USER-CENTERED DESIGN AND A SINGLE EUROPEAN SKY

Liesbeth Boer, Aske Plaat, Jaap van den Herik

Leiden Centre of Data Science

Leiden University

Leiden, the Netherlands

ABSTRACT

Looking at airplanes, trains, and cars, it is well known that airplanes are the safest traffic vehicles. There are many reasons for this. A striking difference between airplanes on the one hand and trains and cars on the other hand is that airplanes use the automatic pilot system, whereas the other two traffic types are in their infancy with respect to an automatic driver. In airplanes an automatic driver is nowadays nothing special.

To allow for a continued growth and flight safety at a European level the Single European Sky(SES) program is launched. The purpose is twofold: (1) to restructure the architecture of the European Air Traffic Management system (ATM) and (2) to change the legislation.

Currently, the question arises: can we model, develop, and simulate an adequate HCI architecture? Three essential features are: (1) human cognition, (2) human mental workload, and (3) situation awareness. The interesting variables are: complexity, location, and feedback. The challenge of our research occurs in high *complexity,* different *locations, and* poor *feedback. A deep analysis of the relations and dependencies in extreme situations may lead to further insight into the best HCI architecture.*

This paper focuses on the modernization of the European Air Traffic Management system. Specifically, we discuss the impact on human mental workload and situation awareness. The air traffic management modernization is known as the Single European Sky ATM Research (SESAR) program. SESAR will bring technical and operational changes that are far-reaching. The changes will fundamentally affect the flight crew's responsibilities and will also impact their performance, and may thus impact flight safety. Mental workload and situation awareness are of central importance to decision-making and performance in complex, dynamic systems, and thus to flight safety. To cope with the technical and operational changes, the flight crew needs new cockpit display systems and new decision support tools. To obtain insights into the intricacies of these systems and tools, we review (1) the proposed ATM changes, (2) the models of decision-making, and (3) the impact of the proposed ATM changes to cockpit decision making. Finally, we will provide recommendations for the design of cockpit systems in order to improve air safety.

1. Introduction

Flight safety has the highest priority in civil aviation. In this paper, we focus on situation awareness and mental workload, two factors that have been shown to be of great importance to flight safety (Harris, 2011). We will embed our discussion in the ongoing changes in Europe's Air Traffic Management (ATM) system. This system has a fragmented structure. It implies that there does not exist a single ATM framework whereby air navigation is managed at a European level. Clearly, the capacity of the European ATM system is challenged by this fragmentation. Together with the endogenous growth of the aviation sector, flying in Europe will soon reach its limits, resulting in more delays, and thus increased costs for the airlines. The purpose of the Single European Sky (SES) program is to restructure the architecture of the European ATM and to change the legislation to allow for a continued growth and flight safety at a European level.

The key objectives of SES are:

- to restructure European airspace as a function of air traffic flow;
- to create additional capacity;
- to increase the overall efficiency of the air traffic management system.

To fulfill these objectives, in 2012 the European Commission has set four high-level goals for the SES to be met by 2020. They are formulated as follows.

- A three-fold increase in capacity, which will reduce delays.
- Improve safety by a factor of 10.
- Environmental impact by minus 10 percent per flight.
- Provide ATM services to the airspace user at a price of less than 50 % of the current costs.

To develop the needed technological capacity, the Single European Sky ATM Research (SESAR) programme was launched in 2004. SESAR is the technical dimension of the Single European Sky (SES).

2. SESAR

SESAR is a complex programme (SESAR, 2014). It is related to the NextGen project by the American Federal Aviation Administration (FAA) (2014). American and European authorities have reached an agreement on interoperability between their future ATM systems. SESAR's technical and operational solutions cannot be realised in one "big bang." Therefore SESAR distinguishes six Priority Strategic Business Needs, representing the business needs of the entire ATM. These business needs are as follows.

