PILOT'S ATTENTION ALLOCATION DURING APPROACH AND LANDING
EYE- AND HEAD-TRACKING RESEARCH IN AN A330 FULL FLIGHT SIMULATOR

G. Anders
Institute for Aeronautics and Astronautics
Technische Universität Berlin, Germany

ABSTRACT

Flight trials with airline pilots were conducted using an A330 Full Flight Simulator (FFS) which is located at the Technische Universität Berlin. Under realistic flight conditions the monitoring behavior of professional pilots was recorded by an eye-movement measuring system on a video basis. In addition, a head-tracking device was installed inside the simulator cockpit to collect head-movement data parallel to the subjects eye-movements. This enables an automatic eye-point of gaze (EPoG) calculation and fast data availability. A computer program is introduced to analyze and explore the display and panel scanning behavior of pilots in a complex and highly automated cockpit environment shortly after the simulator training session.

INTRODUCTION

The introduction of the glass cockpit has changed the working situation in a modern aircraft cockpit. The high degree of automation has not only established a high level of safety by reducing the overall workload in the cockpit, it has also led to a complexity, where the correct comprehension and anticipation of system behavior requires intensive training and much experience. Pilots have become supervisors of complex systems and their human-machine interaction is mainly characterized by monitoring tasks.

Monitoring - an information selection and gathering process - is the key skill to obtain and maintain situation awareness (SA). Together with system knowledge, the perceived information is essential to assess the system status and to anticipate future changes (Endsley, 1994). Insufficient awareness of the system behavior or engagement status has led to misconception and misunderstanding on the system operators side. Especially the interaction with the auto-flight system can be critical. Automation surprises and mode confusion were often the contributing factors in the chain of events that resulted in aircraft incidents or accidents (Dornheim, 1995). A study by Jones & Endsley (1996) of 143 incidents revealed that 76,3% of 262 investigated situation awareness errors could be attributed to the operator's failure to perceive the situation correctly. A basic investigation of the relevant human-machine interaction may contribute to the understanding of the information selection and management process as well as situation and mode awareness aspects in a modern glass cockpit.

METHOD

The utilized Airbus A330 full flight simulator at the Technische Universität Berlin is certified for airline training and provides a real cockpit environment with respective research capabilities (Hüttig, Anders & Tautz, 1997). The simulator's Scientific Research Facility (SRF) allows the recording of any simulator parameter in real time. Microphones and video cameras inside the simulator record environmental sounds, voice communication, general cockpit settings and the actions of the operators. In addition an eye- and head-tracking device has been installed inside the simulator to measure the monitoring behavior of pilots.

Several flight trials were conducted in the full flight simulator in 1999. A total of 16 pilots from Lufthansa, Condor, FTI, Eurowings and LTU (average age: 36,7 years, piloting experience 14,4 years and 7500 flight hours) participated in the experiments and formed eight crews. After an initial crew briefing and the adjustment of the measurement equipment for one pilot inside the cockpit, each crew flew three or four standard instrument approach scenarios to different major airports in Germany (Düsseldorf, Frankfurt, Munich and Stuttgart). Each flight started from flight level 210 (21.000 feet altitude) in managed descent mode and included an ILS (Instrument Landing System) approach and landing. An instructor inside the simulator cockpit played the role of air traffic control (ATC). New targets for altitude, speed or heading as well as approach and landing clearances were assigned to the crew by simulated VHF communication. Identical instructions at pre-defined flight conditions were given to each crew to achieve comparable flight progression for one scenario. Different sets of ATC instructions were given during

the approach scenarios to other airports. All four scenarios were designed as typical every-day approaches with step descents to intermediate altitudes and radar vectors to the ILS. Different events such as an altitude re-clearance, a considerable flight plan shortening, a late ILS clearance or a go around command were incorporated into some scenarios to distinguish the pilot's behavior in situations with significant configuration changes of the auto-flight system.

