HMIAC - SURVEY ON HUMAN-MACHINE INTERACTION IN AIRCRAFT COCKPITS

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Abstract

With the purpose to assess the effects of highly automatic flight control systems and the automation of the pilots' working environment in general, a questionnaire was developed at the DLR Institute of Flight Systems. In an anonymous on-line survey among professional airline pilots with more than 120 participants subjective opinions regarding the trend of ever-increasing flight deck automation were captured, addressing operational topics such as workload, situational awareness and trust as well as subjects regarding the preparation of working in highly automated environments such as suitability of checklists, procedures and flight training. The results considering the operational aspects of flight deck automation are presented in this paper.

1 Introduction

The introduction of automated systems in commercial transport aircraft resulted in a substantial increase of the air transport system safety level (figure 1). However, in recent times incidents such as flight LH44, touching the runway with the left wing at Hamburg on March 1 2008 [1], or the crash of AF447 enroute from Rio de Janeiro to Paris on June 1 2009 [2], indicate that there are open issues with respect to the interaction of pilots and highly automated flight control systems. This is further affirmed by statistics ana-

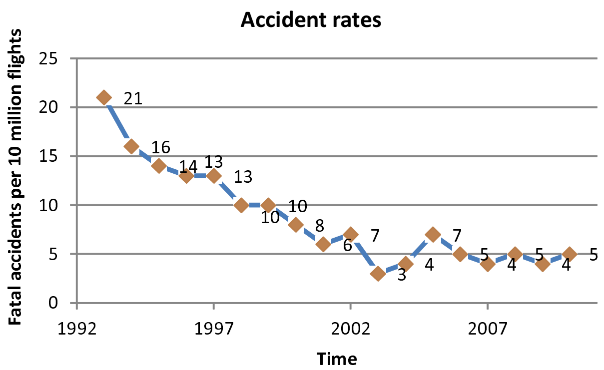

Fig. 1 : Evolution of accident rates 1993-2010, fatal accidents per 10 million flights [3]

lyzing the type of aircraft incidents or accidents. ICAO has established a common taxonomy [4] to categorize occurrences related to flight safety. According to this taxonomy, the current most relevant fatal accident category (figure 2) is LOC-I (Loss of control in flight), which translates to the fact that the main circumstance for fatal accidents involves the pilot handling the aircraft. Therefore the question arises if the interaction of pilots with their highly automated working environment is fully understood and implemented in a way that minimizes failures in the process of interaction. During the introduction of highly automated flight deck environments it has already been pointed out that automated assistance can have ambivalent effects [5, 6, 7]. This is mostly due to a mis-match of the human users' cognitive abilities and the design of automated sys-

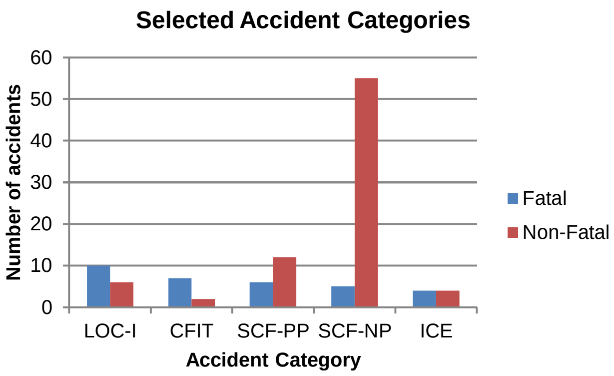

Fig. 2 : Number of accidents (2001-2010) with respect to different incident and accident categories[1] [3]

tems involving all aspects, not just the user interface, of these systems. The design of cockpit systems has been guided mostly by technical constraints [8] in the past with less consideration for the humans' specific capabilities. Understanding the human pilot and creating systems that best accommodate humans' cognitive strengths and support their weaknesses in the aircraft cockpit is therefore the desirable objective. In order to reach this goal, it has been indicated [9] that there is a need for field studies. That is why this work aims to provide a contribution to understanding the process of interaction between humans and highly automated aircraft systems by exploring experts' opinions and the experience of professional airline pilots regarding the current status quo of automation. This exploration is conducted as a survey among these pilots based on a questionnaire addressing a variety of different aspects regarding the interaction of pilots with their aircraft. The results of this study will be used to identify further areas of research in the domain of automation in aviation and to complement existing research activities by capturing operators' subjective opinions. As such, no recommendations for improving the design of automated flight control systems or the flight deck are given at this time.

