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HUMAN FACTORS ISSUES OF TCAS: A SIMULATION-BASED STUDY

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Since its introduction in the 90's, TCAS II, presented as a straightforward and very reliable technological tool, has significantly reduced the risk of collision. Paradoxically, the introduction of this system has been accompanied with numerous incidents and one major accident in 2002, mainly due to unclear rules, poor air-ground cooperation and poor human decision. In order to investigate these potential human factors issues, a part-task air-ground simulation was conducted: 10 pilots and 10 controllers were involved in the simulations of 4 scenarios containing TCAS occurrences. Data collected included video camera recordings for behavioral analysis, Heart Rate (HR) for stress evaluation, questionnaires and debriefings for perceived risk levels and situational awareness assessment. The observations and errors were analyzed through the CREAM methodology. The debriefings were led through a self-confrontation technique, together with pilots and controllers. Results show that the simulations of TCAS situations were able to produce a significant physiological stress response with significant increase of HR when a resolution happens. Questionnaires and debriefings show that, in most of the observed cases, aircrew, and controllers are not sharing the same mental picture of the involved traffic and the risk of collision. This raises important issues in terms of cooperation between controllers and aircrews in such demanding occurrences. This should allow identifying risky situations and the related generic causes. The results will be discussed, aiming at a potential improvement of the system, in terms of Human Machine Interface, training and consistency of procedures.

Introduction

The prevention of mid-air collision has been a major safety issue in aviation for years. Since its introduction in the 90's, the Traffic Alert and Collision Avoidance System II (TCAS II), presented as a straightforward and very reliable technological tool, has significantly reduced the risk of collision. The latest version, TCAS II Version 7 was built upon lessons learned from TCAS II use and problems (Wickens, 1992) TCAS II is now a mandatory device for all commercial aircraft with more than 19 passengers seats. This system issues two types of alerts : the Traffic Advisory (TA) which identifies a traffic as an intruder whose position should be closely monitored (but no actions are required for the aircrew) and the Resolution Advisory (RA) that recommends a vertical escape maneuver to maintain a self separation. Paradoxically, the introduction of this system has and still contributes to severe incidents and was the main cause of one major accident, the mid-air collision between a B757 and a Tupolev at Uberlingen Lake in 2002. The major cause of this accident lies in the decision of the Tupolev captain to follow, (accordingly to his company's manual), the Air Traffic Controllers (ATC) instruction to immediately initiate a descent though it was contrary to the RA order (BFU, 2004). Even if an improvement seems to show up over the last years mainly due to aircrew and Air Traffic Controllers (ATCO) drastic changes in information and training (Powell and Baldwin, 2002) it is still observed cases where aircrews failed to follow the RA or over-reacted or simply disregarded the alert. Obviously, this system still raises many human factors issues that directly impair air safety. A preliminary study (Cabon et al, 2003) conducted by means of collective and individual interviews of controllers and pilots emphasized the following issues: stress, man-machine interface, training, airline procedures and aircrew-ATC communications. The present study aims to investigate the potential human factors issues in an air-ground simulation. The use of simulation is essential as the previous studies emphasised the need to reproduce in real time the temporal pressure and the stress that experience both pilots and ATCOs during a TCAS sequence.

Method

Simulation Settings

All the simulation settings were designed by the Centre d'Etudes de la Navigation Aérienne (CENA) in Toulouse (France).The three main elements were:

- An Airbus A320 part-task simulator including for both the Pilot Flying (PF) and the Pilot Non Flying (PNF), the main displays and tools that are needed to present and respond to a TCAS resolution: the Navigation Display (ND), the Primary Flight Display

[1] Previous name was CENA (Centre d'Etudes de la Navigation Aérienne), which is part of DSNA.

(PFD), the Flight Control Unit (FCU) and a side stick. Radio communications with ATC are available.

- An ATC position with the 2 radar displays and paper strips for the planning and executive controllers.
- A "pseudo-pilots" position where 2 experts play the role of the surrounding traffic. The ATC did not know during the simulation what aircraft was actually "piloted" or "pseudo-piloted".

The main and most valuable feature was the integration of the actual TCAS software and HMI in the cockpit simulator and for the other simulated aircraft.

Scenarios

While high technical fidelity was out of scope, operational aspects were taken as important. For this study, 4 scenarios have been especially designed. The first one (Biarritz) was designed by the CENA to induce a high probability to trigger a TCAS alert. In this scenario, always presented first, neither the ATCOs nor the aircrews knew that the study was dealing with TCAS operation. The three other scenarios (named respectively Marseille, Orly and Reims) were based on real incidents that were selected in collaboration with the CENA and the Service du Contrôle du Trafic Aérien (SCTA). In these scenarios, the ATCO were asked to "play a part", reproducing certain errors in order to induce a conflict likely to trigger a TCAS alert. Each scenario lasted between 10 to 15 minutes.

