies have also indicated that operator's vigilance decreases after time with the absence of changes in the environment. This means that the ability to act correctly and rapidly on the occurrence of events decreases over time. It will be then more difficult for an ATCO or a pilot to detect and react to an unexpected event when it occurs after a long period of low taskload. It has been found that several ATC-related accidents happened during conditions of understimulation and low workload, often related to work monotony. Monotony occurs in simple, repetitive tasks or in low stimulation situations, and results in a state characterized by physiological deactivation, sleepiness, boredom and connected with performance fluctuations. However, an attempt of maintaining attention at a sufficient level in low taskload conditions can generate the experience of high workload in the operators [157].

Straussberger and Schaefer ([143], [144]) used physiological methods in ATC studies, finding that a deactivation in correspondence with heart rate decrease and heart rate variability increase. It confirms that traffic repetitiveness and very low (dynamic) traffic density evoke a state of monotony, recognisable with a reduced physiological activation, subjective sleepiness and behavioural impairments. At the same time, they observed reduced workload but also impaired cognitive functions, while fatigue increased with higher time-on-task.

It is well known and demonstrated that an increase of workload and task difficulty lead to a performance decrement that reflects in a decrease of accuracy and number of completed tasks, while

[2] Extract from HindSight 21, June 2015, focused on Workload. Article: Workload and the surprise factor, by Captain Ed Poole. Link: http://www.skybrary.aero/bookshelf/books/3067.pdf

reaction times and number of errors increase. The increase of mental workload could lead to a decrement of Situation Awareness which, in turn, could lead to worse performances ([113], [114], [49]). However, the adoption of compensation strategies by the subject (e.g. strategy adjustment, fatigue after-effects and speed-accuracy trade-offs) can result in the lack of visible effects of workload variations on subject performance.

Different methods and techniques have been used to measure workload, including the use of secondary tasks: NASA-TLX, eye tracking and electrocardiography (the full list of measures can be found in Appendix A – Workload Card). From literature review, it seems that the most reliable measures of mental workload can be obtained with a combination of EEG, ECG, Electrooculography (EOG) and subjective data.

Few studies investigated behavioural markers associated with workload variations. In aviation, pilots behavioural markers are used in Crew Resource Management (CRM) courses to teach pilots about non-technical (cognitive and social) skills that are essential for effective and safe flight operations. In CRM, workload is mentioned as one of the elements to be observed, but the observation regards how the operational tasks are prioritised and assigned to the crew instead of how the pilot behaviour change in high/low workload conditions. Thus, the CRM markers can be useful for Teamwork, Communication and Trust assessment but not for other HPE components. An interesting work on the use of behavioural markers as indicators of ATCOs' performance decrement is the experimental study conducted by Edwards [43], in which the relationships between single factors (workload, fatigue, stress, arousal, SA) and performance measures (STCA frequency, route direct frequency, time to assume aircraft and time to respond to offered aircraft) were investigated, together with a set of associated observed behaviours. A set of 52 behaviours were selected and their correlation with factors and performance measures was analysed. The results are summarised in Table 7.

The Table shows how workload seems to be related to ATCOs seat position, mouth open, mouse holding, smiling, use of negative words, facial expressions such as pout and head movements. The study also revealed a significant, positive correlation between posture and workload. However, Di Nocera et al. [33], in a study on motor restlessness as an indicator of mental workload, found that greater restlessness effects were associated to the low workload condition instead of the high workload one. People apparently make more incidental motor activity when taskload is low, and the authors interpreted this data as a possible consequence of boredom. These conflicting results can be explained by noting that behavioural markers can be dependent on the operational scenario and on the performed task. As none of the two studies was conducted on pilots performing real or simulated flying tasks, the visible effects of workload variation on pilots' posture still has to be explored.

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In fact, all the markers listed above should be tested and validated in a cockpit, with pilots performing a set of specific tasks. Other aspects that might be observed and tested are the pilots heart rate, respiratory rate and eye blink rate and duration, all of them associated to high workload conditions.

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Table 7: Spearman's Correlation coefficient for behavioural indicators, self-reported factors and performance measures across 5 taskload periods [43]

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

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

Finally, another point of Edwards study is worthy to be mentioned here. As the operators (ATCOs in her study) might adopt compensation strategy to ensure the quality of the performance, other indicators, not directly associated with performance, might be needed. Based on semi-structured ATCOs interviews, she identified two types of indicators:

- Internal (subjective to the controller);
- External (observable indicators).

She found out that changes of subjective feelings and performance changes were reported as important indicators that a controller may be reaching the edge of performance. In comparison, physiological changes and visible cues indicators were not interpreted to indicate that a controller was reaching the edge of his performance or that a potential performance decline was likely. From interviews analysis she was able to identify several internal indicators in high workload conditions, that she categorized in “Cognitive changes” (don't know the next steps; reduced self-awareness, etc.), “Changes to control” (reactive, no back-up plan, no space for unexpected event/ working to capacity…), “Physiological changes” (heart beat faster, sweat, red cheeks), and “Subjective feeling” (feeling of losing control, panic and uncertainty, not comfortable). The indicators change in the low workload condition, where the Cognitive changes mentioned were “pay less attention” and “easily distracted”, the changes to control

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"leave situations develop for longer" and "trying to create more complex situations" and the associate subjective feelings mentioned were "boredom" and "relaxed".

Among the external indicators of high workload condition, she mentioned changes in the perception (Can't talk to executive/ executive doesn't hear you), visible cues (Fidgety, move closer to screen, colleagues not talking to one another), changes to voice (talking faster/ more "say again", change in the tone of voice), the verbal cues already mentioned (swearing, blaming others) and the performance changes (miss actions, mixing call signs, can't see simple solution, overlook aircraft). In low workload condition, it can be noticed a change in the perception (often related to an incorrect assessment of the situation), a different posture (sit back in the chair, away from radar screen) and behaviour with colleagues (more talkative) and with visible performance changes (overlooking aircraft, forgetting aircraft, repeated "sloppy" mistakes, fall behind traffic due to distraction).

Recovery measures and mitigation means

Recovery and mitigation means are proposed for high and low levels of workload, as both extremes are potential sources of errors.

WORKLOAD	Mitigation	Recovery
Technical	Automation and information system design Procedures	Alarm and attention getters (combination of light, sound and vibration to alert the pilot) Maximum use of automation in flight and on ground Support system for information filtering, guiding the situation analysis and the decision making (e.g. HMI, Autopilot, FMS)
Organisational	Task definition and repartition (e.g. taskload smoothing, through task allocation and task balance over time and among pilots) Staffing arrangements, scheduling and rostering (e.g. keep consecutive night shifts to a minimum, keep long work shifts and overtime to a minimum, consider different lengths for shifts, examine start-end times, examine rest breaks) Training on how to handle workload issues (detect and react) Workload monitoring programme (e.g. post flight debrief, issues reporting)	Operational documentation (FCOM, procedures, check-list for task sharing and reallocation) to guide the pilot in situation handling (e.g. monitor relevant indicators, parameters) throughout the whole process (i.e. until the end of the situation) Break in the current activity (either to break the routine effect or to reduce the overload) Giving responsibilities to other people within the organization Changing Processes

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Individual / Team	Awareness of other's tasks requirements	Assessment (or at least detection) of others' current workload (either in the cockpit or on the ground through party line) Task sharing and/or reallocation • In the cockpit (PF/PNF) • With the ground • With the automation (e.g. auto-pilot) Task prioritisation and changes in strategy (e.g. postpone tasks, reject controllers' requests, reduce communication load)

2.2.2. Stress

According to psychological theories, stress is determined by the balance between the perceived demands from the environment and the individual's resources to meet those demands ([59], [100]). According to Cognitive Activation Theory of Stress (CATS, [148]), stress is a response to certain external demands that usually corresponds to an automatic increase of the cognitive processes and neurophysiological activation and arousal, even if it's possible that in certain situations and for certain individuals the stress response implies an activity decrease. Stress can be categorized into two basic forms:

- acute stress, is of relatively short duration and is often experienced as high workload caused by high taskload;
- chronic stress, is prolonged stress that can result from occupational or non-occupational sources.

McEwen and Seeman [107] described four possible situations that may cause chronic stress: too frequent stress exposure, failure to habituate to repeated exposure of the same kind of stressor, inability to shut off the stress response, despite that stress has terminated, and situations that cause regulatory disturbances of the stress system.

It has been seen that stress can influence performance and may impair attention and memory [106], and can contribute to an increase of human errors and accidents. In general, stress affects how we perceive and process information, as well as what decisions we make, leading to an increase in the number of errors and mistakes. The most common behaviour effects are ([142], [104]):

- attentional narrowing or decrease in attention levels which translates into perceptual (narrower field of vision, selective hearing) and cognitive tunnelling;
- scattered and poorly organized visual scan;

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- reductive thinking and filtering (considering only a few hypotheses, thus rejecting certain tasks or ignoring some warning signs);
- premature closure (making a decision without exploring all information);
- hurried decisions, even when there is no time pressure (leading to the speed accuracy trade-off). Not surprisingly, the best decision-makers seem to be those who take their time under stress;
- decrements in working memory capacity and retrieval.

Throughout a video camera pointed to the operator is possible to detect fast and frequent head movements, body position changes, and some negative facial expressions like asymmetric lip deformation, which are usually associated with stressful situations. Stress also modifies the pilot behaviour like voice prosody. Use non-standard phraseology when communicating, fail to understand what is being said over the radio, revert to the use of their native language if different from the one being used (usually English), or look for items in a place where they used to be, but are no longer located. It has been also seen that respiratory rate increases in stressful conditions.. Increased blinking frequency and eye movements are detected in stress conditions too.

Edwards study on ATCOs [43] confirms that facial expressions (open mouth, smile, frown, pout), head movements (shake head, jerky head movements) and verbal cues (negative words, communication changes, shouting) are good markers of stress. Other observable indicators identified by Edwards are the demeanour changes (easily frustrated, angry/confrontational, sad, blaming others) and performance changes (falling behind, incorrect instructions). Markers of internal, physiological changes identified were heartbeat and sweat, with negative feelings such as uncomfortable, anxious, nervous, tense. Finally, findings from Di Nocera et al. [33] suggest that posture may be used as an observable indicator of experienced workload and stress.

Although there is no reliable "golden standard" measure for the assessment of stress, some experts claim that heart rate variability is the best indicator of stress. This system should give an overall view of the stress level, but it is probably not useful when the stress process should be followed in great detail. Another interesting psycho-physiological measure of stress is the pressure/grip force, measured through specific pressure/grip sensors on seats and tools.

Recovery measures and mitigation means

Excessive stress could be a source of failure in the decision making process (from the information collection, analysis and interpretation up to the execution phase). However too low levels of stress could also be an indication of being "out of touch" with current situation. As a consequence, mitigation and recovery means for both cases are proposed below.

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STRESS	Mitigation	Recovery
Technical	Automation and information system design	Maximum use of automation in flight and on ground Support system for information filtering, guiding the situation analysis and the decision making (e.g. HMI, Autopilot, GPS)
Organisational	Awareness session on the consequences of stress degradation (too much stress: difficulty to focus, to make decision vs too low stress: complacency, reduced vigilance) Stress and well-being training programme Training and practice of stressful situations (e.g. to engage in getting new knowledge about incidents and situations not yet encountered) Stress monitoring programme (e.g. for chronical stress), providing opportunity to share concerns, including the process/mechanism for stress reporting (e.g. knowing where and who to report to, and that there are no negative consequences) Task definition and repartition (e.g. taskload smoothing, through task allocation and task balance over time and among pilots) Staffing arrangements, scheduling and rostering (e.g. avoid non-rotating night shifts, keep consecutive night shifts to a minimum, keep long work shifts and overtime to a minimum, keep the schedule regular and predictable, examine rest breaks)	Operational documentation (FCOM, procedures, check-list for task sharing and reallocation) to guide the pilot in situation handling (e.g. monitor relevant indicators, parameters) throughout the whole process (i.e. until the end of the situation) Break in the current activity (either to break the routine effect or to reduce the overload)
Individual / Team	Behavioural training on stress management, including awareness of stress impact on self and on others Practice regular exercise and relaxation routine	Communication with others (pilot, airline, ATC) to express concern regarding own or others' stress level, share situation analysis and decision making Relaxation exercises

2.2.3. Fatigue

Fatigue is a multidimensional state that includes physical, mental and related to sleepiness components [4]. According to Marcora et al. [103] mental fatigue is a psychobiological state that is caused by prolonged periods of demanding cognitive activity. Fatigue has also been seen as a gradual and cumulative process associated with an aversion for effort, sensation of weariness, reduced motivation, efficiency, vigilance and alertness, and impairments in task performance [64].

Despite the amount of research on this factor, the fatigue concept is still poorly understood within the scientific community [105], there is no developed theory concerning its origins or functions, and different types of fatigue (mental, physical, sleepiness) are usually mixed. Also, a standard definition of fatigue is still missing [75]. In particular, it's difficult to discriminate between mental fatigue and drowsiness as they show such similar neurophysiological patterns that they can be seen as mental states along a continuum. Drowsiness is an intermediate state between wakefulness and sleep defined as a progressive impairment of awareness, associated with a strong desire or inclination for sleep [138]. Mental fatigue and sleepiness can be regarded as a consequence of sustained mental activity and lack of resources due to mental task execution, but also as a result of monotonous and boring situations when demand for sustained attention is high but little information is conveyed. In this case, monotony can be regarded as a source of task-induced mental fatigue that contributes to performance deterioration and strengthen the fatigue response stress.

From literature review, a lack of studies on sane and no deprived-sleep subjects emerged, as well as the absence of standardised methods for drowsiness. Apparently, the more reliable techniques to monitor drowsiness state are EEG and Electrooculography (EOG), possibly combined. In drowsy state, these physiological measures show:

- EEG alpha activity that starts to appear or increases in spectral power density as a relatively early sign of drowsiness.
- EEG theta activity that starts to appear or increases in spectral power density as a sign of severe drowsiness; Theta >50% of the epoch is sleep onset.
- EOG slow eye movements usually start to appear in connection with sleep onset and severe sleepiness.

A method to quantify drowsiness, using EEG and EOG as a reference indicator, is a visual scoring called Objective Sleepiness Scales (OSS) developed by Muzet et al. [112]. This is based on the evaluation of drowsiness executed by expert doctors who visually observe (after driving) alpha and theta activity on a short-time window of data recorded during driving.

Effects of fatigue/drowsiness on human performance can be usually seen in the decrease of quality and accuracy of task performance, as well as in the increase of reaction times and reduction of decision ability. It can be said that drowsiness reduces the overall ability of single and multiple tasks execution. Examples of ATCOs performance changes [43] are multiple small mistakes, frequency checks,

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overlooking aircraft, mixing up call signs, don't hear read back, incorrect plan without realisation, inappropriate reactions, “running behind traffic”, forgetting/ surprise.

Among the behavioural markers, Edwards [43] mentioned yawning, laid back, eyes closed, falling asleep, slower speech, more discussion with CC, looks tired, colour of face, less active, and quieter as indicators of ATCOs fatigue/drowsiness. From our literature review, the increase of eye blinking and narrow gaze (impaired tracking and scanning of the environment), facial tone decreases and frequent head tilts seem to be associated to mental fatigue. The face in other directions, e.g. down or sideway, for an extended period of time can be related to fatigue or inattention too.

Slightly different markers were found for drowsiness. According to Muzet [112], some characteristic movements and attitudes are typical of pre-falling-asleep phases: yawning, body repositioning movements, head movements and all the arm/hand movements performed by the subject in direction of his head; for example movements for scratching some part of his head (nose, hair, eyes, etc.), movements of the hands in the hair (all the commonly called “auto-centred movements”). Among the various potential limb and body movements, the following ones are characteristics of a drowsy state:

- movements of the upper part of the body: for example the back of the pilot moving forward;
- re-positioning of the pilot body onto the seat rest: for example a change of the pushing zone on the back or on the rest of the seat;
- movements toward a "sink" position (in the upper part of the seat);
- movements of the neck or falling head;
- auto-centred movements.

Eye blinking and narrow gaze are associated to drowsiness too, as the decrease of respiratory rate.