[1]CFIT: Controlled Flight Into Terrain; SCF-PP: System / Component Failure, related to PowerPlant; SCF-NP: System / Component Failure, Non-Powerplant; ICE: Icing

2 Methodology

The basis of the survey forms a questionnaire with 122 individual questions. It is grouped into a biographical data section plus seven distinctive sections covering the following aspects:

- Automation in general
- Trust
- Situational Awareness
- Mental Workload
- Checklists, Manuals and Procedures
- (Interface) Design
- Training

Pilots were asked to provide their opinions as answers to either closed-ended questions (for ratings or assessments of a specific topic), or to open-ended questions in the form of textual feedback for comments and suggestions. Three different types of closed-ended questions were used: Single choice questions where only one answer could be selected, multiple choice questions where multiple answers were allowed, and ranking questions where participants were asked to decide where they fit along a scale continuum. In case of the ranking questions, a six point ordinal (Lickert) scale was used with varying answering possibilities (see table 1 for example scales).

Scale	Frequency	Agreement	Difference
6	always	strongly agree	very much
5	very often	agree	a good deal
4	often	somewhat agree	somewhat
3	sometimes	somewhat disagree	little
2	hardly ever	disagree	very little
1	never	strongly disagree	not at all

Table 1: Ordinal scale for closed-ended questions

To cover the fact that different approaches to automation in modern transport aircraft exist [10], which might result in ambiguous responses, pilots were asked to provide in the biographical section the aircraft type that they operate primarily. Depending on this answer, either one of two adapted questionnaires were presented to them. These questionnaires were customized to reflect the specific characteristics of the flight deck (such as the presence of side-sticks vs. control columns or the different usage of autoflight modes) in airplanes manufactured either by Boeing or Airbus.

2.1 Provision of Questionnaire

The questionnaire was implemented using the survey software *LimeSurvey* [11], which provides the possibility to publish questionnaires as a World-Wide-Web application. By this approach it was possible to fulfill the two conflicting, essential requirements of this survey: *credible anonymity* and *restricted access* exclusively for professional airline pilots. Due to the fact that this survey might address informations related to flight safety, company policy or product liability it has to be guaranteed and credibly communicated to the participants that their identity is never revealed. On the other hand it is mandatory that access to the questionnaire is granted exclusively for professional airline pilots to ensure relevance and applicability of responses. Ensuring restricted access by giving user accounts to pilots conflicts with the first requirement of credible anonymity. To overcome this, the questionnaire was published using a hidden uniform resource locator (URL), which could not be indexed by Internet search engines. This address was distributed to pilots by participating airlines and through the German pilot union *Vereinigung Cockpit* [12].

2.2 Statistical Analysis

For validation of the questionnaire and the resulting responses different statistical analyses were performed. The reliability of the different scales was tested with Cronbach's alpha, a coefficient that describes the inter-rater-reliability or internal consistency of a questionnaire. In this case the measure of 0.880 indicates a reliable construct as the total is above 0.6.

For evaluation of the responses mainly frequencies of answers and their distribution were analyzed. Due to the fundamental differences in the automation concept of the two main manufacturers of large transport aircraft, Boeing and Airbus, the responses were evaluated to check for significant differences in the distribution of answers with respect to the pilot's primarily operated aircraft type. The tests performed to check the statistically significant dependence of answers on the primarily operated aircraft type were the *Chi-Square test* for nominal data and the *Mann-Whitney U test* in case of ordinal data.

3 Results

The questionnaire HMIAC was accessible for airline pilots from August 26 2010 to November 30 2010. During this time frame, 125 data sets have been collected from which 76 were fully completed. Out of the 76 completed data sets two of the participants were not taken into consideration because the content of some answers indicated non-proficiency. The total time required to complete the questionnaire was between 45 and 60 minutes.