During all experiments extensive simulation data and cockpit videos were recorded to re-establish the operational context during later analysis. The eye- and head-movements of one crew member were measured with an iView-HED+HT system by SensoMotoric Instruments. The Pilot Flying (PF) in the captain's seat was chosen for measurement because it is his role to perform primary flying tasks.

Figure 1: Eye-tracking device (headband)

Figure 1 shows the headband of the eye-tracking device. A mounted scene camera, eye camera, infrared light source and a semi permeable mirror were used to record the scenery and to measure the movements of the eyes on a video basis (cornea-reflex-method, see Carpenter & Robson, 1998). After an adjustment and calibration procedure of approx. 10 minutes the system was ready to use. A gaze vector was determined every 20ms and was then transformed to a gaze point in the pilot's field of vision. This point was shown as a cursor overlay in the video taped scene. Since no fixed reference to the environment was defined and head movements of the pilot resulted in a changing field of vision, further processing of the scene video was necessary. The focused cockpit information had to be determined manually for each video frame.

Figure 2: Cockpit setup of measurement system

The additional head-tracking device enhanced the data acquisition and decoding process. A transmitter on a custom made tripod was placed inside the simulator (see figure 2) and an additional sensor was mounted to the headband. During measurement the transmitter generated a defined magnetic field, in which the sensor was able to determine its 3D position and rotation. The position of the subject's eyeball could then be calculated by a constant offset. This point in space is the origin of the synchronously measured gaze vector. Finally, the eye-point of gaze in the cockpit could be calculated based on a previously defined 3D model of the environment. All data was constantly logged into a file.

Difficulties during the system setup were encountered, due to electro-magnetic disturbances caused by the electronic devices, switches and displays inside the cockpit. Therefore, the distance between the transmitter and the magnetic sensor on the subjects headband was minimized to 6 inches to ensure both, acceptable data quality and obstacle free head movement. A fairly defined seating position for pilots in the cockpit supported this setup.

Areas of interest were defined to attribute each eye-point of gaze to cockpit information (see figure 3 and 4). Major displays and panels were chosen on a rough level of detail: Primary Flight Display (PFD), Navigation Display (ND), Engine and Warning Display (EWD), System Display (SD) or the Main Panel (MPn), Glare Shield (GSc) and Overhead Panel + Center Pedestral (OCA). The Flight Control Unit

(FCU) is part of the GSc whereas the two Multi-purpose Control and Display Units (MCDU) in front were separately defined as CDU. MAP describes the charts and other information on paper. OUT represents the window area.

Figure 3: Areas of interest inside the cockpit

On a more detailed level the PFD was subdivided into the areas of interest FMA, SPD, AH, G/S, ALT, V/S, LOC, HDG, FRQ and QNH.

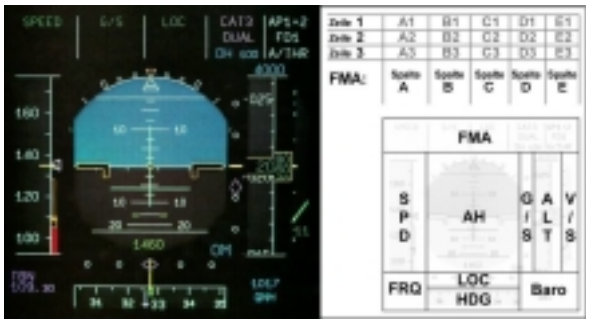

Figure 4: Areas of interest within the PFD

A fixation analysis of all gaze points lead to a sequence of fixations (≥ 100ms) on areas of interest inside the cockpit.

RESULTS

A total of 23 data sets were retrieved from the experiments. Some approach scenarios had to be sorted out because of instructor errors and a diversion from the pre-defined scenario or because of unacceptable data quality. One pilot for example had very long eye-lashes, which covered the pupil often during measurement. The data sets of 7 professional crews, who flew 7 approaches to Frankfurt, 6 to Munich, 6 to Düsseldorf and 4 to Stuttgart, were finally used for further analysis. Average scenario duration was 15.87 seconds. Eye-point of gaze data was recorded with and without head-tracking support and is represented either by a cursor overlay on the scene video or as an intersection point between the gaze vector and the 3D model of the cockpit environment. The video data was decoded manually which was very time consuming. The EPoG data based on additional head-movement information was instantly available.