1. *Traffic synchronization*: it (1) refers to the tactical organization of air traffic in real-time and (2) covers all aspects related to improving arrival/departure management owing to a better traffic sequencing, resulting in an optimization of climbing and descending traffic profiles.

2. *Airport integration and throughput*: it ensures the full integration of airports within the ATM environment and will ensure an increase of runway throughput and improved surface movement.

3. *Moving from airspace to 4D trajectory management*: it creates an environment where air and ground participants share a common view of the aircraft's trajectory. This provides a systematic sharing of air traffic trajectories between several participants in the ATM process, which enables a dynamic adjustment of airspace characteristics to meet the predicted demand.

4. *Network collaborative management of the ATM network*: the purpose is to achieve an efficient network of operations based on collaboration and information sharing. It relies on short-, medium-, and long-term planning which enables a precise update of the Network Operational Plan (NOP).

5. *Conflict management and automation*: the purpose is to limit the risk of collision through the management of aircraft trajectories. To achieve this business need, enhanced algorithms for a short-term conflict alert will ensure earlier warning and lower false alert rates.

6. *System Wide Information Management (SWIM)*: this business need is facilitated by greater sharing of ATM system information, to give the right information at the right time to the right person to make the right decisions. SWIM will be the intranet of the air traffic managements and allow flight crews to obtain near real-time information about aeronautical items, airport, flight, meteorology, surveillance, flow, and capacity. This will enable flight crews to make better decisions, especially in unforeseen events.

To address these business needs of SESAR, new technical and operational solutions will be implemented. Through these solutions the flight crew will obtain (1) satellite-based navigation and surveillance, (2) digital route information, and (3) weather forecasts in an integrated solution. The integration allows the three items to be embedded into decisions, resulting in a safe flight with lower visibility conditions.

3. Operational vision of SESAR

To illustrate the consequences of these changes, we will now discuss the operational vision of SESAR, with emphasis on human mental workload and situation awareness. We do so in seven paragraphs below; they follow the full range of planning a flight to the arrival of the aircraft.

Under SESAR, an operator will plan a flight and the outcome will be an electronic representation of the intended flight plan. If necessary this electronic flight plan can be updated when conditions change. Through a shared communication network the operators and air traffic managers will have the same information. The flight crew will receive the final flight plan before start-up and data communications will provide the flight crew with pre-departure clearance with adjustments to the flight plan.

When the aircraft is taxiing out from the gate the flight crew's situation awareness will be improved by a flight deck display that represents aircraft progress on a moving map of the airport surface. This new flight deck display is important for preventing surface conflicts, especially on busy airports and in low visibility conditions.

SESAR will have multiple departure paths from each runway, improving departure performance. Improved Area Navigation (RNAV) and Required Navigation Performance (RNP) procedures will provide greater navigation accuracy. Multiple departure paths will enable controllers to place each aircraft on its own separate track, improving capacity, while avoiding known constraints, such as noise abatement procedures, thunderstorms and other severe weather conditions near the airport.

In order to reduce radio-frequency congestion and the possibility of misunderstandings, the flight crew will receive both routine and strategic information via data communication. As the aircraft climbs out into the en-route airspace, SESAR will offer improved aircraft position information to enable flight in reduced separation standards. With SESAR, flight crews can monitor positions of other aircrafts on their display, allowing air traffic control to transfer some spacing responsibility to the flight crew. The flight crew will be recommended to change trajectory or speed if weather, traffic conflicts, military airspace restrictions, or other constraints along the aircraft planned flight path will be identified.

SESAR traffic management tools will analyze flights hundreds of miles away from the airport to calculate scheduled arrival times, which will improve the flow of arrival traffic to the maximum.

The flight crew will receive information on projected arrival time, sequencing, route and runway assignments so that a final flight path can be determined. Appropriately equipped aircraft will fly defined vertical and horizontal paths (optimized profile descent), from cruising altitude down to the planned runway.