3.1 Participants

The sample mainly consists of male participants (93.2%) and only some female cooperators (6.8%) and almost all are from Germany (91.9%). The ages have been grouped into eight categories and the average age of the experts sampled was 36.5 years (figure 3). The majority of

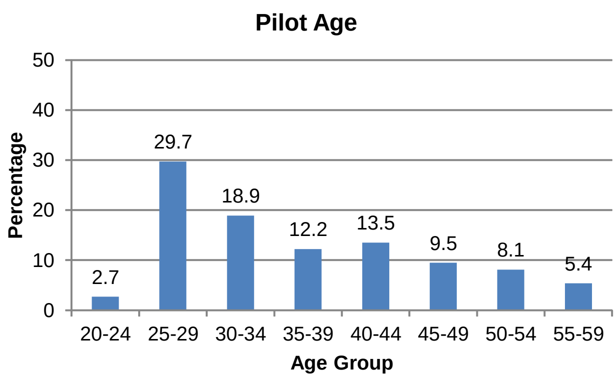

Fig. 3 : Age distribution of participants

the sample (67.6%) received their ATPL / CPL from airline training as opposed to 24.3% of the participants who went through a self-sponsored full time course. The actual status and functions of participants are ranked from captain (36.5% [21.6% short distance; 14.9% long distance]) and first officer (51.4% [39.2% short distance; 12.2% long distance]) to multifunctional occupations (11.7%). The total amount of flight experience (including aircraft and simulator) varies from 2,500 hours to more than 20,000 flight hours with most of the pilots stating that they have between 5,000 and 10,000 hours of experience (figure 4), with an average experience for all participants of 7,687 hours. The primarily operated aircraft types are either manufactured by Boeing (35 responses or 47.3%) or Airbus (32 responses or 43.2%) so the focus of the analysis is on these two manufacturers. All Airbus and Boeing pilots stated that the flight deck of their primarily operated aircraft type is highly automated.

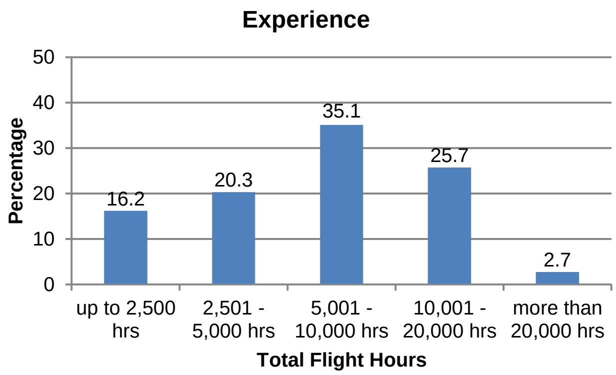

Fig. 4 : Experience of participants

3.2 Automation in General

The results from the questionnaire regarding automation in general including the advantages and disadvantages coincide with established findings [13, 14], but also reveal new details. Figure 5 depicts the relevant results in relation to the total amount of responses, figure 6 details the results with respect to the number of responses for each specific aircraft manufacturer. None of the participants rated the trend towards increasing automation as wholly positive, but more than 80.0% con-

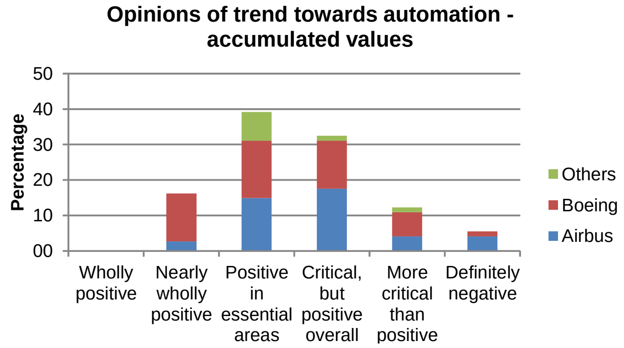

Fig. 5 : General opinion towards automation considering total number of responses

sidered it at least positive overall (figure 5). Figure 6 depicts that Airbus pilots seem to be more critical towards automation than Boeing pilots, but the Mann-Whitney U test does not show a statistically significant difference in distribution of answers.