Figure 5 shows the attention allocation to areas of interest during approach and landing based on the manually interpreted video data. The displayed cumulative fixation time is averaged for all 23 approaches and illustrates the importance of the PFD (40%) as primary source of information during flight. The sub-diagram (also in figure 5) shows that most of the fixation time within the PFD is attributed to flight parameters presented on the speed band (SPD), artificial horizon (AH) and altitude band (ALT). The cumulative fixation time on the heading band (HDG) is fairly low since the ND (18%) gives a better indication of the horizontal situation. The cumulative fixation time on other areas of interest is 5% (GSc, MPn, CDU) or lower. For 11% of the scenario time there is no fixation at all due to movements of the eyes (saccades) or deficiencies during measurement. The results in general are comparable with the findings in Tautz (1998). The average attention allocation to areas of interest is very similar for all four approach flights. Even the differences between pilots are not outstanding.

A closer look at the recorded data is necessary to explore the individual monitoring strategy. Flight parameters, events and actions have to be considered. The timeline in figure 6 shows the fixations on major areas of interest as a function of time to threshold in seconds. It is the most detailed representation of the pilot's scanning behavior and has been discussed in Hüttig, Anders & Tautz (1999). Figure 7 shows the timeline display of selected simulation data from the same approach scenario. Dynamic flight parameters for altitude, speed and heading are plotted over the time to threshold. Certain events such as VHF communication, mode changes of the auto-flight system and FCU input actions of either pilot are marked with a vertical line from above or below. The data of both timelines enable the identification of fixations on a specific area of interest and attribute it to parameters of the situational context and vice versa. Since the monitoring behavior of pilots is not only data driven but follows multiple conceptual strategies of different priority, another representation of the EPoG data appeared to suit better. Figure 8 shows the moving average of the cumulative fixation time, which

is calculated for each area of interest with the range of 30 seconds at an interval of 1s and is plotted over the time to threshold. The resulting timeline diagram can also be interpreted as the dynamic attention allocation behavior during flight. Shifts of attention are now transparent and the usage of visual resources can be analyzed in conjunction with simulation and event data.

Characteristic patterns can be identified in the moving average timeline diagram similar to a heart beat diagram in medical science. The PFD graph varies between 25% and 75% for most of the time. It has a low value when other areas of interest show a peak, e. g. the ND at 540s and 70s to threshold or the GSc at 650s and 300s. The average attention allocation to the PFD even drops to 0% at 960s, 820s and 440s when values for MAP and CDU are high. Remarkably high is the PFD value at 750s and shortly before landing (at 50s), where attention shifts from PFD to OUT.

DISCUSSION

In contrast to the summarized attention allocation for all approach scenarios, which has a heuristic value, individual monitoring strategy can only be analyzed by a closer look at the recorded data. The described findings for the selected approach scenario are comprehensible, if parameters of the situation and piloting knowledge are taken into account. The PFD is the most important display and draws increasingly attention during approach and landing until the aircraft is out of clouds and the runway is in sight. The peaks of attention to the GSc result from ATC instructions to change a flight parameter, which is set on the FCU by the PF. The attention to the areas of interest MAP and CDU is high during phases of flight, in which the pilot is briefing the approach (at 960s) or when the flight plan has to be changed (e. g. after a “Go direct…” instruction by ATC at 860s or after the announcement of a runway change at 460s).

All these examples show reasonable pilot behavior for the described situations and other results for different pilots or approach scenarios show comparable characteristics. However, differences can be discovered for special situations. The drop of PFD attention to 0% in figure 8, for example, does not represent typical behavior. During other flights the attention to the PFD is also low in situations with focus on MAP, CDU, GSc or ND, but it is rarely as low as 0%. According to the moving average calculation a value of 0% means that not a single fixation has occurred on the PFD for 30 seconds or more. In the sense of a proposed ‘minimum monitoring requirement’ this limit could serve as an indicator for weak performance. Other performance indicators can be derived by expecting the access of certain information within a defined time after an event, e. g. checking the Flight Mode Annunciator (FMA) within 10 seconds after a mode change.