Recovery measures and mitigation means

FATIGUE	Mitigation	Recovery
Technical	Optimal use of automation in flight and on ground (i.e. trade-off between fatigue/workload reduction and sleepiness/disengagement risk) Support system for information filtering, guiding the situation analysis and the decision making (e.g. HMI, Autopilot, FMS)	Support systems to alert the pilot: bright light, sound and vibration Working environment to keep pilots awake and alert: bright lights, cool dry air obtrusive or loud music, some invigorating aromas (such as peppermint) Sleeping area

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Organisational	Fatigue monitoring programme Training and information programme on fatigue awareness and management (best practices on fatigue monitoring) Task definition and repartition (e.g. taskload smoothing, through task allocation and task balance over time and among pilots) Staffing arrangements, scheduling and rostering (e.g. avoid non-rotating night shifts, keep consecutive night shifts to a minimum, plan free weekends, keep long work shifts and overtime to a minimum, consider different lengths for shifts, examine start-end times, examine rest breaks)	Workload (re)distribution through task sharing and/or reallocation (rostering, role changes, increased automation level) Break in the current activity (either to break the routine effect or to reduce the overload) Giving people the opportunity/right to sleep
Individual / Team	Behavioural training on fatigue monitoring and management Routines to keep oneself alert and reduce the risk of fatigue	Sleep Awareness on current fatigue level through feedback from self and others Keeping awake & alert: Caffeine, nutritious diet, walking, stretching & chewing gum, active conversation, strategic nap (e.g. 30min.) Activity break, possibly mixing tasks requiring "high" physical or mental work with low-demand tasks Tasks and strategy prioritisation, e.g. to focus on safety and prefer non complex strategies when fatigued

2.2.4. Situation Awareness

Situation Awareness (SA) has been defined as the up-to-the minute comprehension of task relevant information that enables appropriate decision making under stress [141]. SA is the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the future; it is considered as a function of several quasi-independent situation types: available situation, perceived situation, expected situation, and inferred situation [17]. Endsley [48] developed a three-stage model of SA:

- perception of elements,
- comprehension of current situation,
- and projection of future status.

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SA, related to pilots, involves the operators' perception of different environmental elements with respect to time and space, together with a comprehension of their meaning and the projection of their status after some variable has changed with time [16]. When people are required to make critical choices, sometimes at a fast pace, the majority of errors occurring is a direct result of failures in SA ([117], [98], [48]).

According to Golightly [in 165], the lack of SA cannot always reflects on task performance, as good awareness of what is occurring does not always lead to effective actions. However, the identification of a secondary event (for example a communication error) could be used as a performance measure. The main effect of a SA decrease is that the operator (ATCO or pilot) lose the whole picture and "run behind". This might result in unsafe actions, unexpected decisions and incorrect reactions to the situation [43].

Over the last decade or so numerous techniques for assessing situational awareness have emerged, and self-rating techniques and inferential ones (that seek implicit evidence of SA from observable correlates) are largely used. Situation Awareness Global Assessment Technique (SAGAT, [47]) is a freezing technique which compares pilot's answers to the real situation (ground truth) in order to provide an objective measure of SA. Situation Preset Assessment Method (SPAM), similar to SAGAT, measures the accuracy and time to respond for detecting decrements in SA. The Global Implicit Measure (GIM) is based on the assumption that a pilot's goals and priorities are constantly changing, and that it should be possible to look at the progress toward accomplishing these goals, using it as measure of SA. The expected actions compared with actual system states and crew actions are used to interpret the level of control and awareness of the crew.

While Situation Awareness Rating Technique (SART, [146]) is a simplistic post-trial subjective rating technique that was originally developed for the assessment of pilot SA, Situation Awareness for SHAPE (SASHA) is another SA assessment technique based on a questionnaire developed in EUROCONTROL SHAPE project to assess the impact of new automation on air traffic controllers [83]. The questionnaire comprises 6 items which address three different aspects of SA (information extraction, integration and anticipation) on 7-point Likert scales, from which a score is calculated. The supporting material is publicly available and the technique has been used in various studies including SA assessment of flight crews, after slight modifications.

Another interesting inferential technique is the "Situational Awareness Linked Indicators Adapted To Novel Tasks" (SALIANT, [111]), which infer a team's SA from observed behaviours. In this work, they identified a set of behavioural indicators of team situation awareness derived from the literature. From their literature analysis, identified behaviours indicating poor team situational awareness were lack of communication, lack of listening, having an argumentative crew, not noticing mistakes, overloaded

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crew members, and being unaware of problem consequences. The set of behavioural markers proposed for team SA assessment are:

- Demonstrated Awareness of Surrounding Environment:
    - Monitored environment for changes, trends, abnormal conditions;
    - Demonstrated awareness of where he/she was .
- Recognised Problems:
    - Reported problems;
    - Located potential sources of problem;
    - Demonstrated knowledge of problem consequences;
    - Resolved discrepancies;
    - Noted deviations.
- Anticipated a Need for Action:
    - Recognised a need for action;
    - Anticipated consequences of actions and decisions;
    - Informed others of actions taken;
    - Monitored actions.
- Demonstrated Knowledge of Tasks:
    - Demonstrated knowledge of tasks;
    - Exhibited skilled time sharing attention among tasks;
    - Monitored workload;
    - Shared workload within station;
    - Answered questions promptly.
- Demonstrated Awareness of Information:
    - Communicated important information;
    - Confirmed information when possible;
    - Challenged information when doubtful;
    - Re-checked old information;
    - Provided information in advance;
    - Obtained information of what is happening;
    - Demonstrated understanding of complex relationships;
    - Briefed status frequently.

Unfortunately, while a variety of techniques have been proposed to measure situational awareness, none of these have been explored fully in terms of their reliability and validity, and each has been criticised on a host of grounds. The multivariate nature of SA significantly complicates its quantification and measurement, as it is conceivable that a metric may only tap into one aspect of the operator's SA. Further, different studies have shown that different types of SA measures do not always correlate

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strongly with each other (e.g. [37], [50], [153]). Accordingly, rather than rely on a single approach or metric, valid and reliable measurement of SA should utilize a battery of distinct yet related measures that complement each other.. Such a multi-faced approach to SA measurement capitalizes on the strengths of each measure while minimizing the limitations inherent in each.

Recovery measures and mitigation means

SITUATION AWARENESS	Mitigation	Recovery
Technical	Optimal use of automation in flight and on ground Optimal HMI design, including use of multimodal support (e.g. visual information, sounds, vibration)	Alarm and attention getters (combination of light, sound and vibration to alert the pilot) audio messages stating the person's name, flashing visual signal) Disruption in the "cognitive" environment (e.g. if previously noisy stop all audio alarm, if cluttered display remove information) Support tools (HMI) for information collection, filtering and analysis, following four cognitive principles [85]: • Automated change detection (HMI display, flashing indicator of changed parameter) • Unobtrusive notification of changes (e.g. peripheral location, subtle sound to inform on change, soundscape approach) • Overview prioritization (e.g. from critical to mundane information, from macro to micro) • Minimal clutter on the situation display but maximal access Radio, Data-link to enable communication, information requests and/or discussions or clarifications

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Organisational	Awareness of the risks associated to reduced vigilance/attention (e.g. consequences of complacency, overtrust in the automation, loss of situation awareness) Training (e.g. in simulators) on how to detect and handle situations of reduced vigilance/attention Training on (re)acquiring situation awareness after disruption/loss Training on teamwork contribution to mutual situation awareness assessment Awareness of fatigue effects on attention/vigilance (and awareness of fatigue avoidance measures) Task definition and repartition (e.g. taskload smoothing, through task allocation and task balance over time and among pilots)	Operational documentation (FCOM, procedures, guidelines on monitoring/scanning patterns, task prioritization) to support regular monitoring and guide the pilot in situation handling (e.g. monitor relevant indicators, parameters) throughout the whole process (i.e. until the end of the situation) Remove sources of distraction (e.g. limit non-essential conversation, extraneous noise, external visitors) Break in the current activity (either to break the routine effect or to reduce the overload)
Individual / Team		Crew resource management to support communication and cross-check among pilots (e.g. mutual assessment of tiredness, vigilance) Task sharing or interactions to re-activate attention/vigilance level Communication with colleagues Prioritization of tasks Avoiding distractions

2.2.5. Attention

Attention is the ability to attend to information in the environment [54]. It is a multidimensional construct that includes:

- focused attention (the ability to focus attention on cues in the environment that are relevant to the task in hand; can also include suppression of distracting stimuli),
- divided attention (the ability to execute two tasks simultaneously),
- and sustained attention/vigilance (the ability to monitor critical events with low frequency of occurrence over prolonged periods of time).

Zomeren & Brouwer [167] and Shallice [134] have proposed a multi-componential model composed of intensive and selective components, and Supervisory Attentional System (SAS). Attention is strictly related to other concepts such as vigilance, SA and mental workload.

Lack of attention or distraction usually affects human performance by causing the omission of procedural steps, forgetfulness to complete tasks, and taking shortcuts that may not be for the better. The effects of distraction can be seen in forgetting the as-left conditions, forgetting to return to the

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original task, the original task out of control during distraction, and not knowing changes after returning to original task. A performance decrement can be noticed when attention, workload and task difficulty increase; the reaction time and number of errors increase as well, while accuracy and number of completed tasks decrease. Reduction of the performance in monitoring, tracking, auditory discrimination, and reduction of visual field can be observed too.

Attentional fixation (or cognitive tunnelling), i.e. the allocation of attention to a particular source of information for a time slot longer than optimal, can have a negative impact on performance too neglecting events from other channels, failing to consider other hypothesis, or failing to perform other tasks. Negative consequences to attentional fixation can be:

- Excessive focus on a single item of a display or on a single task;
- Augmented risk proneness;
- Degraded social abilities;
- Loss of communication between both pilots and an increase of aggressiveness;
- Reasoning capabilities suffer from confirmation bias that leads pilots to neglect any environmental cues that could question their reasoning;
- Reduction of the performance in monitoring, tracking, auditory discrimination, and reduction of visual field.

Indicators of negative influences of attention and vigilance identified by Edwards [43] for ATCOs were mainly internal, while just “overlook aircraft” and “don’t hear/see” were collected as observable indicators. Cognitive perception changes were primarily described as indicators of reduced attention/vigilance (not as sharp, surprised, focussed, tunnel vision, focusing on one area of sector and not scanning others etc.), followed by changes to control (scan differently, not leaving a problem).

Lack of attention/vigilance can be also seen in the slowing down of responses, lapses that reflects in the increasing number of critical signals missed over time (vigilance decrement), failures to detect signals where observers are asked to respond to the more frequent neutral events and to withhold responding in the presence of the less frequent critical signals. Distraction/inattention can be monitored looking at the head position and eye gaze, to check if they are directed towards the relevant elements of the working environment.

Recovery measures and mitigation means. See below, in vigilance section.

2.2.6. Vigilance

Sustained attention/vigilance is a state of readiness to detect and respond to certain small changes occurring at random time intervals in the environment [101]. In several studies ([30], [116], [155])

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sustained attention/vigilance is defined as the ability to maintain the focus of attention to a task and to remain alert to stimuli over prolonged periods of time, in order to detect and response to infrequent critical events. Vigilance is strictly related to other concepts, in particular SA and attention and often the three concepts overlap.

Skybrary (Flight Safety Foundation, OGFHA, 2010) proposes an interesting overview on the three components:

"Attention is a cognitive process that is important to virtually every activity people perform. It is one of the most studied processes in cognitive psychology and neuroscience and is considered to be the gateway to perception and all other higher level cognitive processes. Without attention, we could not selectively process information and discriminate important information from the unimportant "noise" that surrounds us. In turn, because we can control our attention, we can be vigilant and be prepared for dangers when they arise. […] Vigilance is a concept closely related to attention; in fact, the word attention is often used when defining vigilance. One definition of vigilance describes it as the process of paying close and continuous attention. It is often described as a quality or state of alertness or watchfulness. Vigilance can also be thought of as the extent of readiness to detect, or the likelihood of detecting, a stimulus that is imperative to safety. […] Attention and vigilance are key components of situational awareness. As such, the accident data displayed in the situational awareness BN are representative of data related to attention and vigilance."[3]

From a behavioural point of view, it's difficult to distinguish attention from vigilance, so the markers for this factor can be considered the same identified for attention. Similarly, the impact of vigilance on pilot performance could be comparable with the attention one, and both influence pilot SA.

Recovery measures and mitigation means.

Vigilance and attention being closely linked, the following recovery measures and mitigation means address both factors.

[3] http://www.skybrary.aero/index.php/Attention_and_Vigilance_%28OGHFA_BN%29

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ATTENTION / VIGILANCE	Mitigation	Recovery
Technical	Optimal HMI design, including use of multimodal support (e.g. visual information, sounds, vibration)	Alarm and attention getters (combination of light, sound and vibration to alert the pilot, audio messages stating the person's name, flashing visual signal) Disruption in the "cognitive" environment (e.g. if previously noisy stop all audio alarm, if cluttered display remove information)
Organisational	Awareness of the risks associated to reduced vigilance/attention (e.g. consequences of complacency, overtrust in the automation) Training (e.g. in simulators) on how to detect and handle situations of reduced vigilance/attention Task definition and repartition (e.g. taskload smoothing, through task allocation and task balance over time and among pilots) Awareness of fatigue effects on attention/vigilance (and awareness of fatigue avoidance measures)	Operational documentation (procedures, guidelines on monitoring/scanning patterns, task prioritization) to support regular monitoring and guide the pilot in situation handling (e.g. monitor relevant indicators, parameters) throughout the whole process (i.e. until the end of the situation) Remove sources of distraction (e.g. limit non-essential conversation, extraneous noise, external visitors) Break in the current activity (either to break the routine effect or to reduce the overload)
Individual / Team		Crew resource management to support communication and cross-check among pilots (e.g. mutual assessment of tiredness, vigilance) Task sharing or interactions to re-activate attention/vigilance level Communication with colleagues Prioritization of tasks Avoiding distractions

2.2.7. Teamwork

Teamwork is defined as the organised, collective working methods between an established group of people ([6], [51], [120]). It consists in a collective and mutual interaction with humans in the system for performance [43], and in ATC the teamwork is monitored through the exchange of information, which includes timeliness, accuracy, clarity and receptiveness.

Breakdown in teamwork may have an adverse effect on the following:

- Communication between colleagues, including briefing on handover;

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- Communication between controllers and pilots;
- Situational awareness;
- Decision making;
- Monitoring of crew actions;
- Monitoring of colleagues;
- Flexibility - ability to adjust to changing workload.

Any or all of these factors taken singly or in combination may contribute to an accident or serious incident. Additionally, breakdown in teamwork may lead to frustration and irritation, low morale and poor job-satisfaction, which are likely to impact on team performance (the vicious circle).

Behavioural markers can be drawn from the list used in CRM (in particular in Line Operations Safety Audits):

1. Operational plans and decisions were communicated and acknowledged. Shared understanding about plans -“Everybody on the same page”.
2. Roles and responsibilities were defined for normal and non-normal situations - Workload assignments were communicated and acknowledged.
3. Crew members developed effective strategies to manage threats to safety - Threats and their consequences were anticipated - Used all available resources to manage threats.
4. Crew members actively monitored and cross-checked systems and other crew members - Aircraft position, settings, and crew actions were verified.
5. Operational tasks were prioritized and properly managed to handle primary flight duties - Avoided task fixation - Did not allow work overload.
6. Crew members remained alert of the environment and position of the aircraft - Crew members maintained situational awareness.
7. Automation was properly managed to balance situational and/or workload requirements - Automation setup was briefed to other members - Effective recovery techniques from automation anomalies.
8. Existing plans were reviewed and modified when necessary - Crew decisions and actions were openly analysed to make sure the existing plan was the best plan.
9. Crew members asked questions to investigate and/or clarify current plans of action - Crew members not afraid to express a lack of knowledge - “Nothing taken for granted” attitude.
10. Crew members stated critical information and/or solutions with appropriate persistence - Crew members spoke up without hesitation.
11. Environment for open communication was established and maintained - Good cross talk-flow of information was fluid, clear, and direct.
12. Captain showed leadership and coordinated flight deck activities - In command, decisive, and encouraged crew participation.

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Other elements to be considered [58]are the establishment of an open communication atmosphere, encourage inputs and feedback from the others, take notice of the suggestions, give personal feedback, offer assistance and suggests conflict solutions.

Recovery measures and mitigation means.

<table>
<tr><th>TEAMWORK</th><th>Mitigation</th><th>Recovery</th></tr>
<tr><td>Technical</td><td>Workspace designed to support communication (including intention recognition) through sharing of resources and information</td><td>Radio, Data-link to enable communication, information requests and/or discussions or clarifications</td></tr>
<tr><td>Organisational</td><td rowspan="2">Crew Resource Management
Task definition and repartition (e.g. taskload smoothing, through task allocation and task balance over time and among pilots)
Staffing arrangements, scheduling and rostering to enable familiarity and trust in team members
Team culture / spirit through
• Team orientation: commitment, collective ownership of the team goals, shared leadership
• Team culture: encourage people to communicate openly, give preference to team goals, exhibit teamwork behaviours
Behavioural training on interpersonal skills (including positive attitude towards others, confidence and charisma), listening ability, responsiveness and ability to give feedback
Technical training on how to co-operate efficiently, to share ideas and knowledge: e.g. pass the correct information (in quality and quantity), to the correct receiver using a manner understandable; this also contributing to avoid errors, increase productivity, and enhance credibility among the co-workers
Domain training to ensure the appropriate information is distributed to the appropriate receiver at the right time, including</td><td>Coordination, i.e. timely integration of activities among team members, based on the mechanisms above (feedback, monitoring, willingness to back-up)
Operational documentation (procedures, guidance to explicit/organise interactions and cross-check among pilots, check-list for task sharing and reallocation)</td></tr>
<tr><td>Individual / Team</td><td>Intention and behaviour made explicit
Familiarity with the task and with the team to ensure better interactions (e.g. team members know whom to communicate with and use the task-related terminology familiar to the team) and support trust building
The team has to stay together for some time to go through teambuilding process and to improve interaction
Back-up behaviour (redundancy) to assist a team member in performing the task and to complete the task for a team member in case of overload
Communication and feedback provision (give and seek feedback about performances) to encourage the shared understanding of the process and goals and e.g. minimise the risk of aiming for the wrong objectives
Mutual performance monitoring and team learning enabling to learn from others' good practices, share mental models, build trust and/or adapt accordingly to the needs of a team e.g. provide support when workload is seen as inconsistently</td></tr>
</table>

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	awareness of others' work domain, (e.g. controllers' work objectives, tools, constraints to better understand their requests and decisions) Collective training and practice to develop mutual understanding of the situation, including the team workers' current goals, needs, expectations and working styles. Personal relationships building through open communication, shared experiences, small talk (e.g. sharing a joke, cherishing successful moments of team members and non-business communication)	distributed among team members

2.2.8. Communication

Communication may be defined as the transfer of meaningful information from one person to another [76] and involves both the production and the reception of messages, although communication is independent from (but related to) the concepts of speech and language ([76], [81]). It is related to Teamwork and both the components are essential to for the delivery of high quality, safe system performance.