Before the flight lands, the flight crew receives via data communications the assigned runway, preferred taxiway and taxi path to the assigned gate. Both the flight crew and air traffic controller will monitor traffic movements on their display and will be alerted by traffic conflicts.

4. Changes for the flight crew

SESAR will bring many changes to the way we fly in Europe. It will fundamentally affect flight crew operations. Below we provide four examples of changes that are currently under study. Decision-making routines will change, which may have consequences to flight safety. Then, the requirements for human performances will change. This implies that SESAR will both add new and redefine existing responsibilities of pilots. Furthermore, the air traffic controllers will see their role shifting towards a more strategic role by supervising the traffic flows. In addition to their operational role, flight crews will have a more tactical role, since they have to make sure that they comply with the agreed 4D trajectory, since they have to analyze different options and scenarios by unpredicted events.

According to Salas et al. (2010) the system will ultimately increase pilot involvement in flight path management and traffic separation. Although this change may open up the skies to a wider variety of flight paths, at the same time it will place a higher burden concerning traffic separation on the pilots.

Consequently, there will be a need for new displays, tools, and automation systems to support the flight crew with the new separation and navigation tasks. Under these new and different operational conditions the flight crew needs to maintain situation awareness while adjusting to changes in workload and flight time. These changes to cockpit systems and routine will affect mental workload and situation awareness.

4.1 Mental workload

Mental workload is also related to the quality of flight crew decision-making. Mental workload depends on the information load in working memory, a characteristic that it shares with situation awareness. According to Harris (2011) there is no accepted definition of mental workload, but in general it is seen as the "cost", in information processing terms, of performing a given flight task. Mental workload is related to Human Information Processing theory and specifically to the finite capacity of cognitive resources. Theories of dual-task performance attempt to explain the information processing limitations that ultimately define a flight crew's workload limits in terms of the number or nature of the task that can (or cannot) be performed within a unit of time.

Both high and low mental workload may impact flight safety. A low mental workload may reduce vigilance, and provide a significant challenge for maintaining situation awareness. In situations where people are subjected to a long period without inputs, reaction time, and accuracy in detecting can decline the alertness significantly. Both high mental workload and low mental workload can influence flight crew performance and decision-making in a negative way.

If automation is employed to reduce high mental workload, the flight crew's attention can be less actively engaged with the task and so, memory for actions conducted by the automation may start to be degraded. On the other hand automation modifications to improve situation awareness might inflict unacceptable levels of high mental workload.

4.2 Situation awareness

The flight crew has to be aware about what is happening around them (other airplanes, weather and terrain changes) and to understand what this information means now and in the future. Situation Awareness is normally related to the goals and objectives of a specific job or function. We adopt a classic definition of Situation Awareness (SA) by Endsley (1988): "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future." There are three separate levels of situation awareness.

- Level 1 SA – **perception** of the elements in the environment. The flight crew perceives the status, dynamics, and attributes of relevant elements through visual inputs, auditory inputs, or an combination of them. This level is based on the perception of data from a single display or from individual display elements on the flight deck.
- Level 2 SA – **comprehension** of the current situation based on level 1 SA elements. The flight crew needs to comprehend what is perceived. This level requires data to be combined in such a way as to provide a bigger picture of the situation. The flight crew needs to have a good knowledge base or mental model to develop an understanding from the many pieces of data perceived.
- Level 3 SA – **projection** of future status. The flight crew fully understands their current situation and uses that information to project ahead to predict what is likely to happen in the near future. The flight crew can only achieve level 3 SA by having a sufficient understanding of the situation (level 2 SA) and a sufficient knowledge of the system they use.

According Endsley et al. (2012) situation awareness is the engine that drives the train for decision-making and performance in complex, dynamic systems. They mention the following three characteristics explicitly.

- Situation awareness is goal-oriented.
- Supporting situation awareness directly supports the cognitive processes of the operator.
- Keeping the user in control is fundamental to adequate situation awareness.