Participants

A total of 10 A320/330/340 pilots (i.e. 5 aircrews) and 10 ATCOs (ACC and APP) were involved in this study.

At the beginning of each session, none of the participant knew the precise scope of this study, in order to avoid anticipation or preparation effects.

Data Collected

Four kinds of data were collected:

- Direct observations and video of both working positions to trace displays, events, actions and communications to subsequently analyze behavior. Specific observation grids were developed using the Cognitive Reliability and Error Analysis Method (CREAM) (Hollnagel, 1998). On top of this, one of the observer was a fully qualified pilot able to pinpoint fine details not caught by the video. Two Human Factors experts also observed aircrew and ATCO.
- Subjective assessment. After each scenario, participants were asked to fill out questionnaires to rate their situational awareness, their stress and various aspects that were relevant to understand how they had perceived the scenario and the TCAS sequence.
- Heart rate (HR). In order to get an objective measurement of stress, heart rate was continuously recorded during the scenario by means of a digitized recorder (Vitaport, Temec ®).
- Collective debriefing. The aim of the debriefing was to collect the verbalization of both pilots and ATCOs on what happened during the scenarios. The debriefing was supported by an auto-confrontation using the video and communication recordings. This debriefing was very useful to assess the situational awareness of participants. It also allowed revealing their a posteriori understanding of the situation, in relation to the ASR or reports they would have to fill in. At the end, a discussion was set up about the main safety-related issues and suggestions to reduce risk in operational environment.

Each session lasted one day from 0900 to 1730. The four scenarios were played in the morning while the afternoon was dedicated to the collective debriefing.

Results

Descriptive Analysis

TCAS Events

During the study, 20 scenarios have been played (i.e. 4 scenarios X 5 days). Both the simulation setting and the scenarios were efficient to induce a significant number of TCAS events allowing the data analysis. The following TCAS events occurred during the simulations:

- 8 TA not followed by a RA,
- 18 sequences TA/RA (some with several RA),
- 37 RA (initial and sense reversal or weakening RA).

A rather good variability of RA was obtained, with a majority of Adjust Vertical Speed which are known to be often misinterpreted by aircrews.

Heart Rate (HR)

Stress was objectively measured in this study using a continuous recording of HR. As there is a considerable inter-individual variability in HR, all the data are expressed as the percentage of variation of the 1st percentile of the total recording (reference). Figure 1 shows an example of HR recording for a pilot and an ATCO during a TCAS sequence.

This example shows a clear physiological reaction to the occurrence of the different TCAS events for the pilot and the ATCO. For the pilot HR increased dramatically after the TA up to 80% when the two first RA "Climb" and "Adjust Vertical Speed" are issued.

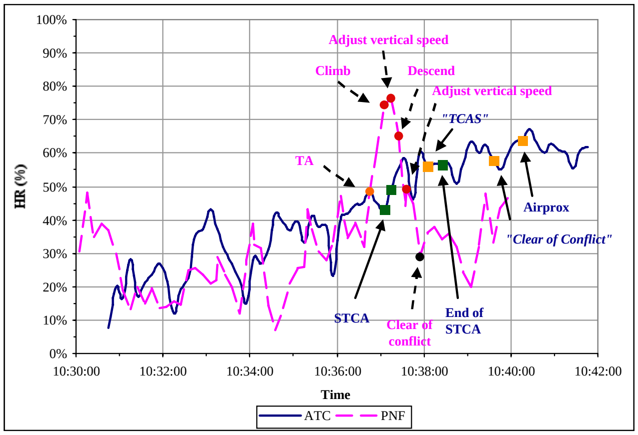

Figure 1. *HR expressed as a percentage of the reference (1st percentile of the total recording) during a TCAS sequence for one pilot (PNF) and one ATC*

Then, HR progressively decreased even with the two subsequent RA suggesting an adaptation of the physiological stress to the situation. The level returns to the initial level (around 30%) after the "Clear of Conflict" announce. For the ATCO, HR increased progressively after the STCA and reached a maximum (>60%) after the TCAS and airprox reporting by the aircrew. In most of the simulations, a similar pattern was observed with some variability in the magnitude of variations. This result confirms that, even in a part task simulator, the scenarios and the environment are able to induce a significant stress effect. In some cases, stress induced changes in behaviour. In one simulation, after the aircrew had solved a multiple RA sequence, a second TA appeared while the crew was resuming normal navigation. This TA was not detected by the aircrew, and even during the auto-confrontation they had difficulties to recognize this event. This suggests a "post-stress" or a "slacking" effect that reduced the available resources of the crew. A systematic analysis is being carried out on the relationship between physiological manifestations of stress and some behavioural changes that occurred during the simulations.