Communication enhancement is one of the primary goals of CRM training procedure, together with enhanced situational awareness, self-awareness, leadership, assertiveness, decision making, flexibility, adaptability, event and mission analysis. Specifically, CRM aims to foster a climate or culture where the freedom to respectfully question authority is encouraged. Communication has been recognised to be a delicate subject for many organisations, especially ones with traditional hierarchies, so appropriate communication techniques must be taught to supervisors and their subordinates, so that supervisors understand that the questioning of authority need not be threatening, and subordinates understand the correct way to question orders.

Effective communication supports individuals in developing a shared awareness of the situation or system, supports teamwork and therefore results in a maintenance or increase of performance. Effective communications may lead to increased planning statements, structure and predictability. Communication errors and miscommunication can produce performance decline and performance-related errors. Although errors did not necessarily contribute to an incident, error of communications suggests the pervasiveness of the communication issues and potential implications on performance. Several studies ([108], [87]) mention miscommunication and language confusion as a pervasive problems in ATC and a frequent cause of pilot error, resulting in being a causal factors in numerous fatal accidents.

Miscommunications may broadly be applied to a range of verbal communications problems ranging from misunderstandings, such as those due to cultural differences, language structure and so on, to more technical problems, such as microphone “clipping” and over-transmitting of another’s radio signal. Miscommunications can also include ambiguity through word choices or distortions of meaning, more likely issues if standard phraseology is not used. Slips are also frequent forms of miscommunication, which result in verbally communicating information that was not intended. Examples of pilot-controller communication errors can be categorized into:

1. actual read back/hear back error in which the pilot reads back the instruction incorrectly and the controller does not correct the error;
2. absence of a pilot read back;
3. hear back errors in which the controller does not correct a pilot read back containing the controller‘s own error from the original instruction.

Miscommunication can be caused by several factors such as pilot or ATCO workload, inadequate language proficiency, non-standard phraseology, distractions and interruptions, fatigue, emergency communication or external contingencies as bad weather.

Recovery measures and mitigation means.

COMMUNICATION	Mitigation	Recovery
Technical	Workspace designed to support communication (including intention recognition) through sharing of resources and information	Radio, Data-link to enable communication, information requests and/or discussions or clarifications (e.g. if expected ones are delayed, if content is insufficient or inaccurate)
Organisational	Behavioural training on interpersonal skills (including positive attitude towards others,	Operational documentation (procedures, guidance to explicit/organise interactions)

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Individual / Team	confidence and charisma), listening ability, responsiveness and ability to give feedback Technical training on how to communicate efficiently, to share ideas and knowledge: e.g. pass the correct information (in quality and quantity), to the correct receiver using a manner understandable; this also contributing to avoid errors, increase productivity, and enhance credibility among the co-workers Domain training to ensure the appropriate information is distributed to the appropriate receiver at the right time, including awareness of others' work domain, (e.g. controllers' work objectives, tools, constraints to better understand their requests and decisions) Collective training and practice to develop mutual understanding of the situation, including the team workers' current goals, needs, expectations and working styles. Personal relationships building through open communication, shared experiences, small talk (e.g. sharing a joke, cherishing successful moments of team members and non-business communication) Task definition and repartition (e.g. taskload smoothing) to provide pilots with time for proper communication Staffing arrangements, scheduling and rostering to enable familiarity and trust in team members	Information requests/ clarifications Intention and behaviour made explicit Familiarity with the task and with the team to ensure better interactions (e.g. team members know whom to communicate with and use the task-related terminology familiar to the team) and support trust building The team has to stay together for some time to go through teambuilding process and to improve interaction

2.2.9. Trust

According to Costa et al. [26] Trust is a multidimensional construct. One taxonomy of trust [93] used in literature discriminates between:

- dispositional trust refers to an individual‘s propensity to trust, based on both predispositions to trust, and subsequent environmental influences;
- situational trust is context specific, arising from the perception of an individual‘s (or machines) trustworthiness.

A second distinction ([109], [110]) is made between:

- interpersonal (cognitive and affective) trust the willingness to be vulnerable to another party based on the belief that the latter party is competent, open, concerned and reliable;
- trust in technology is described as an intervening variable that mediates between the system and an operator‘s interaction strategy with the system. Trust influences reliance on automation, and in particular it guides reliance when complexity and unanticipated situations make a complete understanding of the automation impractical [97].

Edwards [43] reports that ATCOs consider trust as important in their work in terms of their relations with colleagues, pilots and management, as well as with regard to their attitude towards technology [14]. Trust in colleagues influences the nature of the employee working relationship (positive versus negative) and the form of knowledge sharing.

To decide whether to trust an individual or system, and the appropriateness of that decision in the given context, influences performance. However, research is limited regarding the association between trust and performance [26]. Inappropriate trust (mistrust or over-trust) in colleagues may result in a lack of checking behaviour or insufficient teamwork. This reduction of monitoring may then result in performance decline. Similarly, inappropriate mistrust in systems may result in a lack of facilitation of performance, whereas over-trust in technologies may result in a reduction in monitoring, leading to a vigilance decline.

Miscalibration between operator and technology can result in mistrust or over-trust (leading to complacency), each with specific implications for performance:

- Inappropriate mistrust may result in an inappropriate lack of technology use, potentially resulting in reduced efficiency or even a reduction in safe performance.
- Over-trust of technology can result in complacency or overreliance on the technology which has been shown to be negatively related to vigilance and monitoring behaviour. Over-trust had influenced the control strategy selected by the operator, which minimised monitoring and can lead to a decrement of SA.

Data from incident reports also suggest an association between over-trust and overreliance in technology and performance decline or performance-related incidents.

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There is no standardised method in literature for the measurement of trust. Usually, trust in colleagues is assessed through questionnaires (i.e. self-assessment) and/or direct naturalistic observations, while trust in automation can be inferred using false alarms and reaction times. When false alarm rate increases, pilot trust in automated devices decreases resulting in the pilot preferring a lower level of automation. Analysis of the pilot mean reaction time in response to devices sensor alert show increased reaction time with increased false alarm rate. The pilot expresses less trust in automation system.

Recovery measures and mitigation means.

TRUST	Mitigation	Recovery
Technical	Participative design to facilitate the new system/tool acceptance through an understanding of its rationale, objectives and functioning Documentation –either paper-based, or embedded in the interface to support the description / understanding of the system state and usage (e.g. what the automation (or any support system) is doing, why it is doing so and what it will do next)	System design including recovery means evoked on Kontogiannis et al. [95] such as: • observability of undesired system states (e.g. warning, colour code reflecting unexpected state on the HMI), • traceability of actions and effects to revise understanding • reversibility of error to help timely correction (e.g. cancel/undo function)
Organisational	Awareness and training programme to ensure • trust in systems; • trust in other people (co-pilot, air traffic controller) Staffing and rostering mixing teams to ensure diversity of shared experiences on practices and motivations	/

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Individual / Team	Trust in system through: • Awareness of error mitigation means introduced in the systems • Experience with the system/tool on simulators to test its limits • Training to learn and practice the system/tool logic, the mitigation means introduced and how to (not) use it, with examples of good and bad practices Trust in other people (co-pilot, air traffic controller) through: • Collective training to share practices and develop mutual understanding (in particular of working style of others) • Awareness of others' work domain, e.g. controllers' work objectives, tools, constraints to better understand their requests and decisions • Personal relationships building through open communication, shared experiences, small talk (e.g. sharing a joke, cherishing successful moments of team members and non-business communication)	Spending time together Communication and feedback provision to explicit possible misunderstanding or wrong interpretation

2.2.10. Factors Interaction

Several interactions and connections between the nine factors composing the HPE emerged from the literature review. Three thematic areas seem to emerge: Mental Workload, Stress and Fatigue is a group of strictly interrelated factors; Situation Awareness (SA), Attention and Vigilance are almost overlapped, with Attention and Vigilance recognised as key components of Situational Awareness; finally Teamwork, Communication and Trust can be seen as the set of "social" factors.

Beyond the three thematic areas, Mental Workload is clearly connected to Attention, Vigilance and Situation Awareness. Also, it is proved [8] that high level of Workload affects Communication abilities. Stress influences Vigilance, may induce monotony and may impair the process of stimuli from environment. Acute Stress may also impair decision making, in particular under time pressure conditions, and communication. Also Fatigue affects Attention, Vigilance and Situation Awareness, and may induce monotony.

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Endsley [48] showed that SA and Workload are independent constructs, with four possible combinations:

- low SA and low workload if the operator does not know what is happening and is not actively trying to find out;
- low SA and high workload if the operator is handling too much information or too many tasks, thus he is not able to process and integrate everything;
- high SA and low workload, in which the important information is being presented and correctly perceived and integrated (the ideal situation);
- high SA and high workload, when the operator is working hard, but successfully handling the situation.

	LOW WORKLOAD	HIGH WORKLOAD
LOW SA	the operator does not know what is happening and is not actively trying to find out	the operator is handling too much information or too many tasks, thus he is not able to process and integrate everything
HIGH SA	the important information is being presented and correctly perceived and integrated (the ideal situation)	the operator is working hard, but successfully handling the situation

SA is also affected by the amount of Workload and Stress. With respect to Vigilance and Attention, physiological factors, such as sleep loss and high blood pressure, can affect attention and vigilance. Motivation, intrinsic or extrinsic, can affect attention and vigilance too.

Teamwork and Communication are affected by all the variations of the individual status (workload or stress increase, SA decrease). Finally, a robust positive correlation between interpersonal trust and team working emerged from the analysis of the literature.

All the interdependencies emerged are summarised in Table 8. In the table, bold ticks indicate a correlation or interdependency between two factors that is confirmed by independent studies (for instance, the correlation between Workload and Situation Awareness emerged both in Endsley research on SA [48] and in Nählinder studies on WL [113], [114]). On the other side, the cross is used to indicate a relation between factors that emerged from literature review, but with a less stable consensus.

Additional links and connections among factors, will be detailed in a further description of the HPE concept. In fact, the knowledge of such interrelations is crucial to ensure that the recovery measures put in place do not have effect on the degradation of another HP factor, i.e. mitigate contingent effects on other HPE factors.

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Table 8: Interdependencies between factors composing the HPE

	WL	Stress	Fatigue	SA	Attention	Vigilance	Teamwork	Comm.	Trust
Workload		✓	x	✓	✓	✓	x	x	x
Stress	✓		✓	✓		✓	x	x	x
Fatigue	x	✓		✓	x	✓			
SA	✓	✓	✓		✓	✓		✓	
Attention	✓		x	✓		✓			
Vigilance	✓	✓	✓	✓	✓				
Teamwork	x	x						✓	✓
Comm.	x	x		✓			✓		x
Trust	x	x					✓	x	

Table 9: Factors/Measures Matrix

	WL	Stress	Fatigue	SA	Attention	Vigilance	Teamwork	Comm.	Trust
ECG	X	X	X	X	X	X			
EEG	X		X	X	X	X			
EMG	X	X	X						
EOG	X	X	X	X	X	X			
fNIR	X			X	X				
GRS/EDA	X	X	X						
Respiratory activity	X	X	X						
Eye-tracking	X	X	X	X	X				X
Subjective measures	X	X	X	X					
Primary / secondary task	X		X	X	X				
Expert observation	X			X	X		X	X	X
Communication analysis		X		X			X	X	
Seat sensors	X	X							
Voice analysis	X	X							
Pressure / grip sensors		X							
Polygraph sensor		X							
Electrochemical sensors		X							
Hormones		X							
Reaction times	X			X	X	X			X

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3 A CONCEPT FOR THE HUMAN PERFORMANCE ENVELOPE

3.1. HPE Concept Workshop

Based on the preliminary results of the literature review, an internal project workshop was organised. Its main aims where to:

- Getting a shared understanding and basic representation of the HPE concept
    - What is it?
    - What does it look like?
    - How do we characterise it?
    - Can we measure/map/monitor it?
- Paving the way to the next phase of the project.

The workshop was held in Brétigny-sur-Orge, at EUROCONTROL Experimental Centre, on the 16th and 17th of April, 2015. It was attended by representatives of EUROCONTROL, DLR, ONERA, Thales Avionics, Deep Blue, Deutsche Lufthansa, Boeing R&TE, Cranfield University and NLR.

Five partners were asked to prepare brief position papers, providing their expectations from respectively ATM, manufacturers, measurement techniques and pilot perspectives. Based on these contributions a common definition of the HPE was reached. A following hands on session aimed to share the descriptions of the 9 HPE factors analysed (see Appendix A for the HPE Factors Cards), select the factors to focus on during the project, and identify the main aspects to take into consideration during the simulations.

The main outcomes of workshop are illustrated in the following chapters.

3.2. The HPE Concept and proposed representations

In P6, the HPE is described as a construct combining a set of interdependent factors and represented with a spider web model. Depending on the value of each factor, the resulting HPE could evolve from fully acceptable (i.e. providing a nominal set of cognitive resources) to not acceptable (i.e. providing an error-prone cognitive and physical environment). Even though a single factor could have a non-acceptable value (e.g. low vigilance), it is assumed that the interaction should enable compensations among factors to be identified, and consequently overall acceptability of HPE to be proven.

Influence of the demand of the tasks on the HPE has to be taken into account. Assuming that a HPE can be characterised for a given actor (e.g. pilot), there might actually be a set of acceptable HPEs for this same actor, each being dependent on the tasks. One way to address this task-related HPE could be to

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isolate specific tasks/situations, assess HPE factors in these situations and determine the feasibility of defining task-related HPE.

The radar model (Figure 6) visually represents the 9 factors initially considered for HPE and described in Section 2.2. The maximum value of a factor doesn't necessarily correspond to optimal HPE (for example, the maximum value of "no workload" can induce performance reduction due to boredom); for each factor, the optimal is represented by the green line, while degradation is illustrated by a reduction of the overall shape.

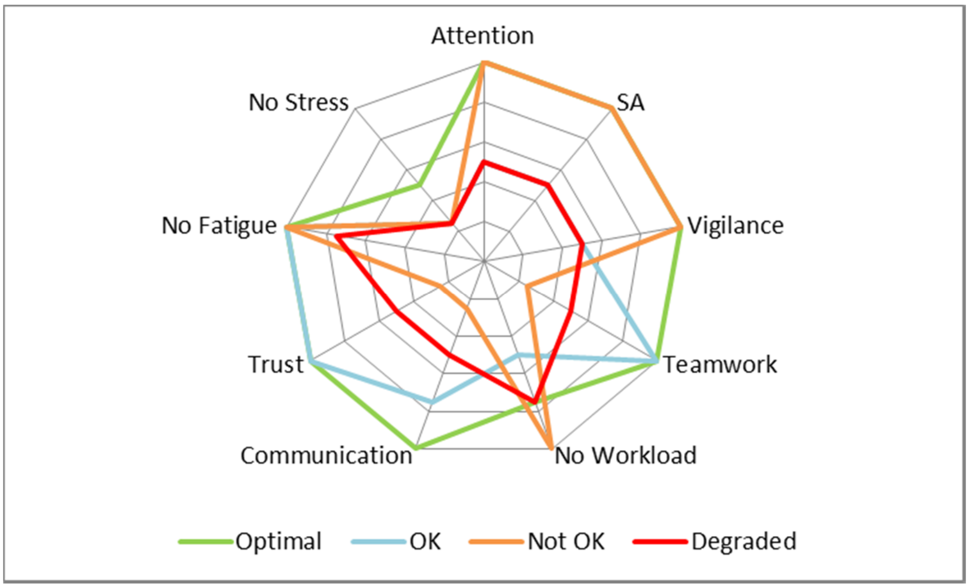

Figure 6: Spider web representation of the HPE concept

For some factors the identification of an acceptable limit is tricky. Workload or Stress should not be too high (risk of overload leading to difficulty to maintain situation awareness and make appropriate decision) but not too low either (risk of reduced vigilance and attention).

Another representation could consider the centre of the radar as the optimal value of a factor, while degradation would be reflected by an extension of the resulting shape (Figure 7). Measuring the distance from the centre would then provide an estimation of the degradation.