Thus, decision-making is dependent on situation awareness. Situation awareness is particularly important in work domains where (1) the information flow can be quite high and (2) poor decisions may lead to serious consequences.

5. Human Information Processing theory

Harris (2011) suggests that Human Information Processing theory (see Wickens, 2004) forms the basis of other key concepts, such as human mental workload and situation awareness. It also provides the foundation for many aspects of the design of the flight deck, particularly the information systems (displays and computer interfaces) and automation. Human response is broken down into three basic stages: (1) perceptual encoding, (2) central processing, and (3) responding. Figure 1 adequately describes the notions and concepts mentioned so far.

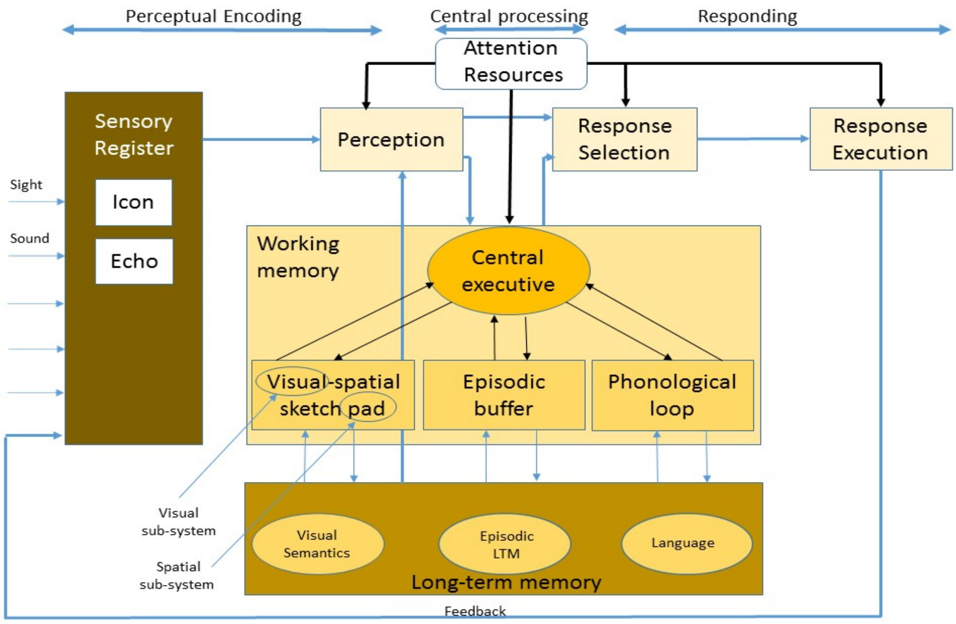

Figure 1: Wickens (2004) schematic model of human information processing

Perception will receive data from the sensory register. This is an active process, because it is linked to the long-term memory. In this process the flight crew begins to interpret and organize the sensory data to produce a meaningful experience of the world.

According to Wickens et al. (2004) much of our processing of perceptual information depends on the delicate interplay between top-down processing and bottom-up processing. Bottom-up processing is data driven: incoming data from the environment forms perception. Top-down processing is goal directed: perception is based on knowledge, desires, and context.

5.1 Two central bottlenecks

There are two central bottlenecks to how much information can be processed at the same time: (1) the amount of information (related to overflow) and (2) working memory (related to cognitive overload).

While some information can be more easily processed simultaneously (for instance, audio and visual information), it is difficult to process other types of information simultaneously. It depends on which part of the brain is needed for a proper processing. If information comes through the same modality (visual, auditory, etc.), it draws on the same resources (central processing), or requires the same response mechanism (speaking, writing). As a consequence, it is more difficult to attend to inputs, such as listening and reading, simultaneously (Wickens, 2002). Limits to how many information elements one can process at the same time forms the first central bottleneck for situation awareness.