As long as there is no valid model of the pilot’s monitoring behavior it is impossible to measure pilot’s performance objectively. Instructors inside a simulator, who can consider all the contributing factors, are still the best judges of the pilot’s over all performance. Even so, indications to weak performance may support the instructor’s work and may improve pilot training. Therefore, eye-point of gaze data has to be available during and shortly after a simulator session and monitoring behavior must be transparent to the instructor and the trainees. Using a head-tracking device in conjunction with the eye-tracker enables a fast and automated EPoG data acquisition. A comparison with the manually decoded data shows 70% to 85% similarity for most of the data sets. The similarity of a few data sets is only 50-60% due to a systematic error during measurement. For the first proof of concept this is an acceptable data quality considering the fact, that fixations on movable objects (MAP) can not be detected automatically. It is believed that the data quality would improve by using an optical head-tracking device.

Besides the graphical representation on timeline charts a computer program was developed to visualize the monitoring behavior of pilots. Figure 9 shows a screenshot of the program. Like the cursor overlay in the scene video the recorded eye-point of gaze is marked by a rhombus on a static cockpit background. In addition, essential displays and switches are animated. The integrated replay utility allows to re-generate any cockpit configuration and display content from the recorded simulation data. The rhombus is also animated showing the eye-point of gaze movements across cockpit information.

CONCLUSION

The acquisition and timeline representation of eye-point of gaze data in conjunction with simulation data has made the pilot’s monitoring behavior transparent to external observers. A replay and visualization of the human-machine interaction in the context of flight progress, events, actions and system status shows both, available and observed information in the

cockpit. This visualization can be used in pilot training to demonstrate good or bad examples of instrument scanning. Novices could learn from experts by observing their visual actions as they already do for manual actions by watching a demonstration video.

By measuring and recording the pilot's eye-and head-movements during a simulator training session visual actions can be observed in addition to manual actions. A visualization tool enables instant feedback of the monitoring behavior. Based on the instructor's judgment and indications to weak monitoring performance the attention allocation of the trainee can be explored and analyzed retrospectively.

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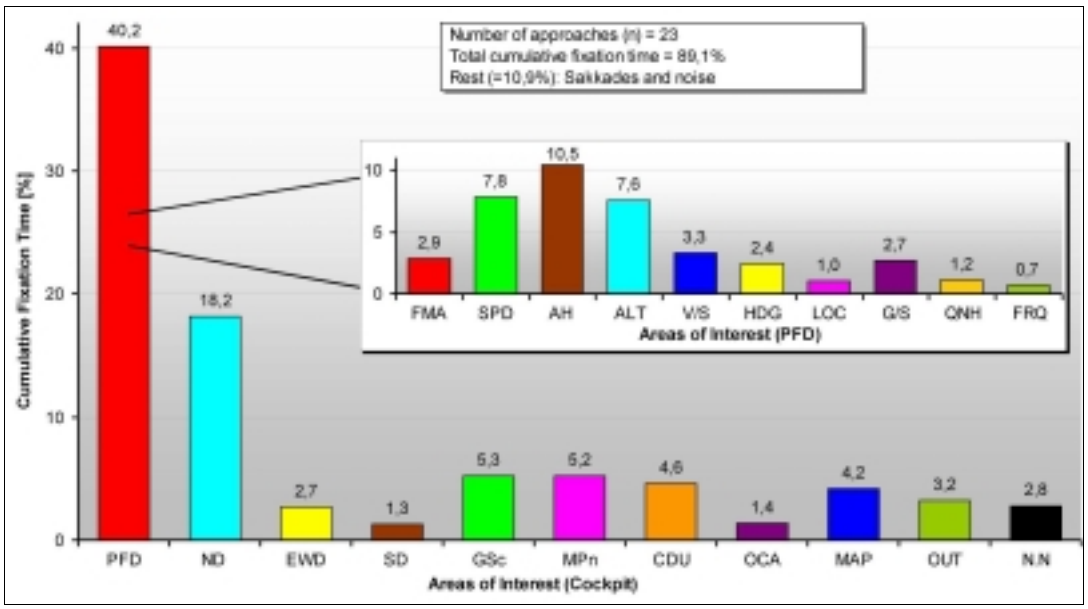