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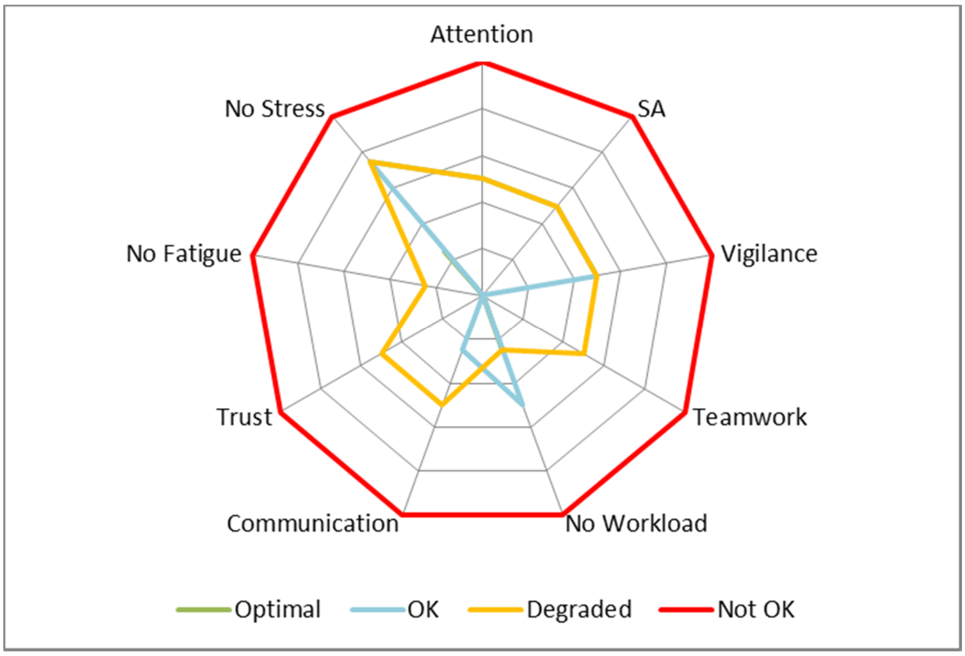

Figure 7: Radar view, with optimal HPE concentrated in the centre, and degradation reflected with extension of the shape.

For each factor, there is a "No Go" limit beyond which there should be a degradation leading to a negative impact on the human performance. For each factor, this "No Go" limit varies according to the situation (e.g. task, environment, context).

There is a mutual influence of each factor level on their respective "No Go" limit, i.e. the limit for a given factor could be larger if another factor is far from its own limit (e.g. a high level of workload could be acceptable in a situation where stress is quite low and teamwork quite good –i.e. efficient).

Although they are of a different nature, trust, communication and teamwork are essential for and influential factors on HPE. Teamwork is perceived as a result of trust and communications (Note: ICAO definition from Doc-9683-AN-950 could be considered). They might not be assessed with physiological measures (and possibly even not measured at all), but they should still appear as constitutive factors of HPE.

3.2.1. Selection of the factors to be investigated through simulations

In order to define the indicators for the HPE, it is needed to make a selection of some of the 9 HP factors to be investigated through simulations. Based on the discussions and presentations in the workshop brainstorm session, it was agreed that the HPE should focus on three main aspects of human performance:

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- Workload
- Stress
- Situational Awareness (also enabling indicators of attention and vigilance)

These factors were chosen as they appeared as the most prominent measures to consider. Although other factors, such as fatigue and teamwork, were also considered as important, the ability to obtain reliable indicators was a challenge which might hinder the validity of application of the resulting HPE model. Additionally, they were considered as the factors with the highest impact on the pilot performance, as well as those mostly likely to be investigated by using simulations. Additional considerations are reported in Table 10.

Table 10: Considerations upon HP factors

Workload	Strict relation between stress and workload, even if workload is more linked to cognitive variations, while stress is more linked to physiological variations (mechanism of adaptation). The **expected impact** of the workload on the pilot performance is the **inability of taking decisions**, deviation from procedures, and deviation from safety limits as the workload increase.	✓
Vigilance/ Attention/ Situation Awareness	Vigilance/Attention and Situation awareness are closely linked, and difficult to considered in isolation. There is no mention of situation awareness in neuro ergonomics, which rather addresses vigilance as a state of alertness. Whereas vigilance and attention might be measured with physiological indicators, situation awareness (as an understanding of the situation) might be more tricky to measure (especially in a real cockpit); the three factors seem to be at different levels. Attention and vigilance are impacted by **environmental factors** such as noise and temperature; or physiological factors such as sleep loss, high blood pressure, etc.	✓
Stress	Stress and Workload are strictly related. The focus of the project will be on the effects of acute stress on performance.	✓
Communications	Are considered as establishing a suitable atmosphere, ensuring the information transfer, both in terms of send and receive information, the information management and handling.	X

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Trust	Can be investigated mainly with subjective indicators, although time between successive checks of a same indicator could be a measure of trust in the system. The Trust concept should also be clarified, as it can represent trust in automation or trust in the team.	X
Self-beliefs, experience, skills and decision making	Although they are essential for an optimal human performance, those are considered as more stable during a flight (hence hardly measurable in terms of drifting) than factors such as workload, stress, fatigue.	X
Fatigue	Studies showed that under extreme fatigue, the human is able to find and use unexpected resources, pushing unexpectedly the limits. However, creating realistic fatigue conditions in a simulator might not be possible, or at least conditions that would force the pilots to compensate with adrenaline (their survival instinct possibly not being triggered in a simulation context).	X

The three factors selected describe different aspects, but are still interrelated in many ways (as illustrated in Section 2.2.10). Certain events or HPE-critical situations can affect more than one factor, they do not describe mutually exclusive aspects of human performance. For example, fatigued pilot state is a situation which may affect both workload (reduced functional capacity, lower workload threshold) and SA (reduced concentration affects vigilance, i.e. maintained attention). Also, low SA can induce a surprise (cognitive mismatch), which may increase stress levels.

In Table 11 the different measurements techniques are mapped on the two experimental environments (simulators and cockpits) and the three HP factors identified, in order to support the definition of a coherent experimental plan.

Table 11: Consolidated measures for the three factors investigated by the working groups

Factors	Simulator		Cockpit operations	
	Physiological	Task	Physiological	Task
Workload	Heart rate Eye tracking Pupillometry Respiratory activity EEG (?)	Expert analysis NASA TLX ISA (?) Reaction time Deviation from optimum flight RT occupancy Expert observation	Heart rate (Ask companies?)	Reaction time (?) Deviation from optimum flight path profile (descending too early/too late) Observation
Stress	Respiratory activities EOG Electrochemical sensors Grip force Voice analysis Scan pattern	Communication analysis Expert observation	Voice analysis Grip force Scan pattern Electrochemical sensors	Observation
Situation Awareness, Vigilance and Attention	EEG (?) EOG HRV Eye movements Scan pattern	Reaction time Subjective techniques Expert observation Testable responses (vigilance?)	EOG HRV Scan pattern (AOI)	Observation Reaction time Deviation from optimum flight path profile

Taking into account the three selected factors in combination, it is possible to define an experimental paradigm for the simulations. The experiment in the simulations should investigate the impact of the different factors, alone and in combination, on the operational performance and, for each of them, identify the critical values under which the performance is impaired or not acceptable. The realism of the simulation is a crucial point, a proper selection of scenarios should ensure that the absence of cues is not detrimental to the results obtained (e.g. absence of kinetic feedback could be detrimental if turbulences are tested, while in other situations it might be less problematic). Although the project aims at detecting drift in the HPE, the scenario should not be too degraded, to avoid destructive testing (i.e. pushing the pilots in "loss of control" situations).

3.2.2. HPE Performance markers

The above three factors are measure of human abilities, but do not indicate whether safety or performance of their operations are being affected, and when certain operational limits are being exceeded. In other words, what is the operational impact of the (for instance) low SA, high or low workload or high or low stress? Are these factors limited on one or two sides? In addition to observing

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the factors individually, their interaction also complicates deriving what a suitable or desired combination of HPE factors is, with respect to operational requirements set for the pilot or crew.

In order to make this connection, operational limits/benchmarks for three core HPE factors will be gauged according to current operational performance standards. Standards for both technical and non-technical crew and pilot flight performance will be used. The following are examples for technical performance measures:

- Manual control: lateral/vertical deviation from flight path, speed variability
- Manual control: ability to recover intended position/speed control
- Autoflight: correct mode selection/arming
- Automation task management/task alleviation
- Briefings, checks, preparations and action on time (e.g. flap retraction, landing lights, autobrakes set)

The following are examples of non-technical performance measures:

- ICAO core competency indicators
- LOSA flight phase-specific observations
- Abnormal situation management
- CRM evaluation techniques.

There are of course more examples of rating standards for both technical and non-technical evaluations (also with reference to the SaMSys study, e.g. measures of teamwork), the above lists are only indicative. In addition to these more generic measures, scenario-specific or task-specific analyses can be developed (e.g. a "Desired Flight Crew Performance" rating approach from Man4Gen), which may help further benchmark the HPE thresholds for specific situations.

However, there are two complexities to consider when determining HPE limits. Firstly, in order to validate the HPE in the operational context, a scenario may consist of several situations. This then requires dynamic limits in the HPE system. A possible solution could be a functionality which is able to detect changes from one situation to another, such as changing flight phases, normal and non-normal operations, level of automation and external factors (e.g. weather, traffic). Within the scope of this project, a limited set of situations/scenarios may be sufficient to demonstrate the concept of the HPE and the benchmarking process. The level of scenario and HPE complexity must be decided on during the scenario development phase.

The second complexity factor is the fact that, similar to how the three HPE factors are interdependent, so are the limits set to them. It may be possible that setting a low tolerance for a certain HPE measure (e.g. by compounding effects of a complex situation), limits for other factors may also shift due to

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interdependence, even if the situation taskload is not specifically limiting that HPE factor. Nevertheless, this can still lead to the HPE being out of bounds on those factors.

3.2.3. Performance map

To study the evolution of the performance, and its quality, it could be possible to relate the quality of performance (good/bad, acceptable/unacceptable) to the success in achieving the task. It means that the performance depends on the scenario or situation investigated and the quality can be evaluated through experts judgment. Several situations are mentioned to induce stress in the operator and investigate its impact on performance:

- Knowledge-based problems to be solved (for example, manual flight tasks);
- Unusual/unexpected situations to be managed (unusual clearances, level bust);
- Team issues such as not responding or uncooperative co-pilot (both situations can be tested only in a simulated environment)
- Time pressure situations/tasks such as alarms reaction (TCAS, fuel alarm).

For each task/situation we could identify the optimal performance area and see how the factor(s) variability impacts the shape of that area. Three potential axes were initially proposed to assess the performance on a task (see Figure 8):

- Amount (more/less)
- Speed (fast/slow)
- Quality (good/bad).

A significant variation in the investigated factor(s) can reflect on the amount, speed and/or quality of operator's performance, inducing a variation in the performance "shape" on the three axes.

Further reflection is required before deciding whether to adopt it in P6 or not; in particular, the axes to assess the performance and the scale to be adopted should be carefully discussed within the consortium.

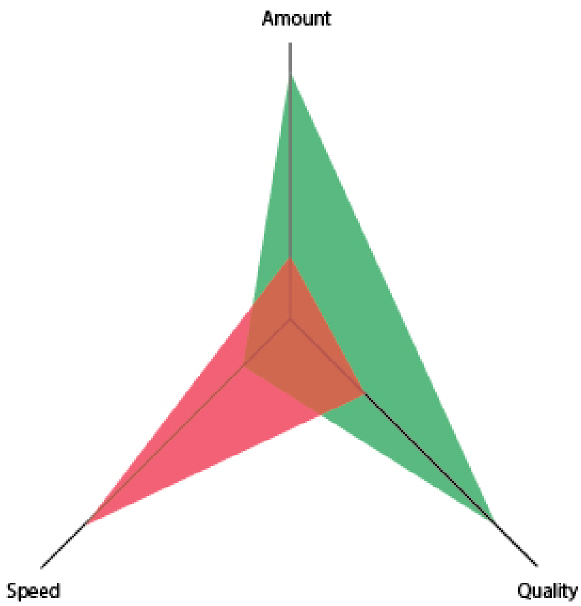

Figure 8: Performance assessment on three axes.

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3.3. Final remarks concerning the experiments

The definition of the **operational performance limits** will be part of the outcomes of the project. Enabling current operational standards and established performance rating schemes can link HPE factors with operational performance implications, and set limits.

Among the proposed **measures** in Table 11, analysis of communications, voice analysis, grip force, electro-oculography, electrocardiography and electrochemical sensors are among the most promising to be used in the simulations.

Scenarios must be developed based on intentions to 1) affect specific HPE factors and 2) affect specific operational performance indicators. Such specifically oriented scenarios can be effective in determining the interdependencies of the different HPE factors, as well as the operational impacts of changes in these HPE factors. As an example, the diagram below (Figure 9) shows the evolution of three factors (attention, vigilance and situation awareness) in a realistic operational scenario, and shows how physiological measures can monitor and detect the variation of HP factors.

Motivation, intrinsic or extrinsic, of the participant pilots can affect HPE scores. This must be taken into consideration while selecting subjects to maintain an accurate representation of current flight crew capacities.

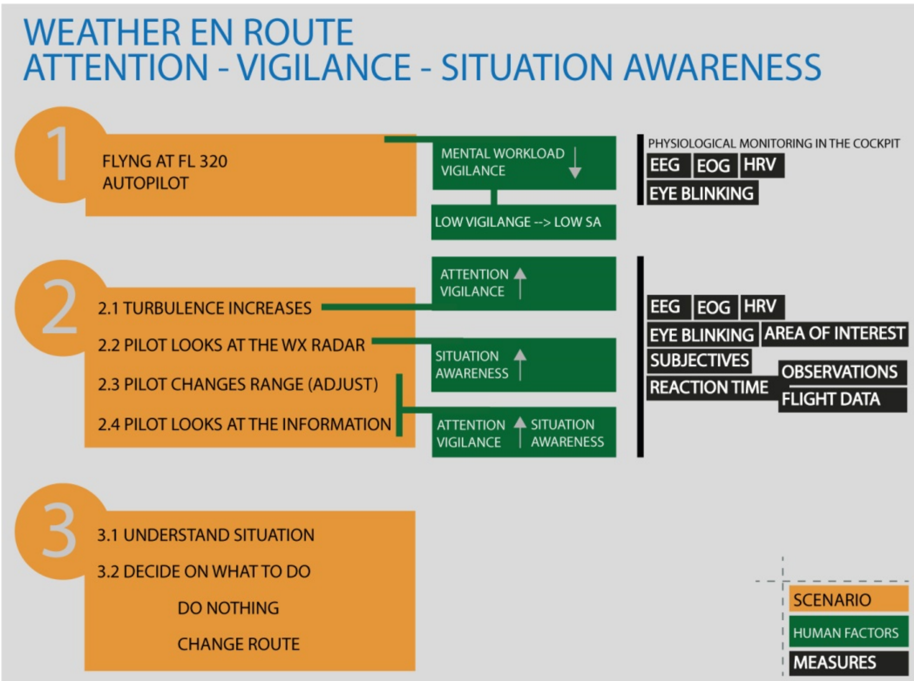

Figure 9: Realistic scenario, HP factors and measurements

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4 HPE-CRITICAL SITUATIONS IN THE COCKPIT

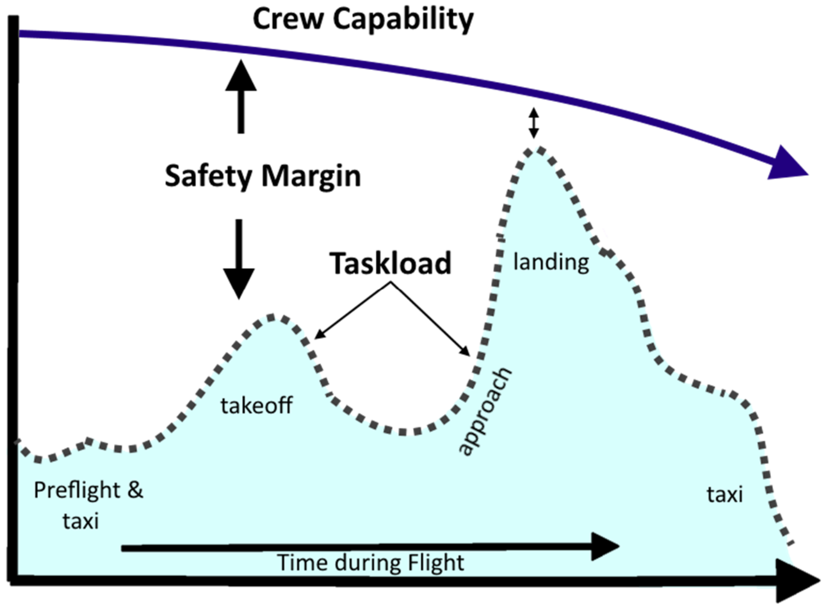
This section serves as collection point for reference situations that could be used to develop the scenarios for the real-time simulations. These scenarios will be refined and adapted in the frame of the workshop with external experts and each work packages to match with refined requirements, validation objectives and experimentation settings evolutions limitations.