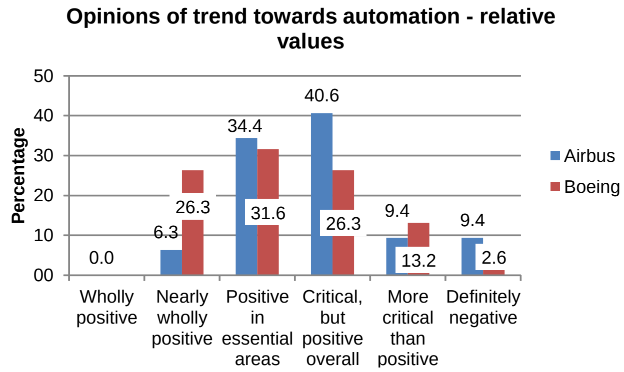

Fig. 6 : General opinion towards automation with respect to primarily operated aircraft type

A major motivation for introducing automation in general and, more specifically, envelope protection functions in modern flight control systems was to reduce the risk for the airplane to leave its safe flight envelope by improper operation of the flight controls. For this reason, it is expected that modern flight control systems are more resilient to pilot error, which was further investigated in this survey. This assumption was reinforced by 90.7% (Airbus-operating pilots) and 88.6% (Boeing-operating pilots) of the participants, agreeing that advanced cockpit systems help remove current or past sources of errors (figure 7), but at the same time 96.9% and 85.7%, respectively, also indicated that cockpit systems create new error opportunities. Further analyses of the questionnaire show that pilots rank the improper operation of flight controls as the main reason for newly introduced error opportunities, followed by technical defects and software problems.

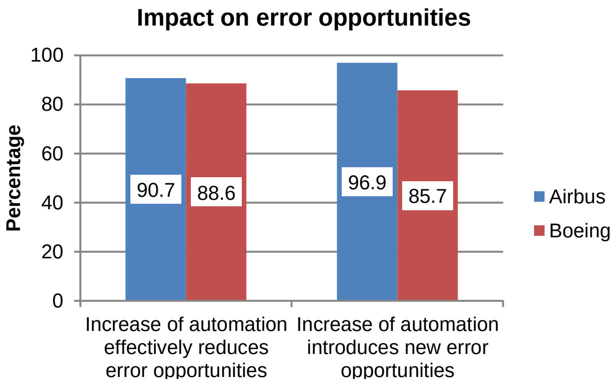

Fig. 7 : Impact of highly automated systems on error sources

As the introduction of flight deck automation seems to have increased safety levels and generated economical benefits, pilots were asked to give their estimation whether the introduction of additional automated functions besides the existing ones has the potential to improve the handling of the aircraft (figures 8 and 9). This assessment has been broken up into the most relevant flight phases from ground operations before take-off to taxi-in after touchdown.

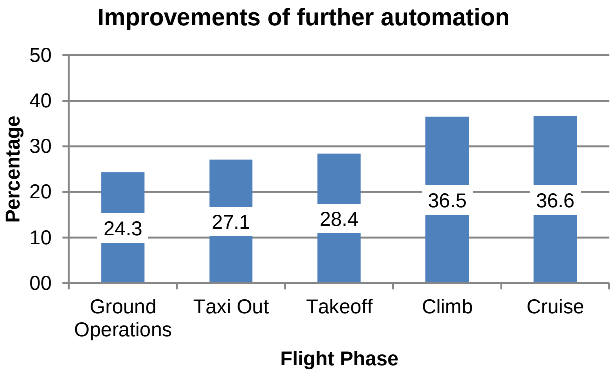

Fig. 8 : Pilots' opinions on the possibility of improved aircraft handling by introduction of additional automated functions with respect to flight phase - Ground Operations to Cruise Flight

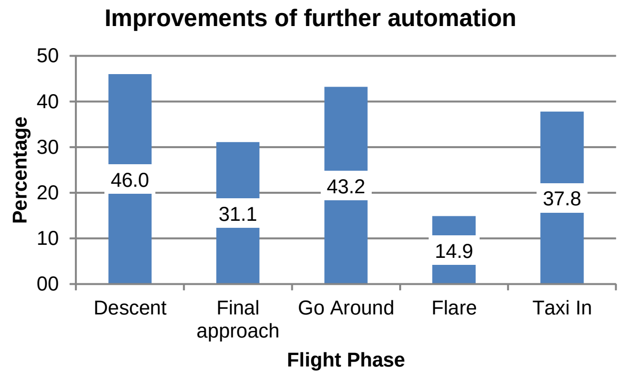

Fig. 9 : Pilots' opinions on the possibility of improved aircraft handling by introduction of additional automated functions with respect to flight phase - Descent to Taxi

The results regarding the introduction of further automation show that the added benefit of further automation is generally assumed to be low, except during descent and go-around, which nearly 50.0% of the pilots agreed on. However it stays unclear which aspects, namely the decision making process or the actual execution of the relevant tasks would benefit most from additional automation, which should be analyzed as part of further research.