After perception has taken place, the next destination for information is working memory. The working memory has three storage components: (1) the phonological loop which deals with verbal information, (2) the visual-spatial sketchpad which deals with non-verbal information, and (3) the episodic buffer holding a central role in the storage and retrieval of items in episodic long-term memory. Working memory has a limited capacity and a person must actively work to keep information there or it will decay. If it will decay we speak of a cognitive overload. Only a limited amount of unrelated information can be held and manipulated in working memory (7 plus or minus 2 “chunks”, Miller’s law). Working memory is very limited, and forms the second major bottleneck for situation awareness.

The long-term memory is our main resource. Here we store factual information, experiential knowledge, and procedural rules of behaviour. Long-term memory is unlimited, has relatively slow access, and forgetting occurs more slowly. There are two types of long-term memory: episodic memory and semantic memory. Episodic memory represent our memory of events and experience in serial form. Semantic memory has a structured record of facts, concepts, and skills that we have acquired. Limits to how many information elements one can keep in memory at the same time forms the second central bottleneck for situation awareness. If there is too much information to be kept in memory then we speak of cognitive overload.

5. 2 User-centered design

Endsley et al. (2000) state that situation awareness is the key to user-centered design. User-centered design challenges the designers to mold the interface around the capabilities and the needs of the operators. Rather than displaying information that is centered around the sensors and technologies that are produced, a user-centered design integrates information in ways that fit the goals, tasks, and needs of the users. Moreover, it keeps the user informed and in control. Currently, cockpit displays are in a transition phase, where older technology is still mostly sensor-oriented, the modern technology is based on intelligent data handling.

6. Conclusion

The modification of European Air Traffic Management will bring technical, operational, and responsibility changes for air traffic controllers and flight crew. These modifications will result in new cockpit displays, new decision support systems, and more data communication, which has to be integrated in the Flight Management Computer for future air navigation. The flight crew will have a more tactical role with increased cognitive activities and decision-making. The quality of decision-making is related to situation awareness and mental workload. Situation awareness is largely influenced by the limitations of information processing (bottleneck 1), and working memory (bottleneck 2). Mental workload is also influenced by the human working memory.

To maintain situation awareness and a manageable workload, it is important that the new displays, decision-support systems, and automation systems will be developed in a user-centered design, which supports information processing and decision-making in a dynamic environment. The design of such a user-centered architecture is the topic of future research.

Acknowledgements
The authors would like to thank NLR, the National Aerospace Laboratory of the Netherlands, in the persons of Harrie Bohnen, Jan-Joris Roessingh and Jelke van der Pal for their stimulating discussions. Moreover we are grateful to Bernard Gustin, CEO of Brussles Airlines for his support to the first author.

References
Endsley, R. M. (1988). *Design and evaluation for situation awareness enhancement*. In processing of the human factors society 32nd Annual Meeting (pp. 97-101). Santa Monica, CA: Human factors Society.
Endsley, R. M., Jones, D. G. (2012). *Designing for Situation Awareness. An approach to User-Centered Design*. Second edition. CRC Press Taylor & Francis Group.
Harris, D. (2011). *Human Performance on the flight deck*. Ashgate Publishing Limited, England.
Salas, E., Maurino, D. (2010). *Human factors in aviation*. London England: Elsevier Inc.
Wickens, C. D., Lee, J. D., Liu, Y., Gordon Beck, S. E. (2004). *An introduction to human factors engineering*. Second edition. Pearson Education, Inc., New Jersey.
Wickens, C. D. (2002). Multiple resources and performance prediction. Theor. Issues in Ergon. Sci., vol. 3. No. 2, 159-177. Taylor & Francis Group.
SESAR joint undertaking from innovation to solution (2014). Administrated between September and October 2014 from http://www.sesarju.eu/
Federal Aviation Administration (FAA) NextGen (2014). Administrated between September and October 2014 from http://www.faa.gov/nextgen/