Initial mapping of the reference scenarios to the validation objectives will be accomplished in the definition of the Validation Strategy. Within this document, the terms "scenario" and "situations" refer to the same meaning. References are included if the local scenario is based on a real accident or incident, in which case the reference is usually the associated report.

4.1. Stretching the envelope

Under normal flying conditions (that is, normal aircraft status and external environment), a full cockpit crew will routinely experience different performance levels. The focus of these critical situations review is on situations in which the HP envelope is deeply stretched towards its boundaries. Some of the factors that may contribute to this are adverse weather conditions, operations in high density traffic, an ATM blunder. Pilots' performance is usually very demanding on take-off, approach and landing.

Figure 10: Pilot performance variation in the different phases of flight



During these stages, any last minute change can overload the pilots, who are left with less time to complete all required tasks. Crew has the total control on avionics (as today) and is always in the loop.

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However, more system support could be requested by the crew and/or more system support could be proposed by the system. The crew decides whether to activate/accept system support or not. Essentially, the safety margin between task demand and crew capacity, as depicted in Figure 10, can be reduced to a "critical" level in three ways:

1. Increase in the taskload
2. Decrease in crew capacity
3. A combination of 1) and 2)

4.1.1. Increasing situation taskload

An increase in taskload can be achieved by several means, and usually the compounding effects of normal flight tasks, non-normal flight tasks and/or environmental factors such as weather or traffic can induce high taskloads, even if only momentarily. Figure 11 illustrates how an increase in taskload (indicated by the red dotted line) can cause an exceedance of the safety margin.

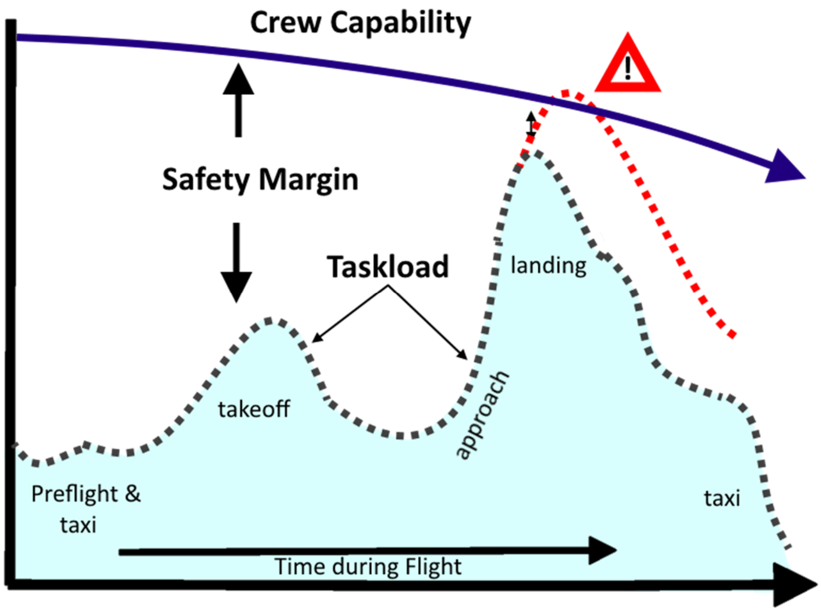

Figure 11: Safety Margin exceedance by situational factors (e.g. bad weather conditions)

Below is a list of several situational factors that can increase taskload. These can of course be combined resulting in compounding effects.

- Bad weather
- Complex terrain conditions
- Revised routing, late runway changes
- Communication problems with ATC due to system problems or language skills

- ATCO or pilot errors/lapses
- Cabin event/emergency
- Poor crew resource management
- System failure, unreliability
- Information unreliability
- Insufficient training for certain procedures and situations
- Multiple concurrent tasks, complex situation
- Reduced automation, increase manual tasking
- Time-limited tasks
- High accuracy tasks

4.1.2. Decreases crew capacity

On the other hand, it is also possible that safety margins are exceeded by a reduction in crew (functional) capacity. Degradation of crew capacity can occur slowly (e.g. fatigue) but accumulate over time, or can occur acutely (e.g. startle). Figure 12 illustrates a single dimension of crew capacity, but as the HPE is three dimensional, such a graph should indicate the taskload for each measure, and the crew capacity for each measure.

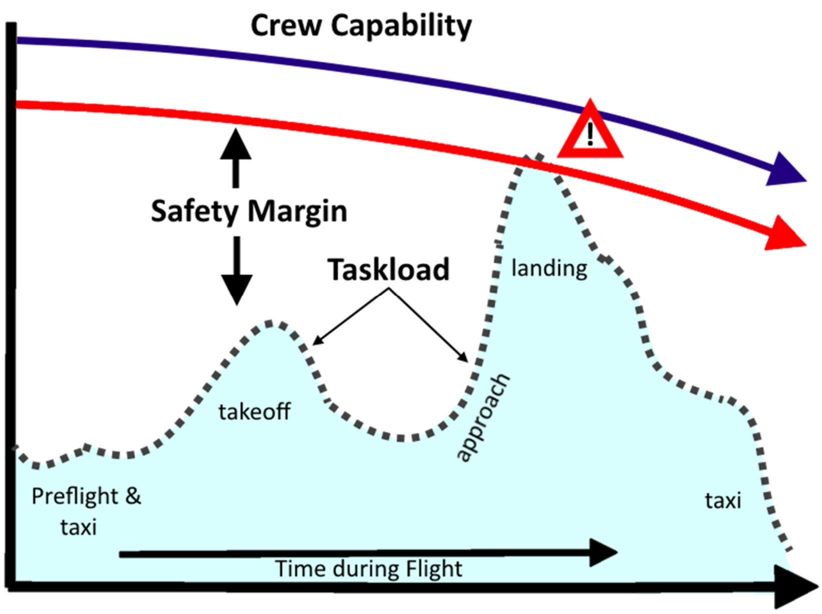

Figure 12: Safety Margin exceedance by psycho-physiological factors (e.g. fatigue)

Flight operations-common psycho-physiological factors which reduce crew capacity are:

- Fatigue & drowsiness

- Alimentation & hydration
- Startle effect
- Perceived temporal pressure/hurry-up syndrome
- Emotional distress
- Interpersonal skills & teamwork
- Cognitive overload

4.1.3. Combination of situation and Human Factors

Although either a change in the situation or a change in crew capacity could be sufficient to result in a critical situation, it is more common that a combination of both occurs. This category of situations are of great interest as only a small decrease in capacity and a small increase in taskload can already achieve critical safety margins. In addition, the effect of an increased taskload often negatively affects crew capacity (e.g. startle, stress, hurry-up syndrome) which contributes to a further reduction in the safety margin. Figure 13 shows how the combined effect (observe the solid and dotted red lines) can induce a much larger exceedance of the safety margin.

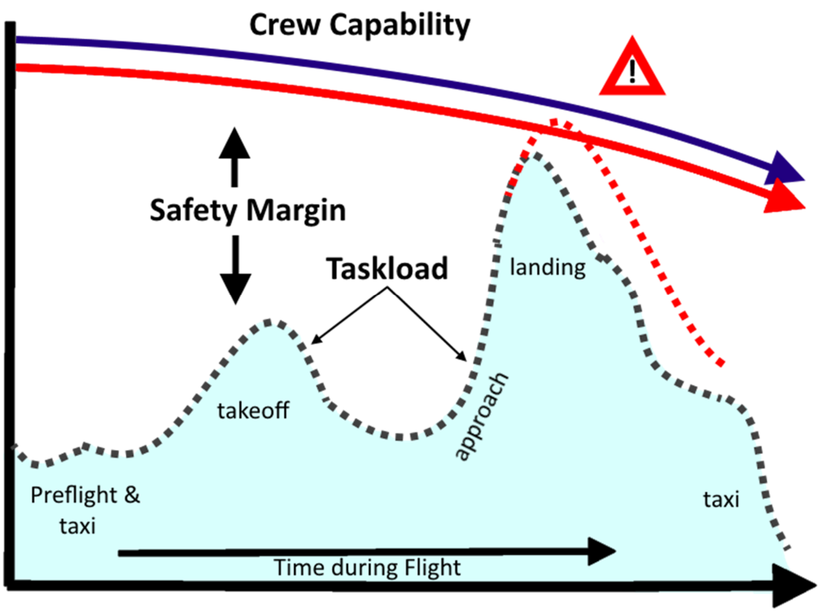

Figure 13: Safety Margin exceedance by situational and psycho-physiological factors (e.g. fatigue and bad weather)

Although there are many possible combinations of factors which will be HPE critical, some examples of HPE critical situations are provided in Section 4.2. The provided overview is not exhaustive, but the critical situations illustrated in this document will be used as inspiration for future scenario design processes.

4.2. Critical situation examples

The critical situations presented in this section have been selected on the base of the nine HPE factors considered in the P6 project, and come from review of previous project such as ACROSS [2], [3]. The critical situations can be generated by taskload increase, crew capacity decrease or by the combination of the two (i.e. variations produced by an unexpected or critical situation that in turn could produce an impact on the pilot's or on the crew's performance). Each situation is briefly explained and indications are provided on HPE factors potentially affected, and situational and human factors at stake.

Table 12: Critical situations summary

Critical situations		HPE Factors	Situation factors
1	Unexpected bad weather and communication problems with controller	Workload Stress	ATC comm. Bad weather Cabin issues
2	Imminent departures under heavy traffic conditions and/or airport congestion	Stress Workload	Time limited tasks Poor visibility
3	Re-routing	Workload Stress Situation Awareness	Revised routing ATC/pilot lapses Reduced automation Communication with ATC
4	Consecutives miss-approaches/go-arounds	Workload Situation Awareness	Terrain Weather Reduced automation Revised routing
5	Multiple systems failure	Stress Workload Situation Awareness	Pilot lapses System failure Info unreliability Insufficient training Complex situation Reduced automation
6	Automation fail, cliff effect of workload	Workload Stress	System failure Info unreliability Insufficient training Complex situation
7	Tired crew, multiple changes on arrival	Situation Awareness Workload	Revised routing Poor visibility Time-limited tasks

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8	Upset recovery during approach with failed attitude indicator	Stress Situation Awareness	System failure Info failure Time-limited tasks Reduced automation
9	Multiple systems failure and aircraft degraded manoeuvrability	Workload Stress	System failure Insufficient training Multiple tasks Reduced automation High accuracy tasks
10	Flight crew incapacitation in adverse weather	Workload Stress Situation Awareness	Bad weather Cabin emergency Multiple tasks
11	Loss of ATC communication	Workload Situation Awareness	ATC communication issues ATCO/Pilot lapse

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1. HEAVY WORKLOAD DURING LANDING IN BAD WEATHER	
Critical situation description	Heavy workload during landing in unexpected bad weather. Approach control was late in providing an initial descent clearance. Communication problems with controller due to his bad English. Controller did not provide any weather information and captain began descent without engaging the weather radar on his map display. Primary FO's weather radar was engaged, but he failed to mention the bad weather. Aircraft entered clouds and suffered moderate to severe turbulence. Cabin crew reported that several passengers became ill and that one flight attendant was incapacitated. Controller cleared aircraft for visual approach, but after breaking out of the clouds the pilots realized they were too high and too close to the airport to continue a stabilized descent. Upon request, the approach controller approved a 270-degree turn to re-join the localizer. After struggling to get the airplane down onto the glideslope, the pilots decided to go around. Pilots discussed the upcoming approach and decided to request vectors and altitude to bring them back around to the localizer for new approach attempt instead of flying the published missed approach which would take them back to the turbulence. Communication problems with the controller ensued. The crew was not able to get confirmation from ATC and after checking that there was only one other aircraft approaching the terminal, they decided to proceed. The flight crew realized that heavier rain was approaching and if this landing failed they would not be able to make another attempt until the rain left the airfield. This led the captain to join the localizer quite early, leaving very little time to stabilize the airplane and meet the glideslope. Fortunately landing proceeded without further incidents.
Phase of the flight	Approach, Landing
Normal/Non-normal	Normal
HPE factor(s) affected	Workload, Stress
Situation factors	ATC communication, bad weather, cabin issues
Other contributing factors	Hurry-up syndrome
References incidents or accidents	This scenario is based on a flight description provided by Sherman [135].

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2. IMMINENT DEPARTURE UNDER HEAVY TRAFFIC CONDITIONS	
Critical situation description	Imminent departure under heavy traffic conditions and poor visibility. Imminent departures require the crew to perform the take-off in less time than a normal. The separation minimum with the preceding traffic is crucial; any delay in the take-off roll could make the traffic in short final to go-around that represents an extra factor that increases the stress/workload of the crew due to “responsibility” with their colleagues. In addition, if the aircraft departing accumulates an important delay that could make them to loss of the en route slot assigned by the CFMU the resulting scenario could end in a “peak workload” for the crew.
Phase of the flight	Take-off
Normal/Non-normal	Normal
HPE factor(s) affected	Stress, Workload
Situation factors	Time limited tasks, poor visibility
Other contributing factors	Hurry-up syndrome
References incidents or accidents	No direct reference to a related accidents or incidents was found. However, some particular pieces of the following accident could be matched with the proposed scenario: • KLM flight 4805 and Pan Am Flight 1736 accident at Tenerife (Spain, 1977), involving two 747s. During ground operations in a heavy congested airport and in low visibility conditions both 747s collided in the runway due to a premature departure of the KLM. Aircraft Accident Report: ICAO CIRCULAR 153-AN/56. • Spanair flight JK5022 accident at Madrid (Spain, 2008) involving one MD82. This accident was caused by a miss configuration of the aircraft for landing (flaps not deployed). The aircraft had a big delay due to systems malfunction and was it second attempt for taking off. Aircraft Accident Report REF: CIAIAC A-032/2008.

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3. RE-ROUTING TO ALTERNATE AIRPORT & CHANGE OF ACTIVE RUNWAY	
Critical situation description	Re-routing to alternate airport & change of active runway. Re-routing in general requires the crew to re-plan the upcoming flight phases. The factors contributing to the increase of workload are those associated to the configuration of the Flight Management Computer following ATC clearances, the identification and change of the required Flight Charts and the re-do of the "descent/approach briefings". Depending of which flight phase this re-route is ordered by the ATC, the peak of workload could be higher (while during cruise crew is likely to have less workload/more time to plan, during final approach is likely to be completely the opposite).
Phase of the flight	En route, Descent, Approach
Normal/Non-normal	Normal
HPE factor(s) affected	Workload, Stress, Situation Awareness
Situation factors	Revised routing, ATC or pilot lapses, reduced automation, communication with ATC
Other contributing factors	Interpersonal skills and teamwork, perceived temporal pressure
References incidents or accidents	The following accidents/incidents are directly related to the proposed scenario: • American Airlines Flight 965 accident at Cali (Colombia, 1995) involving one 757. During the initial approach to runway 01 the ATCO ask the crew if they wanted to fly a straight-in approach to runway 19 rather than coming around to runway 01. The crew agreed to land at 01 and made a mistake when inputting the data in the FMC. They lost the Situational Awareness in a very Complex terrain conditions and the aircraft crash into "Los Andes" mountains. Aircraft Accident Report. Some particular pieces of the following accident could be matched with the proposed scenario: • American Airlines 1420 accident at Little Rock (USA, 1999), involving one MD82. Although the aircraft crash by a runway overrunning caused by the wrong configuration of the spoiler, during final approach the active runway was changed by the sudden change of winds. Aircraft Accident Report REF: NTSB/AAR-01/02.

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4. CONSECUTIVES MISS-APPROACHES/GO-AROUNDS	
Critical situation description	Consecutives miss-approaches / go-arounds. Performing a go-around is a procedure that increases the workload of the crew during certain amount of time, even before the execution of the procedure as the crew has a short slot to decide if land or go-around. Factors contributing to the workload are those related to the re-configuration of the aircraft from: approach/land to climb. This re-configuration includes operating Gear, Flaps & Slats, Spoilers, FMC, MCP, etc. and must be completed in short time. In addition, the crew should maintain communication with the ATC that includes manipulating also the radio panel. Consecutives go-arounds can significantly impact the crew as they could get frustrated and stressed by fact they cannot land the aircraft
Phase of the flight	Approach, Landing
Normal/Non-normal	Normal/Non-normal
HPE factor(s) affected	Workload, Situation Awareness
Situation factors	Terrain, weather, reduced automation, revised routing
Other contributing factors	Hurry-up syndrome, Fatigue
References incidents or accidents	The following accident/incident is directly related to the proposed scenario: • East Coast Jets Flight 81 at Owatonna (US, 2008) involving one BAE 125-800A. The airplane was cleared for an approach to runway 30. The crew apparently decided to execute a go around. Eyewitnesses reported that the plane struck aerials. It came down 2400 feet past the runway end and cut a swath through a corn field. Aircraft Accident Report REF: NTSB/AAR-11/01.