3.3 Trust

Trust is a psychological mode of feeling confident about a reliable and dependable (system) behavior. Trust, next to situational awareness and mental workload, therefore is also a factor that influences understanding as well as predictions of aircraft performance, which again affects the interaction of humans with aircraft systems. For this reason, trust is a desirable factor specifically in the interaction of pilots with their aircraft because it motivates positive outcomes.

According to the replies of the 74 pilots under consideration, 70.2% feel more comfortable in highly automated cockpits than in traditional ones. This goes along with more than 90.0% of both Airbus and Boeing pilots who place confidence in automation themselve (figure 10). About the same number of respondents considers the general opinion about trust in automation

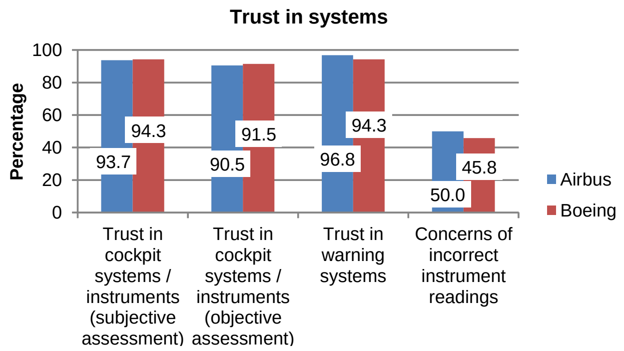

Fig. 10 : Trust in reliability of flight deck systems

as overwhelmingly positive. These findings are supported by the majority who trust in the reliability of warning systems or do not worry about incorrect information from instrument readings. These results seem to be slightly contradictory to the fact that most pilots (figure 11) already experienced incorrect sensor readings (53.1% of Airbus pilots, 80.0% of Boeing pilots) or inadequate activation of warning systems (65.6% of Airbus pilots, 60.0% of Boeing pilots).

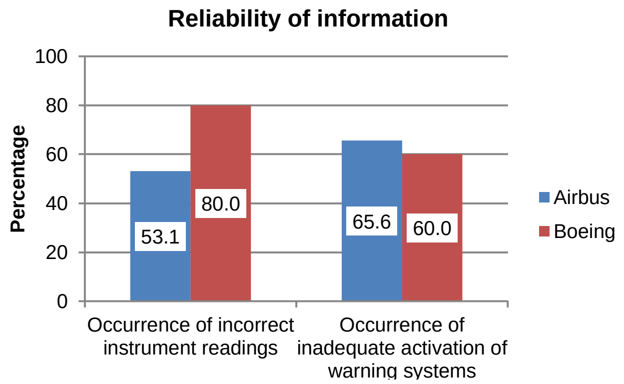

Fig. 11 : Reliability of information provided by cockpit systems

This amount of trust in automated cockpit systems is reduced when it comes to unexpected, unknown or critical situations (figure 12). Under such circumstances, nearly 90.0% of the pilots indicated that they mostly trust their own assessment, while only close to 70.0% rely on the information provided by cockpit systems. Rather surprising is the fact that they put about the same level of trust in their peers' judgement of the situation.

Using the Mann-Whitney U test in order to

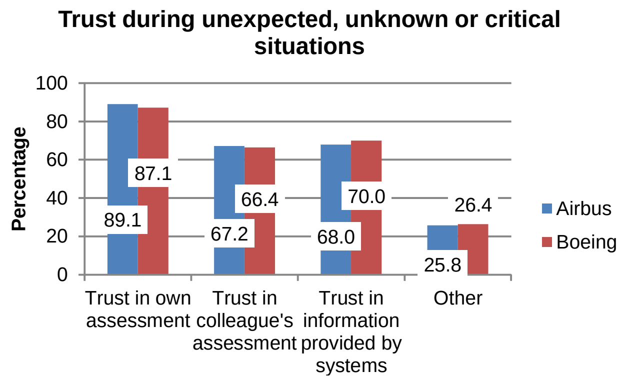

Fig. 12 : Trust during critical situations

analyze whether there is a significant difference between the distributions of responses concerning the aspect of trust in aircraft systems from Airbus or Boeing pilots shows that the patterns of answers do not differ significantly. The only exception from this result is the question to which extent pilots have been confronted with incorrect sensor readings, which seems to be more likely for airplanes manufactured by Boeing than by Airbus.