Figure 5: Attention allocation to areas of interest (average cumulative fixation time, n=23)

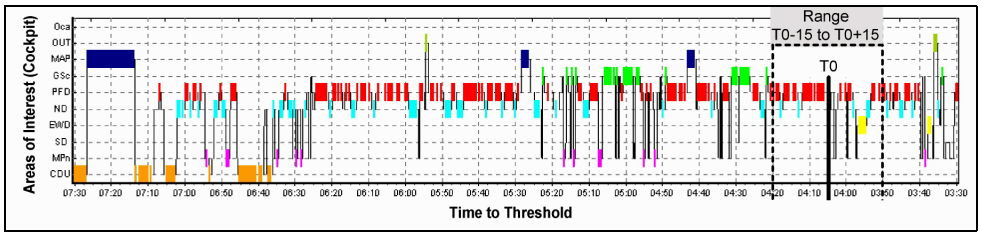

Figure 6: Timeline diagram (portion) of the fixation sequence on the areas of interest in the cockpit.

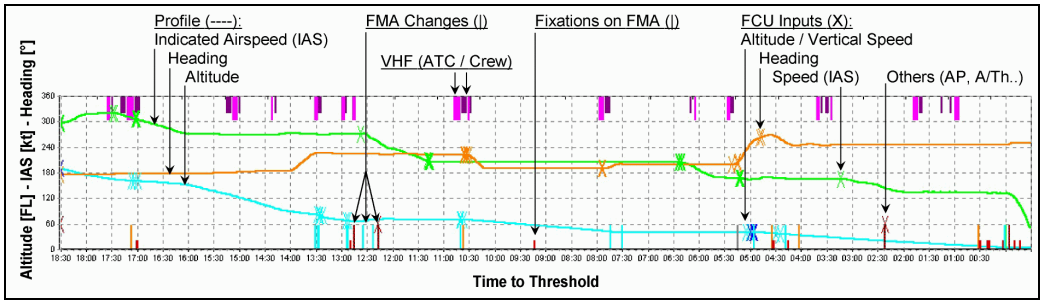

Figure 7: Timeline diagram of selected simulation data

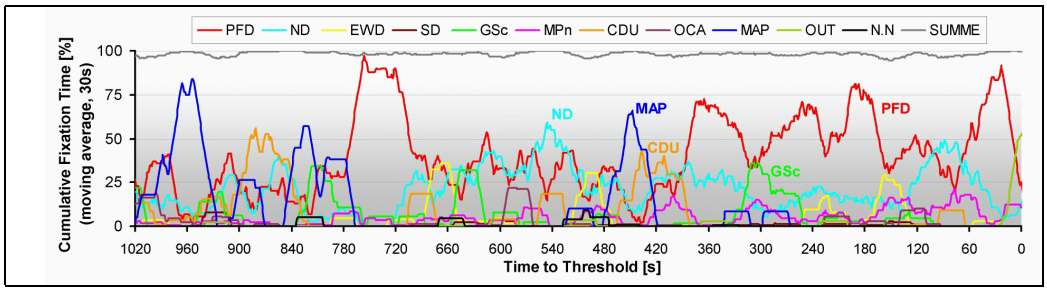

Figure 8: Moving average of the cumulative fixation time on the areas of interest in the cockpit

Figure 9:
Computer replay and visualization of selected system inputs and outputs as well as EPoG data for a retrospective analysis and exploration of the human-machine-interaction.