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5. MULTIPLE SYSTEMS FAILURE (ECAM L2)	
Critical situation description	Multiple systems failure (ECAM L2). The crew losses the Situational Awareness while trying to understand/prioritize the high amount of ECAM level 2 messages due to multiple systems failure/malfunction. The crew finds themselves into a situation where the best path to solve the problems is not obvious, they centres all the attention in understanding the main cause of the problem while they lost control of the aircraft and situational awareness. When the crew notices that they have lost the control of the aircraft they concentrates completely in getting it back (aviate) and leaves the solution of the ECAM 2 messages for later on. The crew has difficulties to recover the aircraft as they completely lost the situational awareness they simply do not know where they are and what is happening.
Phase of the flight	Climb, En route, Descent, Approach, Landing
Normal/Non-normal	Non-normal
HPE factor(s) affected	Stress, Workload, Situation Awareness
Situation factors	Pilot lapses, system failure, information unreliability, insufficient training, complex situation, reduced automation
Other contributing factors	Startle effect, fatigue, emotional stress, cognitive overload, teamwork/CRM
References incidents or accidents	*N/A*

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6. AUTOMATION FAIL, CLIFF EFFECT OF WORKLOAD	
Critical situation description	Automation fail, cliff effect of workload. After take-off, crew has initiated climb. Suddenly system messages indicate a non-critical problem/failure on one of the major aircraft system. This aircraft system is usually well automated and works the majority of the time, but because of this failure (positively identified), suddenly workload becomes important. Procedure exists but crew is trained only once in a while on this. The procedure is initiated right away. Crew feels pressure. In addition, it is questionable to maintain the reaching of top of climb altitude as the primary objective because of the identified failure, can the aircraft make it? Should we ask ATC for another altitude block and tell them we are having a situation? Risks of the situation: • Crew faces heavy workload: cliff effect due to automation failure. • Crew makes mistake because although the situation is correctly identified and the procedure exist, it is so rarely trained that they misses something. • Crew stressed, unable to make priorities or makes wrong assessments, makes wrong decisions. • Poor communication / coordination with ATC
Phase of the flight	Climb, En route, Descent
Normal/Non-normal	Non-normal
HPE factor(s) affected	Workload, Stress
Situation factors	System failure, info unreliable, insufficient training, complex situation
Other contributing factors	Startle effect, perceived temporal pressure, cognitive overload
References incidents or accidents	Man4Gen scenario WP5

7. TIRED CREW, MULTIPLE CHANGES ON ARRIVAL	
Critical situation description	Tired crew, multiple changes on arrival. Business aircraft crew flew from Europe to the US. Did a local flight (medium-short haul <3h) in the US (but with a change of time zone) and is now flying back to Europe. Crew is therefore on its third flight shift with respect to Flight Time Limitations. Fatigue and "bad quality" sleep due to various time changes has built up fatigue. Destination is a not so familiar airport. After Top Of Descent briefing, Weather changes on destination, reducing airport landing capabilities. ATC puts the aircraft on hold, then asks if the crew can accept a change of runway for landing. The proposed runway would allow landing sooner than if they wait for the planned runway. However the proposed runway is shorter and probably contaminated because of the weather. In this situation, crew is tired, feels like landing to end the mission and go home but has to make a decision on accepting or rejecting the ATC proposal. The amount of information to retrieve and performance calculations to be made are quite important. Moreover, the approach may be tricky (CAT 2) due to poor visibility. Risks of the situation: • Crew unable to make an informed and solid decision, loses time and safety margins. • Crew elaborates a poor plan of action, because of fatigue, forgetting or poorly executing one of the required tasks (for example performance recalculation with bad parameters…), poorly planning the missed approach conditions etc. • Crew focuses on one aspect only of the situation because of time pressure and fatigue and skips an important piece of information (runway is contaminated for example).
Phase of the flight	Descent, Approach, Landing
Normal/Non-normal	Normal
HPE factor(s) affected	Situation Awareness, Workload
Situation factors	Revised routing, poor visibility, time-limited tasks
Other contributing factors	Fatigue, hurry-up syndrome, teamwork, alimentation
References incidents or accidents	*N/A*

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8. UPSET RECOVERY DURING APPROACH WITH FAILED ATTITUDE INDICATOR	
Critical situation description	Upset recovery during approach with failed attitude indicator. The scenario is based on Air Transport International flight 805, which experienced a loss of control and crashed in near Toledo Express Airport, Ohio, on February 15th, 1992. The flight crew consisted of an experienced captain and a less experienced first officer plus flight engineer. The first officer was the pilot flying. The aircraft attempted twice to fly the ILS approach and had to execute missed approaches. The captain then took over the controls, executed a turn and put the aircraft in a nose high attitude, the aircraft stalled and recovery was not successful. The captain was neglecting crew resource management and was acting in the ways of an instructor. Night IMC conditions prevailed during the approaches. The captain's attitude indicator was likely malfunctioning, while the first officer's attitude indicator was operating correctly. Airline pilots do not train recovery from a stall on a regular basis. Usually, the training only includes slow flight until the stall warning and then subsequent acceleration to the appropriate speed. It is assumed that both pilots were fatigued and the captain experienced spatial disorientation prior to the stall. The first officers situational awareness was poor as shown by the two unsuccessfully attempts to capture the ILS. The wind was 13knots, gusts up to 20kt.
Phase of the flight	Approach, Landing
Normal/Non-normal	Non-normal
HPE factor(s) affected	Stress, Situation Awareness
Situation factors	System failure, information failure, time-limited tasks, reduced automation
Other contributing factors	Startle effect, Emotional stress (frustration), Teamwork
References incidents or accidents	NTSB Report DCA92MA022.

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9. MULTIPLE SYSTEMS FAILURE AND AIRCRAFT DEGRADED MANOEUVRABILITY	
Critical situation description	Multiple systems failure and aircraft degraded manoeuvrability. It is a generic scenario where the cause of multiple system failures comes from a particular risk. The crew is composed of 2 pilots. The weather is considered as nominal but could be worsened (if needed for evaluation purpose). This high workload scenario occurs when the crew faces an unprecedented amount of multiple systems failures/malfunction and the associated numerous warning messages displayed on ECAM, meanwhile pilot flying get difficulty to manoeuvre the aircraft. Neither incapacitation, lack of pilots' coordination (cross-checks…), nor misunderstandings with ATC/ground are considered in this case. The crew faced an untrained situation caused by a particular risk and related failures: • Loss of wiring in wing or fuselage, leading to partial loss of systems: Loss of control of some flight control surfaces, loss of flight envelope protection, Partial loss of electrical system, and Partial loss of fuel system. • Reduced manoeuvrability (as a consequence of above mentioned failures): Reduced roll or pitch rate capability, Fuel imbalance or fuel trapped in trim tank.
Phase of the flight	Climb, En route, Descent, Approach, Landing
Normal/Non-normal	Non-normal
HPE factor(s) affected	Workload, Stress
Situation factors	System failure, insufficient training, multiple tasks, reduced automation, high accuracy tasks
Other contributing factors	Startle effect, cognitive overload, teamwork
References incidents or accidents	QF32

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10. FLIGHT CREW INCAPACITATION IN ADVERSE WEATHER	
Critical situation description	Flight crew incapacitation in adverse weather. The following scenario illustrates the challenges of a single pilot operation (configuration 3) as a result of a flight crew incapacitation. Adverse weather conditions aggravate the circumstances the remaining pilot is exposed to. Initial Situation: Medium haul flight (also suitable for short or long-haul flights) with two pilots (1CPT, 1FO), Weather situation critical at destination airport, Inclement weather situation prevailing at most eligible en route alternate airports. En route: Turbulence and icing create high workload level in the cockpit, Deteriorating weather - low visibility operation at destination airport, Flight crew incapacitation (CPT or FO). Descend & Approach: Decision making under high workload, Descend and approach planning under high workload, Single pilot missed approach. Several aspects may lead to human error caused by high workload and consequent (partial) loss of situation awareness: Decision-making Process: Options and risks with respect to approach and landing conditions need to be evaluated (continue to destination or divert to alternate airport?), Unilateral considerations regarding operational parameters (aircraft performance, airport data etc.). Planning & Execution: Cockpit preparation is performed without assistance (PNF tasks, e.g. avionic setup, landing calculation, brake setting etc.), No supervision of single pilot in terms of standard operating procedure considerations (does the system setup meet all requirements and limits, especially for low visibility operation?), No supervision of single pilot in terms of aircraft control (deviation call outs, wind readouts, identification of runway lighting etc.). Missed Approach: No support during go-around procedure (instrument and system checks without verification of second pilot), No supervision of the single pilot in terms of aircraft control (deviation call outs, wind readouts, identification of runway lighting etc.), Unilateral considerations regarding consequences and options (fuel situation, weather development, alternate airport data etc.).
Phase of the flight	En route, Descent, Approach, Landing
Normal/Non-normal	Non-normal
HPE factor(s) affected	Workload, Stress, Situation Awareness
Situation factors	Bad weather, cabin emergency, multiple tasks
Other contributing factors	Emotional stress, teamwork, cognitive overload
References incidents or accidents	*N/A*

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11. LOSS OF ATC COMMUNICATION	
Critical situation description	Loss of ATC Communication. Pilot communication with ATC is lost due to some failure (e.g. technical or human factors related). Loss of air-ground communication (pilot-ATC) may be transitory or prolonged (PLOC) and may occur due to different reasons that can be categorised in either: technical failure or human factors related failure. Technical causes of communication loss accordingly comprise failure of aircraft communication equipment but in general may also be caused by failure of: ATC ground communication equipment or the communication link related system itself, through radio interference or technical communication link system failure (e.g. satellite service provider system failure). Human factors related causes of communication loss are mainly related to maloperation of communication equipment (e.g. changing to wrong frequency or not changing frequency). Loss of communication directly and, possibly even more so, indirectly leads to critical situations and potentially significant increased workload: loss of situational awareness, loss of separation due to missed ATC instructions, pilot actions necessary to restore normal communication and, if possible, resolve confusion, pilots' inability to pass information to ATC, risk of military interception due to inability to contact aircraft.
Phase of the flight	Take-off, Climb, En route, Descent, Approach, Landing, Roll-out
Normal/Non-normal	Non-normal
HPE factor(s) affected	Workload, Situation Awareness
Situation factors	ATC communication issues , ATCO/Pilot lapse
Other contributing factors	Teamwork (with ATC)
References incidents or accidents	A319, en route, Nantes France, 2006 A320, en route, Denver CO USA, 2009 E135 / B738, en route, Amazon Brazil, 2006 http://www.skybrary.aero/index.php/Category:Accidents_and_Incidents http://www.skybrary.aero/index.php/Loss_of_Communication http://www.skybrary.aero/bookshelf/books/111.pdf

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5 CONCLUSIONS AND RECOMMENDATIONS

This work represents the first activity of the project "Human Performance Envelope" and intends to set the concepts that will be used in the subsequent tasks. Most of the contents in this document are based on the review and analysis of previous works and research activities, and are here illustrated to be tested and validated during the exploratory simulations to be performed in the next phase.

From the literature review, the document presented a non-exhaustive list of human factors influencing HPE with its definition, way to measure it and mitigation means. Those information are summarised through HPE Cards that are intended to be a living tool that will be updated/adapted throughout the outcomes of the project. Among the list of human factors aspects described, it was agreed that the project should focus on the three following: Workload, Stress and Situation Awareness (also enabling indicators of attention and vigilance). These factors were chosen as they appeared as the most prominent measures to consider. Indeed, they were considered as the factors with the highest impact on the pilot performance, as well as those mostly likely to be investigated by using simulations. Although other factors such as fatigue and teamwork were also considered as important, the ability to obtain reliable indicators was a challenge which might hinder the validity of application of the resulting HPE model. In addition, a non-exhaustive list of critical situations was initially defined in order to degrade the HPE. Three ways to reduce the safety margin between task demand and crew capacity to a "critical" level were identified: (1) Increase in the taskload; (2) Decrease in crew capacity; (3) a combination of 1 and 2. This will be used as input to developed cockpit scenario for real time simulations (next step).

The simulations will aim to study the HPE degradation (factors and scale). In particular they will analyse how to detect degradation (through operational performance markers and indicators), and how the pilots currently react to HPE degradation. In order to investigate the evolution of the HPE and its potential degradation, the validation plan will define a set of reference scenarios. Such scenarios will draw on initial concepts from:

- Critical situations identified in the SoA
- Scenarios developed and validated during the workshop with external experts.

Once the reference scenarios will be defined, a preliminary list of operational performance, behavioural markers and indicators will be defined, based on the work previously done in similar contexts (e.g. ATC context in [43]).

During the simulations, and based on a thorough experimentation plan defined in D6.2 "Test plan for preliminary systems/pilots cognitive task analysis", behavioural markers and indicators will be collected, and analysed in their interactions and consequences.

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This work will allow to define, in the second part of the project, the recovery means: informing pilot/system/proposing mitigation or recovery (from information provision to adaptive automation). However, it can be anticipated here that the project is expected to address accommodation (pilots support) rather than full automation (detecting drift in the HPE and bringing the system back to a safe level). Actually, whereas it is feasible to inform the pilot that his/her workload/stress/vigilance seems to be drifting (hence the HPE degrading), in a stressful situation (e.g. fuel shortage, technical failure), there is no way to remove this stress level. The main technological solutions defined should then be focused on avoiding reaching such situation, and detecting drifting in the HPE while it is still within acceptable limit.

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Appendix A HPE Factors Cards

HPE Factors Cards are intended to be a tool for P6 in which all the shared and consolidated information about the HPE components are structured and organised in a concise manner. The Cards reported here are the result of the state-of-the-art on the HPE components and the HPE Concept workshop, in which these cards were reviewed and integrated with new pieces of information.

The Cards are intended to be used from now on, for all the duration of the project, as a living tool to be refined and updated with new project findings. For example, details on measures reliability can be integrated after the real time simulations, as well as the effects of the factor on human performance.

Colour coding was used to highlight the more close relations between factors.

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MENTAL WORKLOAD

Definition(s)	Mental workload refers to the portion of operator **information processing capacity** or resources that is actually required to meet system demands (Eggemeier & Damos, 1991). Workload is not an inherent property, but rather it emerges from the **interaction between the requirements of a task**, the circumstances under which it is performed, and the skills, behaviors, and perceptions of the operator (Hart & Staveland, 1988). Mental workload is a hypothetical construct that describes the extent to which the cognitive resources required to perform a task have been actively engaged by the operator (Gopher & Donchin, 1986).		
Task-related measures	**Technique(s)**	**Observable(s)**	**P6 use**
	NASA-TLX (subjective)	Higher rating based on self-assessed level of workload.	Simulator
	Primary and secondary task (performance-based)	Performance decrement: when workload and task difficulty increase, reaction time, number of errors increase as well, while accuracy and number of completed tasks decrease. Compensatory strategies (e.g. strategy adjustment, fatigue after-effects and speed-accuracy trade-offs) can be applied by the subject, resulting in the lack of visible effects of workload variation on performance.	Simulator Cockpit
	Witness observation from experts of strategy changes	An subject matter expert is someone widely recognised as a reliable source of technique or skill with faculty for monitoring or evaluating wisely in a specific well-distinguished domain, for example aviation. Observers can be asked to evaluate the degree to which individuals are carrying out actions and exhibiting behaviors that would be expected to promote the achievement of a task. For example the expert observation can be used for monitoring pilot's behavior (strategy changes) to figure out the level of workload in association with other techniques. Monitoring of distraction and inattention: duration of visual distraction, monitoring head position if it is directed to the relevant elements of the working environment.	Simulator Cockpit
Psycho-physiological measures	**Technique(s)**	**Observable(s)**	**P6 use**
	Functional Near Infrared (fNIR) spectroscopy	Deoxygenated Hemoglobin generally declines during 4-6 seconds response to increased mental workload and then trend back towards steady state. Overall, sustained mental workload is correlated to a sustained increase in Oxygenated Hemoglobin and an initial drop followed by recovery towards equilibrium for Deoxygenated Hemoglobin.	Simulator
	Electrocardiography (ECG)	Heart rate increases with increased mental workload, while heart rate variability decreases with increased mental workload. Blood pressures increases with increasing mental workload.	Simulator Cockpit

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	Respiratory activity: strain gauges sensor on the operator chest, in the seat or linked to safety belt (respiratory rate) and spirometer (breathing rate)	Respiratory rate increases with increment in mental workload. Volume per breath decreases with increment in mental workload.	Simulator
	Electrooculography (EOG) for eye blink rate and eye blink duration Eye tracking for pupil diameter, eye fixation and horizontal eye movements (HEM)	Eye blink rate and duration decrease with increasing mental WL. Pupil diameter and HEM increase with increasing mental WL. Eye fixation.	Simulator
	Eye Tracking	Eye gaze patterns	Simulator
	Electroencephalography (EEG)	Theta band power increases when mental WL increases. Alpha band power decreases when mental WL increases. Beta band power increases when mental WL increases.	Simulator
	Electromyography (EMG)	Muscle tension increases with increased mental WL.	/
	Electrodermal activity (EDA)	As workload increases, EDA increases as well.	/
Expected effects on performance	Increase of workload and task difficulty lead to a performance decrement that reflects in a decrease of accuracy and number of completed task, while reaction times and number of errors increase. The increase of mental workload could lead to a Situation Awareness decrease which, in turn, could lead to worse performances. However, the adoption of compensation strategy can result in the lack of visible effects of workload variations on subject performance.		
Design solutions to prevent or mitigate negative effects on performance	Automation and information system design Procedures Alarm and attention getters (combination of light, sound and vibration to alert the pilot) Maximum use of automation in flight and on ground Support system for information filtering, guiding the situation analysis and the decision making (e.g. HMI, Autopilot, FMS)		
Interactions with other Factors	**Attention and vigilance**, **Stress**, **Fatigue** (Mental Fatigue – Drowsiness)		