3.4 Cognitive Aspects

Results from accident reports referring to questions of automation indicate that the human's specific (cognitive) abilities are a crucial factor in the process of interaction between the pilot and the aircraft. As automated systems in the cockpit execute continuous activities the pilot has to impose categorical structures on a dynamic environment over time. Although such event categories normally follow a typical structure, the possibility of surprising events exists at any time. The brain generally tries to be prepared for such situations and constantly generates expectations about the world it encounters and biases choice points by means of predictions and beliefs. So it is of interest to which extent situational awareness is affected in modern, highly automated cockpits environments.

3.4.1 Situational Awareness

Covering each and every aspect of situational awareness in the context of flight deck automation would go far beyond the scope of this paper, an extensive treatment of this topic has been presented by Endsley [15], whose definitions have been used as a basis for the present survey.

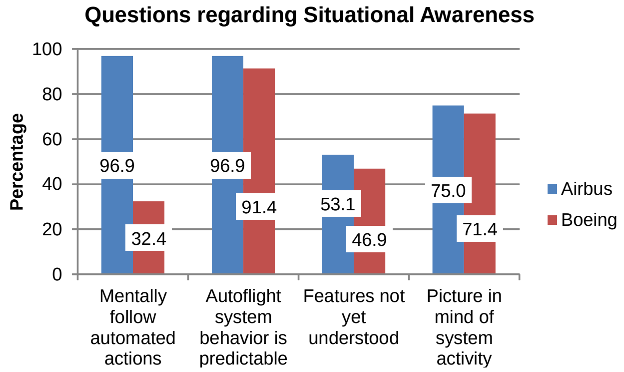

Fig. 13 : Aspects of situational awareness in highly automated cockpit environments

An important aspect of maintaining situational awareness is to be mentally involved in the control loop. According to the responses from the questionnaire 96.9% of the 32 pilots that primarily operate Airbus-built aircraft mentally follow automated actions, which is substantially different from the amount of 32.4% of the 35 pilots operating Boeing-type aircraft (figure 13). Despite this disparity both groups of pilots agree that the behavior of automated flight systems is often or always predictable. The complexity of current avionic systems is reflected by the fact that more than half (53.1%) of Airbus-operating pilots stated that features exist which are not yet understood, while a little less (46.9%) of their colleagues operating Boeing-type aircraft agreed on this. The Mann-Whitney U test for the corresponding set of responses reveals that this difference in the distributions of answers between both groups of pilots is statistically significant. On the other hand pilots seem to have a good understanding of the automated systems' structure and mode of operation because 75.0% of Airbus and 71.4% of Boeing pilots claim to have a picture about the systems' activities in mind.

The main difference between Airbus and Boeing pilots is the amount of pilots who mentally simulate or anticipate automated actions, which Airbus pilots seem to do more often than Boeing crew. One reason could be Airbus' more complex automation that differs from Boeing aircraft and consequently may require greater effort to understand. This is further confirmed by the amount of Airbus pilots who confess that there are automated features in their cockpit they do not understand yet.

3.4.2 Mental Workload

Mental workload can be understood as the mental stress and strain created by being busy in the cockpit and heavily depends on the context of the situation or task as well as on the environment. As such, the degree of automation of the working environment heavily influences the pilots' mental workload. According to the participating pilots (75.0% of Airbus pilots, 59.9% of Boeing pilots), the introduction of automation enables them to better manage their mental workload (figure 14). Although this seems to vary between both groups of pilots, the Mann-Whitney U test does not confirm a statistically significant difference in the distribution of answers. Contrary to that, pilots also state that especially during non-standard situations, current approaches to flight deck automation can actually increase mental workload in comparison to cockpit environments with a lesser degree of automation. 50.9% of Airbus-operating pilots and 68.6% of Boeing-operating pilots agree on this view.

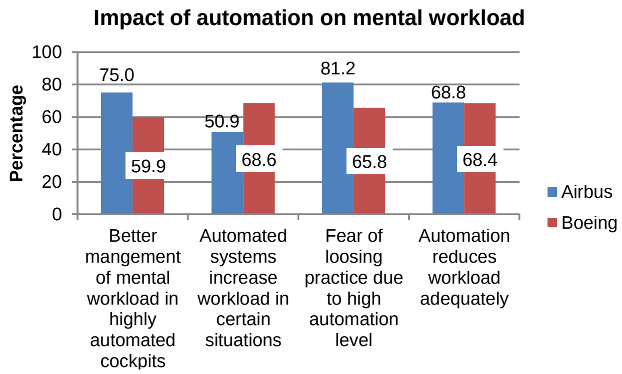

Fig. 14 : Influence of automation on mental workload

The amount of workload also influences to some extent a person's level of training and routine in the long term, which translates to the fact that the increase in automation may result in a decrease of a person's proficiency level. This is confirmed by the majority of the questioned pilots (82.2% for Airbus, 65.8% for Boeing), who fear that their basic flying skills are deteriorating due to increasing automation levels. Nevertheless, pilots seem to embrace the amount of workload that gets reduced by the introduction of highly automated flight decks, which close to 70.0% of the total population of pilots affirm. This is further confirmed by a majority of the same amount who states that they prefer working in highly automated cockpits over performing their duties in traditional ones.

3.5 Flight Deck Human-Machine Interfacing

Related to the concept of mental workload it is of interest whether changes in ergonomics so far helped to lower the mental workload and therefore improve human capabilities or whether cockpit and systems improvements were counterproductive. Besides the influence of the flight deck human-machine interface design on the crew's mental workload, its influence on the pilots' situational awareness is of equal importance. The amount and presentation of information can substantially alter the awareness of the system state and the overall situation, so the quantity of information should match the human's information processing capabilities.

The most obvious change from traditional cockpit environments to highly automated designs is probably the introduction of the Electronic Flight Instrument System (EFIS) or "glass cockpit" which resulted in the transition from mechanical dials and gauges to computerized displays. This development went along with a consolidation of information and its presentation which affects the crew's perception and processing of information.

The *Primary Flight Display* (PFD) is the pilot's main interface for gathering operational information such as attitude, altitude and speed. It forms an integral part of the human-machine control loop which requires a high degree of quality of the data and information presented.

The *Navigation Display* (ND) is the key instrument for providing a strategic overview of the flight as it displays informations regarding the aircraft position, flight plan, heading, track, wind and the weather situation in general. Therefore both instruments play a vital role for the crew in maintaining situational awareness. Close to all pilots rated the design of both displays as highly adequate for communicating the essential informations (figure 15). This assessment is equally valid for aircraft manufactured by Boeing as well as Airbus.

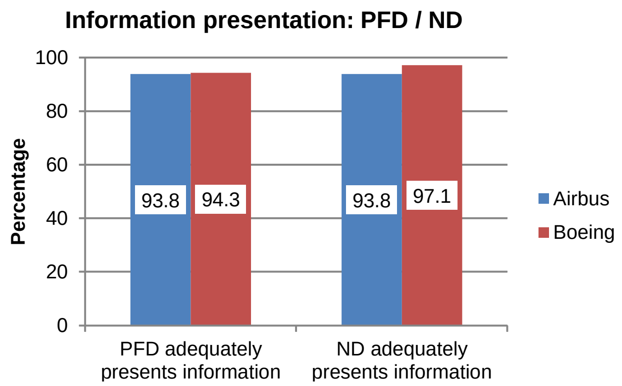

Fig. 15 : Pilot opinions on information presented by the Primary Flight (PFD) and Navigation Display (ND)

The picture looks different when it comes to the diagnostic interfaces. The Engine-Indicating and Crew-Alerting System (EICAS) as it is used in Boeing aircraft and the Electronic Centralised Aircraft Monitor (ECAM) found in Airbus aircraft, though slightly different in their basic concept, serve the main purpose of supporting the crew in diagnosing the state of the aircraft systems. Not being used as frequently as the PFD or ND under nominal conditions, both play a vital role in abnormal or emergency situations. The main issue that pilots of both Airbus and Boeing aircraft uniformly rise is that the informations on both types of displays are hardly well arranged (figure 16). In the case of the EICAS this is further confirmed by the fact that only 42.9% of the pilots agree that the information is clearly presented. In contrast, pilots primarily operating Airbus-manufactured airplanes approve (84.4%)