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STRESS

Definition(s)	According to psychological theories stress is determined by the **balance between the perceived demands from the environment and the individual's resources** to meet those demands (Frankenhaeuser, 1986; Lundberg, 1995). From a physiological view, a typical stress response means that autonomic activity increases, although in certain situations and in certain individual's the stress response might be different (even a decrease is possible). Stress can be categorized into two basic forms: **acute stress**, relatively short in duration and is often experienced as caused by high taskload; **chronic stress**, prolonged stress that can result from occupational or non-occupational sources. McEwan and Seeman (1999) described four possible situations that may cause chronic stress: too frequent stress exposure, failure to habituate to repeated exposure of the same kind of stressor, inability to shut off the stress response, despite that stress has terminated, and situations that cause regulatory disturbances of the stress system.		
Task-related measures	**Technique(s)**	**Observable(s)**	**P6 use**
	Video camera on the operator	Fast and frequent head movements, and body position changes. Some negative facial expressions like asymmetric lip deformation with stressful situations.	/
	Communication analysis	Use non-standard phraseology when communicating, fail to understand what is being said over the radio, revert to the use of their native language if different from the one being used (usually English), or look for items in a place where they used to be, but are no longer located.	Simulator
	Cognitive observations	Stress affects information perception and process, as well as the decision process, leading to an increase in number of errors and mistakes. Common behaviour effects are: • attentional narrowing or decrease in attention levels which translates into perceptual (narrower field of vision, selective hearing) and cognitive tunnelling; • scattered and poorly organized visual scan; • reductive thinking and filtering (considering only a few hypotheses, thus rejecting certain tasks or ignoring some warning signs); • premature closure (making a decision without exploring all information); • hurried decisions, even when there is no time pressure (leading to the speed accuracy trade-off). Not surprisingly, the best decision-makers seem to be those who take their time under stress; • decrements in working memory capacity and retrieval.	Simulator Cockpit
	Seat foil sensor	Seat pressure and seat movements.	/
Psycho-physiological measures	**Technique(s)**	**Observable(s)**	**P6 use**
	Voice analysis	Stress modifies the pilot behaviour like voice prosody (pitch of voice, length of sounds, loudness, or prominence).	Simulator Cockpit
	Pressure/grip force sensors	Grip force.	Simulator Cockpit

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	Respiratory activity: strain gauges sensor on the operator chest, in the seat or linked to safety belt (respiratory rate) and spyrometer (breathing rate). Inductive and impedance plethysmography, piezoelectric pneumography, piezoresistive pneumography	Respiratory rate increases in stressful conditions. Volume per breath decreases with increment of stress. Changes in thorax circumference and cross section, or trans-thoracic impedance.	Simulator
	Electrocardiography (ECG)	Heart rate increases while heart rate variability decreases in stressful situations. Blood pressures increases with stress.	/
	Electromyography (EMG)	Facial and trapezoid muscle tension increase in stressful conditions.	/
	Electrooculography (EOG)	Increased blinking frequency and eye movements.	Simulator
	Eye tracking	Scan pattern.	Simulator Cockpit
	Electro dermal activity (EDA)	EDA increases with stress.	/
	Polygraph sensor or pill	Heat flux/skin temperature.	/
	Electrochemical sensors	lactate in sweat, pH, sodium concentration in sweat.	Simulator Cockpit
	Analysis of hormones release quantified in blood, saliva and urine	Increased adrenaline and noradrenaline, and steroid cortisol during stressful situations.	/
Expected effects on performance	It has been seen that stress can influence performance and may impair attention and memory, and can contribute to an increase of human errors and accidents. In general, stress affects how we perceive and process information, as well as what decisions we make, leading to an increase in the number of errors and mistakes.		
Design solutions to prevent or mitigate negative effects on performance	Automation and information system design Maximum use of automation in flight and on ground Support system for information filtering, guiding the situation analysis and the decision making (e.g. HMI, Autopilot, GPS)		
Interactions with other Factors	Stress can influence performance and may impair attention and memory, and can contribute to human errors and accidents. Interaction with **Mental fatigue, Mental Workload**, **Vigilance**, monotony, **Situation Awareness**, stimuli from environment, decision making under time pressure conditions, and **Communication**.		

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FATIGUE (MENTAL FATIGUE – DROWSINESS)

Definition(s)	Fatigue is a multidimensional state that includes **physical, mental** and related to **sleepiness** components (Åhsberg et al., 1997). Fatigue is a **gradual and cumulative process** associated with an aversion for effort, sensation of weariness, reduced motivation, efficiency, vigilance and alertness, and impairments in task performance (Grandjean, 1970). Drowsiness is an intermediate **state between wakefulness and sleep** defined as a progressive impairment of awareness, associated with a strong desire or inclination for sleep (Slater, 2008). Due to the similar neurophysiological characterization, it's difficult to discriminate between mental fatigue and drowsiness, and they may be considered as transitional states on a continuum. Mental fatigue and sleepiness can be regarded as a consequence of sustained mental activity and lack of resources due to mental task execution, but also as a result of monotonous and boring situations when demand for sustained attention is high but little information is conveyed. No standardized methods for drowsiness exist, but the more reliable techniques seems to be the combination between EEG and EOG.		
Mental Fatigue - Task-related measures	**Technique(s)**	**Observable(s)**	**P6 use**
	Systems using sensors monitoring operators' awareness through a video camera from which can be extracted, e.g. eye blinking, pupil diameter, gaze and saccadic eye movements, facial tones, head movements	Eye blinking increases with mental fatigue. Pupil diameter and stability decreases in fatigued state. Gaze is reflected by impaired tracking and scanning of the environment in mental fatigue state (narrow gaze). Saccadic eye movements decrease with mental fatigue occurrence. Facial tone decreases when the subject is mental fatigued. Frequent head tilts indicate the onset of fatigue. The face in other directions, e.g. down or sideway, for an extended period of time is due to fatigue or inattention.	N/A
Mental Fatigue - Psycho-physiological measures	**Technique(s)**	**Observable(s)**	**P6 use**
	Electroencephalography (EEG)	Increase in delta, theta and alpha power bands, and decrease in beta band, even though some researchers have found an increase of this rhythm. Divergent results are due to the attempt of the operator to maintain a state of alert during the task, giving rise to an increase rhythm.	N/A
	Electrooculography (EOG) for eye blink rate and eye blink duration Eye tracking for pupil diameter, eye fixation and horizontal eye movements (HEM)	Eye blink rate and duration present both an increase with mental fatigue. Pupil diameter and HEM decrease with increasing mental fatigue. Occasional episodes of eye fixation may occur.	N/A
	Electrocardiography (ECG)	A decline of heart rate, and low frequencies of heart rate variability; an enhancement of high frequencies of this variable has observed with mental fatigue.	N/A
	Electromyography (EMG)	Muscle tone declines with mental fatigue and drowsiness.	N/A
Drowsiness - Task-	**Technique(s)**	**Observable(s)**	**P6 use**

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related measures	Karolinska Sleepiness Scale (KSS)	Rating based on self-assessment of drowsiness state.	N/A
	Systems using sensors monitoring operators' awareness through a video camera from which can be extracted, e.g. eye blinking, pupil diameter, gaze and saccadic eye movements, facial tones, head and body movements, yawning and mouth features Other sensor for monitoring body and head position: actimeter, EMG of the tibialis anterior, body/limb motion tracking with vision technologies	Some characteristic movements and attitudes are typical of pre-falling-asleep phases: yawning, body repositioning movements, head movements and all the arm/hand auto-centred movements (movements for scratching some part of the head - nose, hair, eye- movements of the hands in the hair). Limb and body movements typical of a drowsy state: • movements of the upper part of the body (example: the back of the pilot moving forward); • re-positioning of the pilot body onto the seat rest (for example a change of the pushing zone on the back or on the rest of the seat); • movements toward a "sink" position (in the upper part of the seat); • movements of the neck or falling head; • auto-centred movements. Eye blinking increases with drowsiness. Pupil diameter and stability decreases in drowsy state. Gaze is reflected by impaired tracking and scanning of the environment during drowsiness. Saccadic eye movements decrease with drowsiness occurrence. Number of yawning increase during drowsy state.	N/A
	Primary and secondary task	Drowsy subjects show decreases in quality and accuracy of task performance, longer reaction times and reduced decision ability. Drowsiness reduces the overall available ability for task execution.	N/A
Drowsiness - Psycho-physiological measures	**Technique(s)**	**Observable(s)**	**P6 use**

	Electroencephalography (EEG)	The involuntary sleep onset is characterized by theta waves, corresponding to eye closure (for some subjects, brief periods of theta activity show with open eyes). Before the individual falls asleep, the EEG is usually characterized by repeated alpha bursts. In most cases alpha bursts occur for a long time, but in subjects lacking alpha waves (approximately 10% of all individuals produce no alpha waves) theta waves will be the first EEG-sign of drowsiness or sleep. With respect to the EOG, the sleep onset is usually preceded by long eye closure duration and slow eye rolling movements. Important features characterising the gradual progression from wakefulness to sleep: • slowness of the alpha EEG rhythm and reduction of its amplitude; • gradual disappearance of occipital alpha and more spatially diffuse alpha presence, moving anteriorly; • reduction of rapid eye movements (REMs); • appearance of horizontal slow eye movements (SEMs); • appearance of theta EEG activity bursts; • appearance of vertex EEG waves. The criteria for drowsiness detection diffuse in literature are: • EEG alpha activity starts to appear or increases in spectral power density as a relatively early sign of drowsiness; • EEG theta activity starts to appear or increases in spectral power density as a sign of severe drowsiness. Theta >50% of the epoch is sleep onset; • EOG slow eye movements usually start to appear in connection with sleep onset and severe sleepiness. A method to quantify drowsiness, using EEG and EOG as a reference indicator, is a visual scoring called Objective Sleepiness Scales (OSS); it is based on the evaluation of drowsiness executed by expert doctors who visually observe (after driving) alpha and theta activity on a short-time window of data recorded during driving.	N/A
	Electrooculography (EOG) for eye blink rate and eye blink duration, PERCLOS (PERcentage of eyelid CLOSure), slow eye movement (SEM) Eye tracking for pupil diameter, eye fixation and horizontal eye movements (HEM) Amplitude-Velocity Ratio of Blinks (AVRB)	Eye blink rate and duration present both an increasing trend with drowsiness. PERCLOS increases with drowsiness occurrence. SEM starts to appear. Pupil diameter and HEM decrease with increasing drowsiness. Occasional episodes of eye fixation may occur. AVRB, measures in milliseconds, increases in drowsy subjects.	N/A
	Complex algorithms for drowsiness detection based on a combination of different measurements	For example: algorithm combining blinking frequency, duration of blinks and eyelid opening level; algorithm combining brain (EEG) and visual activity (EOG).	N/A
	Electrocardiography (ECG)	Decreased heart rate and increased heart rate variability are reported.	N/A

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	Respiratory activity: strain gauges sensor on the operator chest, in the seat or linked to safety belt (respiratory rate)	Respiratory rate decreases with drowsiness occurring.	N/A
	Electrodermal activity (EDA)	EDA declines with drowsiness.	N/A
Expected effects on performance	Effects of fatigue/drowsiness on human performance can be usually seen in the decrease of quality and accuracy of task performance, as well as in the increase of reaction times and reduction of decision ability. It can be said that drowsiness reduces the overall ability of single and multiple tasks execution. Some examples of ATCOs performance changes are: multiple small mistakes, frequency checks, overlooking aircraft, mixing up call signs, don't hear read back, incorrect plan without realisation, inappropriate reactions, "running behind traffic", forgetting/ surprise.		
Design solutions to prevent or mitigate negative effects on performance	Optimal use of automation in flight and on ground (i.e. trade-off between fatigue/workload reduction and sleepiness/disengagement risk) Support system for information filtering, guiding the situation analysis and the decision making (e.g. HMI, Autopilot, FMS) Support systems to alert the pilot: bright light, sound and vibration Working environment to keep pilots awake and alert: bright lights, cool dry air obtrusive or loud music, some invigorating aromas (such as peppermint) Sleeping area		
Interactions with other Factors	**Attention, Vigilance, Mental Workload, Situation Awareness, and Stress**. Time-on-task (TOT), difficulty of the task (e.g. more cognitive demand), multiple task performance, monotony.		

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SITUATION AWARENESS

<table>
<tr><td rowspan="5">Definition(s)</td><td colspan="3">SA is the up-to-the minute comprehension of task relevant information that enables appropriate decision making under stress (Smith & Hancock, 1995).
SA is a function of several quasi-independent situation types: available situation, perceived situation, expected situation, and inferred situation (Boy & Ferro, 2004).
Endsley (1995) developed a three-stage model of Situation Awareness (SA): perception of elements, comprehension of current situation, and projection of future status. SA is the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the future.
SA, related to pilots, involves the operators’ perception of different environmental elements with respect to time and space, together with a comprehension of their meaning and the projection of their status after some variable has changed with time (Borghini et al., 2012). When people are required to make critical choices (Parasuraman et al., 2008; Lundberg, 1999; Endsley, 1995), sometimes at a fast pace, the majority of errors occurring is a direct result of failures in SA.</td></tr>
</table>

Task-related measures	Technique(s)	Observable(s)	P6 use
	Situation Awareness Rating Technique (SART) and Situation Awareness Rating Scale (SARS); subjective methods adopted in military studies (e.g. one pilot)	SART and SARS, measures based on self-assessment level of SA.	Simulator
	Situation Awareness Global Assessment Technique (SAGAT) and Situation Preset Assessment Method (SPAM); behavioural measures adopted in military studies (e.g. one pilot)	SAGAT, pilot’s answers are compared to the real situation (ground truth) to provide an objective measure of SA. SPAM, similar to SAGAT, measures the accuracy and time to respond for detecting decrements in SA.	Simulator Cockpit
	Situational Awareness Linked Indicators Adapted To Novel Tasks (SALIANT)	SALIANT technique infer a team’s SA from observed behaviours. The focus is on behavioural processes and indicators related to team situational awareness. This method results in a behavioural checklist that can be used to behaviourally assess situational awareness in teams.	Simulator Cockpit
	Global Implicit Measure (GIM) performance-based measure of SA. Observations of crew behaviour and actions.	GIM is based on the assumption that a pilots’ goals and priorities are constantly changing, and that it should be possible to look at the progress toward accomplishing these goals, using it as measure of SA. Pilot actions with aircraft systems: expected actions can be compared with actual system states and crew actions to interpret the level of control and awareness of the crew. Verbal protocols, consist of asking the subjects to “think out loud” while performing the task. Communication analysis, mostly used in studies of team strategies, the interaction between participants is recorded and analysed.	Simulator Cockpit

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	Expert observation	An subject matter expert is someone widely recognised as a reliable source of technique or skill with faculty for monitoring or evaluating wisely in a specific well-distinguished domain, for example aviation. Observers can be asked to evaluate the degree to which individuals are carrying out actions and exhibiting behaviours that would be expected to promote the achievement of a task. For example, the expert observation can be used for monitoring pilot's behaviour to figure out the level of SA in association with other techniques (e.g. eye tracker to measure eye movements). Monitoring of distraction and inattention: duration of visual distraction, monitoring head position if it is directed to the relevant elements of the working environment.	Simulator Cockpit
Psycho-physiological measures	**Technique(s)**	**Observable(s)**	**P6 use**
	Electroencephalography (EEG)	It can indicate high mental activity, which can be an indicator of high (cognitive) workload.	Simulator
	Functional Near Infrared (fNIR) spectroscopy	Measure of mental workload through blood oxygenation in the brain.	/
	Eye tracking	Eye/gaze tracking: ability to see what flight crew are looking at, identify information that can be seen, and areas that are being scanned.	Simulator Cockpit
	Electrocardiography (ECG)	Heart rate and heart rate variability as in mental workload.	Simulator Cockpit
	Electrooculography (EOG)	Eye blink rate and duration as in mental workload.	Simulator Cockpit
Expected effects on performance	SA is not directly related to overall task performance, as good awareness of what is occurring does not always lead to effective actions. However, the identification of a secondary event (for example a communication error) could be used as a performance measure. The main effect of a SA decrease is that the operator (ATCO or pilot) lose the whole picture and "run behind". This might result in unsafe actions, unexpected decisions and incorrect reactions to the situation.		

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Design solutions to prevent or mitigate negative effects on performance	Optimal use of automation in flight and on ground Optimal HMI design, including use of multimodal support (e.g. visual information, sounds, vibration) Alarm and attention getters (combination of light, sound and vibration to alert the pilot) audio messages stating the person's name, flashing visual signal) Disruption in the "cognitive" environment (e.g. if previously noisy stop all audio alarm, if cluttered display remove information) Support tools (HMI) for information collection, filtering and analysis, following four cognitive principles: • Automated change detection (HMI display, flashing indicator of changed parameter) • Unobtrusive notification of changes (e.g. peripheral location, subtle sound to inform on change, soundscape approach) • Overview prioritization (e.g. from critical to mundane information, from macro to micro) • Minimal clutter on the situation display but maximal access Radio, Data-link to enable communication, information requests and/or discussions or clarifications
Interactions with other Factors	Higher **Mental Workload** could results in a decrease in Situation Awareness, which, in turn, could lead to a performance degradation. Request to make critical choices produces more risk of error and failures in Situation Awareness. SA and workload are independent constructs, and the amount of **Stress** and **Mental Fatigue** also affects SA. **Communication** is affected by SA. SA is also strictly dependent from the levels of **Attention** and **Vigilance**.

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ATTENTION

Definition(s)	Attention is the ability to **attend to information** in the environment (Eysenck, 2001). It is a **multidimensional construct** that includes focused attention, divided attention and sustained attention/vigilance. Van Zomeren & Brouwer (1994) and Shallice (2002) have proposed a multi-componential model composed of intensive and selective components, and Supervisory Attentional System (SAS).		
Task-related measures	**Technique(s)**	**Observable(s)**	**P6 use**
	Reaction times Target detection Sustained Attention to Response Task (SART)	Slowing down of responses, lapses of attention that reflects the increasing number of critical signals missed over time (vigilance decrement). Failures to detect signals where observers are asked to respond to the more frequent neutral events and to withhold responding in the presence of the less frequent critical signals.	Simulator Cockpit
	Primary and secondary task	Performance decrement: when attention, workload and task difficulty increase, response times, number of errors increase as well, while accuracy and number of completed tasks decrease.	Simulator Cockpit
	Direct observation of the pilot: body, limb movement trackers.	Monitoring of distraction and inattention: duration of visual distraction, monitoring head position if it is directed to the relevant elements of the working environment. Fixed camera pointed to the pilots can be used for the observation.	Simulator Cockpit
Psycho-physiological measures	**Technique(s)**	**Observable(s)**	**P6 use**
	Head mounted oculometer or specific glasses	Monitoring of distraction and inattention: duration of visual distraction, monitoring the direction of eye gaze and head position towards the relevant elements of the working environment. Two syndromes are present: 1. Perseveration, incapacity to shift from a goal to a new one to react adequately to the evolution of the environment. 2. Attentional fixation (or cognitive tunnelling), allocation of attention to a particular information, diagnosis hypothesis or task goal, for a longer duration than optimal, given the expected cost of neglecting events on other channels, failing to consider other hypothesis, or failing to perform other tasks.	Simulator (?) Cockpit (?)
	Eye tracking	Eye/gaze tracking: ability to see what flight crew are looking at, identify information that can be seen, and areas that are being scanned.	Simulator
	Electrocardiography (ECG)	Heart rate and heart rate variability as in mental workload.	/
	Electrooculography (EOG)	Eye blink rate and duration as in mental workload.	Simulator Cockpit
	Electroencephalography (EEG)	Lower alpha desynchronization (decreased band power) may reflect attentional processes.	Simulator

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	Functional Near Infrared (fNIR) spectroscopy	Measure of mental workload through blood oxygenation in the brain. In vigilance tasks the performance decrement has been repeatedly associated with decreased blood flow velocity in the right hemisphere.	/
	Transcranial Doppler (TCD) sonography Positron Emission Tomography (PET) Functional Magnetic Resonance Imaging (fMRI)	Decreases in cortical activity (resulting in performance lapses) are simultaneously associated with decreases in metabolic activity in right frontal brain regions, thus performance decreases covary with decreases in right cerebral arterial blood flow velocities during vigilance tasks.	/
Expected effects on performance	Lack of attention/vigilance or distraction usually affects human performance by causing the omission of procedural steps, forgetfulness to complete tasks, and taking shortcuts that may not be for the better. A performance decrement can be noticed when attention/vigilance, workload and task difficulty increase; the reaction time and number of errors increase as well, while accuracy and number of completed tasks decrease. Reduction of the performance in monitoring, tracking, auditory discrimination, and reduction of visual field can be observed too.		
Design solutions to prevent or mitigate negative effects on performance	Optimal HMI design, including use of multimodal support (e.g. visual information, sounds, vibration) Alarm and attention getters (combination of light, sound and vibration to alert the pilot, audio messages stating the person's name, flashing visual signal) Disruption in the "cognitive" environment (e.g. if previously noisy stop all audio alarm, if cluttered display remove information)		
Interactions with other Factors	Attention is strictly related to other concepts such as **Vigilance, Situation Awareness and Mental Workload**. Thus, attention could be affected by an higher mental workload, and could result into a performance degradation.		

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VIGILANCE

<table>
<tr><td>Definition(s)</td><td colspan="3">Sustained attention/vigilance is a state of readiness to detect and respond to certain small changes occurring at random time intervals in the environment (Mackworth, 1957).
Sustained attention and vigilance is the ability to maintain the focus of attention to a task and to remain alert to stimuli over prolonged periods of time, in order to detect and response to infrequent critical events (Davies & Parasuraman, 1982; Parasuraman, 1998; Warm et al., 2008). Vigilance is strictly related to other concepts such as attention, SA, mental fatigue, drowsiness, and mental workload.</td></tr>
<tr><td rowspan="2">Task-related measures</td><td>Technique(s)</td><td>Observable(s)</td><td>P6 use</td></tr>
<tr><td>Reaction times
Target detection
Sustained Attention to Response Task (SART)</td><td>Slowing down of responses, lapses of attention that reflects the increasing number of critical signals missed over time (vigilance decrement).
Failures to detect signals where observers are asked to respond to the more frequent neutral events and to withhold responding in the presence of the less frequent critical signals.</td><td>Simulator
Cockpit</td></tr>
<tr><td rowspan="5">Psycho-physiological measures</td><td>Technique(s)</td><td>Observable(s)</td><td>P6 use</td></tr>
<tr><td>Electroencephalography (EEG)</td><td>Lower alpha desynchronization (decreased band power) may reflect attentional processes.</td><td>Simulator</td></tr>
<tr><td>Transcranial Doppler (TCD) sonography
Positron Emission Tomography (PET)
Functional Magnetic Resonance Imaging (fMRI)</td><td>Decreases in cortical activity (resulting in performance lapses) are simultaneously associated with decreases in metabolic activity in right frontal brain regions, thus performance decreases covary with decreases in right cerebral arterial blood flow velocities during vigilance tasks.</td><td>/</td></tr>
<tr><td>Electrocardiography (ECG)</td><td>Heart rate and heart rate variability as in mental workload.</td><td>/</td></tr>
<tr><td>Electrooculography (EOG)</td><td>Eye blink rate and duration as in mental workload.</td><td>Simulator
Cockpit</td></tr>
<tr><td>Expected effects on performance</td><td colspan="3">Lack of attention/vigilance or distraction usually affects human performance by causing the omission of procedural steps, forgetfulness to complete tasks, and taking shortcuts that may not be for the better. A performance decrement can be noticed when attention/vigilance, workload and task difficulty increase; the reaction time and number of errors increase as well, while accuracy and number of completed tasks decrease. Reduction of the performance in monitoring, tracking, auditory discrimination, and reduction of visual field can be observed too.</td></tr>
<tr><td>Design solutions to prevent or mitigate negative effects on performance</td><td colspan="3">Optimal HMI design, including use of multimodal support (e.g. visual information, sounds, vibration)
Alarm and attention getters (combination of light, sound and vibration to alert the pilot, audio messages stating the person’s name, flashing visual signal)
Disruption in the “cognitive” environment (e.g. if previously noisy stop all audio alarm, if cluttered display remove information)</td></tr>
<tr><td>Interactions with other Factors</td><td colspan="3">Attention and Situation Awareness, Mental Workload, Stress, Mental Fatigue.</td></tr>
</table>

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TEAMWORK

<table>
<tr><td>Definition(s)</td><td colspan="3">Teamwork is the organized, collective working methods between an established group of people (Bailey & Thompson, 2000; Erdem & Ozen, 2003; Rasmussen & Jeppesen, 2006).
In ATC environment is the exchange of information, including timeliness, accuracy, clarity and receptiveness. Teamwork is a collective and mutual interaction with humans in the system for performance (Edwards, 2013).</td></tr>
<tr><td rowspan="4">Task-related measures</td><td>Technique(s)</td><td>Observable(s)</td><td>P6 use</td></tr>
<tr><td>TARGET (Targeted Acceptable Responses to Generated Events) and BOS (Behavioural Observation Scale).</td><td rowspan="3">The shared physical workspace and control tools facilitate teamwork.
Study in ATC simulation showed that the controller pairs who engaged in specific team processes such as situational enquiries, maintaining awareness through monitoring and statements of intent maintained effective teamwork and a high level of performance and were most efficient at controlling high volumes of traffic. Controllers who had highest performance also engaged in preplanning, and selection of control strategies during the lower taskloads before higher volumes of traffic. Without engaging in these mechanisms, or the effective application of team strategies, performance was not maintained to a high level suggesting the importance of effective teamwork to maintain efficient and safe performance. However, the artificial problem scenarios may limit the generalisation of the findings to the operations room.</td><td>N/A</td></tr>
<tr><td>Direct naturalistic observation/simulation study (especially in ATC domain)</td><td>N/A</td></tr>
<tr><td>Analysis of incident reports</td><td>N/A</td></tr>
<tr><td>Expected effects on performance</td><td colspan="3">Performance may be enhanced with specific effective teamwork elements (e.g. organization and coordination of teamwork, efficient communication). Conversely, inadequate teamwork has been associated with performance declines and human errors. Breakdown in teamwork may have an adverse effect on the following: Communication between colleagues, including briefing on handover; Communication between controllers and pilots; Situational awareness; Decision making; Monitoring of crew actions; Monitoring of colleagues; Flexibility - ability to adjust to changing workload.
Any or all of these factors taken singly or in combination may contribute to an accident or serious incident. Additionally, breakdown in teamwork may lead to frustration and irritation, low morale and poor job-satisfaction, which are likely to impact on team performance (the vicious circle).</td></tr>
<tr><td>Design solutions to prevent or mitigate negative effects on performance</td><td colspan="3">Workspace designed to support communication (including intention recognition) through sharing of resources and information
Radio, Data-link to enable communication, information requests and/or discussions or clarifications</td></tr>
<tr><td>Interactions with other Factors</td><td colspan="3">Communication, Trust, Mental Workload, and Stress.</td></tr>
</table>

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COMMUNICATION

Definition(s)	Communication may be defined as the **transfer of meaningful information** from one person to another (Hogg & Vaughan, 2002) and involves both the production and the reception of messages, although communication is independent from (but related to) the concepts of speech and language (Hogg & Vaughan, 2002; Huttunen et al., 2011). In ATC environment is the exchange of information, including timeliness, accuracy, clarity and receptiveness. Teamwork is a collective and mutual interaction with humans in the system for performance (Edwards, 2013).		
Task-related measures	**Technique(s)**	**Observable(s)**	**P6 use**
	TARGET (Targeted Acceptable Responses to Generated Events) and BOS (Behavioural Observation Scale).	Effective communication supports individuals in developing a shared awareness of the situation or system, supports teamwork and therefore results in a maintenance or increase of performance. Effective communications may lead to increased planning statements, structure and predictability.	N/A
	Direct naturalistic observation/simulation study (especially in ATC domain)	Generally, verbal and written communication errors and miscommunication have been critical contributor to risk in several domains. Communication errors and miscommunications have been associated with performance decline and performance-related incidents.	N/A
	Analysis of incident reports	Examples of pilot-controller communication errors were categorized into three forms: 1. actual read back/hear back error in which the pilot reads back the instruction incorrectly and the controller does not correct the error; 2. absence of a pilot read back; 3. hear back errors in which the controller does not correct a pilot read back containing the controller's own error from the original instruction. Miscommunications can include ambiguity through word choices or distortions of meaning, and this is more likely if standard phraseology is not used. Slips are also frequent forms of miscommunication, which result in verbally communicating information that was not intended. Miscommunications can result from the intelligibility of speech may be affected by the physical systems such as radiotelephony system blocking calls or distorting communications. Wrong fitting headphones that can produce high level of ambient noise in the operations room.	N/A
	Speech recordings	As a function of increased cognitive load, the mean utterance-level fundamental frequency increases.	N/A
Expected effects on performance	Communication errors and miscommunication can produce performance decline and performance-related errors. Although errors did not necessarily contribute to an incident, error of communications suggests the pervasiveness of the communication issues and potential implications on performance. Effective communication supports individuals in developing a shared awareness of the situation or system, supports teamwork and therefore results in a maintenance or increase of performance. Effective communications may lead to increased planning statements, structure and predictability.		

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Design solutions to prevent or mitigate negative effects on performance	Workspace designed to support communication (including intention recognition) through sharing of resources and information Radio, Data-link to enable communication, information requests and/or discussions or clarifications (e.g. if expected ones are delayed, if content is insufficient or inaccurate)
Interactions with other Factors	**Teamwork, Mental Workload, Situation Awareness, and Trust.**

TRUST

Definition(s)

Trust is a multidimensional construct (Costa et al., 2001). One taxonomy of trust (Kiffin-Peterson & Cordery, 2003) used in literature discriminates between:

- **dispositional trust** refers to an individual's propensity to trust, based on both predispositions to trust, and subsequent environmental influences;
- **situational trust** is context specific, arising from the perception of an individual's (or machines) trustworthiness.

A second distinction (Mishra, 1996; Muir & Moray, 1996) is made between:

- **interpersonal** (cognitive and affective) trust the willingness to be vulnerable to another party based on the belief that the latter party is competent, open, concerned and reliable;
- **trust in technology** is described as an intervening variable that mediates between the system and an operator's interaction strategy with the system.

Edwards (2013) reports that ATCOs consider trust as important in their work in terms of their relations with colleagues, pilots and management; as well as with regard to their attitude towards technology (Bonini, 2001).

To decide whether to trust an individual or system, and the appropriateness of that decision in the given context, influences the resulting influence on performance. Research is limited regarding the association between trust and performance (Costa et al., 2001).

Task-related measures

Technique(s)	Observable(s)	P6 use
Questionnaire studies	Evaluation of belief and mistrust in interpersonal trust: colleagues who appeared confident were more likely to be trusted. Perception of competence influenced the development of trust. Overall, competence and personality were the variables that were considered influence most whether they trusted fellow controllers or not. Trust in technology influences performance through miscalibration. When an unfamiliar technology is used, calibration between operators and system is needed, and this includes the operator evaluation on when is appropriate to trust the technology and when is not. Inappropriate trust (mistrust or over-trust) in colleagues may result in a lack of checking behaviour or insufficient teamwork.	N/A
Direct naturalistic observation (especially in ATC domain)		N/A
Analysis of incident reports		N/A
False alarm and reaction times	High number of false alarms increases pilot reaction time and reduce its trust in automation, resulting in a preference for lower levels of automation.	N/A

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Expected effects on performance	Interpersonal trust may lead to a reduction in human error. Miscalibration between operator and technology can result in mistrust or over-trust (leading to complacency), each with specific implications for performance: • Inappropriate mistrust may result in an inappropriate lack of technology use, potentially resulting in reduced efficiency or even a reduction in safe performance. • Over-trust of technology can result in complacency or overreliance on the technology which has been shown to be negatively related to vigilance and monitoring behaviour. Over-trust had influenced the control strategy selected by the operator, which minimised monitoring. Data from incident reports also suggest an association between over-trust and overreliance in technology and performance decline or performance-related incidents. Inappropriate trust (mistrust or over-trust) in colleagues may result in a lack of checking behaviour or insufficient teamwork. This reduction of monitoring may then result in performance decline. Similarly, inappropriate mistrust in systems may result in a lack of facilitation of performance, whereas over-trust in technologies may result in a reduction in monitoring, leading to a vigilance decline. When false alarm rate increases, pilot trust in automated devices decreases resulting in the pilot preferring a lower level of automation. Analysis of the pilot mean reaction time in response to devices sensor alert show increased reaction time with increased false alarm rate. The pilot expresses less trust in automation system.
Design solutions to prevent or mitigate negative effects on performance	Participative design to facilitate the new system/tool acceptance through an understanding of its rationale, objectives and functioning Documentation –either paper-based, or embedded in the interface to support the description / understanding of the system state and usage (e.g. what the automation (or any support system) is doing, why it is doing so and what it will do next) System design including recovery means evoked on Kontogiannis et al. such as: • observability of undesired system states (e.g. warning, colour code reflecting unexpected state on the HMI), • traceability of actions and effects to revise understanding • reversibility of error to help timely correction (e.g. cancel/undo function) •
Interactions with other Factors	Robust positive correlation between interpersonal trust and **Team Working**. **Stress and Mental Workload.**

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