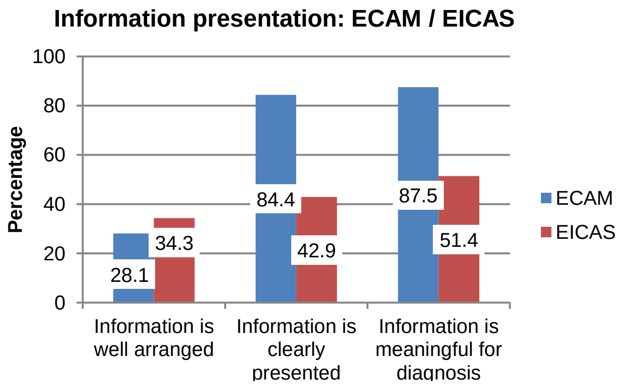

Fig. 16 : Pilot opinions on information provisioned by ECAM and EICAS

that the aspect of unclear information presentation is not an issue on the ECAM. This distribution is maintained when being asked if the presented information is meaningful for diagnosis, which 87.5% of the Airbus pilots acknowledge. Pilots using the EICAS consent to this statement only in roughly half of all cases (51.4%).

Pilots affirmed a tendency in this survey that in modern cockpit environments rather too much information is simultaneously provided, which has been especially confirmed by the evaluation of free-text comments. However, when being specifically asked for information and data that might be missing during selected flight phases, the responses slightly differ from this general assumption. During flight phases of generally low workload (initial climb, climb and cruise), just under one-third of the pilots unanimously indicated the need for additional information (figure 17).

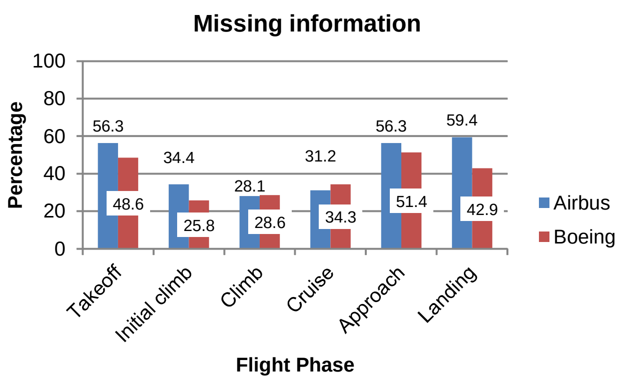

Fig. 17 : Missing information on current flight decks with respect to flight phase

In more demanding situations (takeoff, approach and landing), over half of the pilots operating Airbus-built airplanes expressed the desire for additional information. This need is acknowledged by approximately or just under 50.0% of the Boeing pilots. In the related free-text comments pilots consistently named an indication of the angle-of-attack and the vertical flight path profile as essential informations which should be added to the flight deck.

4 Summary

In an anonymous survey subjective opinions of flight crews concerning the status quo of automation in modern transport aircraft have been captured and evaluated. The underlying questionnaire, addressing issues of automation in general, trust, situational awareness, mental workload, checklists, manuals, procedures, (interface) design and training, consisted of more than 120 individual questions and was distributed on-line to the participating airlines and individual flight crews. An overview of the results from 74 valid data sets has been presented in this paper, focusing on operational aspects.

The participating pilots generally assess the current situation in highly automated decks positively, the transition to automated cockpit environments is fully accepted, and flight crews put a substantial amount of trust in automated systems. Judging from their experience, the introduction of highly automated systems has resulted in a reduction of workload, specifically under nominal operating conditions. In abnormal or emergency situations, greater concerns regarding automatized functions exist. Doubts are also prevailing about the effects of increasing automation on the practical capabilities. According to the majority of the participants, some components of modern flight deck environments should be overhauled to improve the interaction with the flight crew. This holds especially true for the diagnostic interfaces ECAM and EICAS, whereas the main interfaces for the basic operation of the aircraft, the primary flight and navigation displays, are considered highly adequate by close to all participating pilots.

The investigation on the current state of automation in aviation with the help of a survey among professional pilots has been shown to be a viable tool in supporting the research activities of the Institute of Flight Systems, as it complements existing research approaches such as the analysis of accident reports, simulator studies and flight tests with the perspective of the actual aircraft end-users, the pilots. Providing a credibly anonymous platform has shown to be a valuable tool for gathering information from the operational domain. This modality has been so well accepted that a substantial understanding of the current issues of interaction in aircraft cockpits could be established. An additional experience was that the inclusion of free-text fields for further comments substantially improved the responses' level of detail, providing an added benefit over a questionnaire in exclusively close-ended form.

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