Thematic Analysis

From the data collected, two topics have been selected as relevant from a Human Factors and operational point of view:

- situational awareness,
- aircrew-ATCO cooperation and communications.

Situational Awareness (SA)

SA has been analysed regarding four main issues:

- data collection,
- timing of the TCAS sequence,
- control over the situation,
- common perception of conflicts by aircrew and ATC

Data collection. Since its introduction, TCAS has introduced a major change in the perception of traffic situation by aircrew. In fact, surrounding traffics are continuously displayed on the ND (CDTI). Therefore, aircrews now try to build an overall picture of the traffic situation based on this information while in the past this was only done through the hearing of the ATC communications (party line). This may impact the R/T communications, even before the TCAS issues an alert. The following examples of aircrew messages to the ATC during the simulations were recorded before and during TA's (most are translated from French):

- Before a TA : *"we've got a traffic", "we've got an aircraft", "traffic TCAS", "you've got a traffic information ?".*
- During a TA : *"we've got a TCAS", "TCAS alert", "we've got a visual", "we've got a visual TCAS" "we have it on TCAS"*

These messages were intended to ask for traffic information or were an answer to an ATC clearance or a traffic information given by the ATC. They are not covered by any procedure or rule and may interfere with the ATC work and induce misunderstanding. For example, the word "visual" may be understood by the ATC as "I have a visual contact on the traffic" or "Traffic TCAS" can be understood as "we've got a RA". The display of traffic on the ND may also lead to false interpretation. For example in the Orly scenario all pilots have seen the traffic as the aircraft ahead on the approach, which was not the case. This misinterpretation has a direct impact on aircrew SA and may lead to incorrect maneuver in case of RA (as it happened in the real situation).

The timing of the TCAS sequences. The analysis of TCAS sequences reveals a large variability in the timing of the TCAS events. In this study, the duration of TA varies from 2 sec to 38 sec. In one case, a RA occurred without being preceded by a TA. The collective debriefing showed that most participants are not aware of this large variability. The absence of TA leads to a situation where the aircrews could not be properly prepared to respond to the RA. In this case, the procedure which is normally followed after a TA in most airlines (the captain announcing "*I (or you) have the control*", switching off the Flight Director) cannot be applied. The high unpredictability of the TCAS sequence impacts SA as prevision and anticipation play a major role in the building process of SA (Endsley, 1998).

The control over the situation by the aircrew. After each scenario, the participants were asked to rate how difficult it was to evaluate the situation and whether they felt they started to loose the control over the situation. Table 1 shows the results of these questions.

		No	Yes
Did you find difficult to assess the situation ?	PF	11	9
	PNF	16	4
Did you felt that you were losing control of the situation ?	PF	20	0
	PNF	20	0

Table 1. *Evaluation and control of the situation by the aircrew*

Results show that the feeling of a global situation assessment is higher among the PNF than for the PF. This can be explained by the fact that PF are mostly focussed on the active following of the RA and are not seeking to have an understanding of the situation. The following statements of PF's during the debriefings confirm this attitude: "You cannot react according to what you understand"," I don't know what happened" "I do not remember to descend", "I focused on the IVSI [NB : where the RA is displayed on Airbus aircraft], I do not look at the ND". During the debriefing, most of pilots stated that the RA TCAS are too unpredictable and that it is preferable to concentrate on the execution of the manoeuvre. In this context, they do not expect or seek traffic information from the ATC.

Common perception of conflicts by aircrew and ATC. One of the most striking results from the collective debriefing was the large shift in the perceptions of ATCOs and aircrews on the same situations. The auto-confrontation of the participants with the video recordings showed that most ATCOs are not aware of how the TCAS is displayed in the cockpit. Aircrews are also not informed about the ATC tools, especially regarding the functioning of the STCA and the characteristics of radar display (precision and refreshment rate). This was confirmed by the results of 2 questions asked to the aircrews and ATCOs (Table 2). These questions have been asked only for the Biarritz scenarios where ATCOs were not aware of the aim of study and did not expect the situation at all.

The most striking results are the large number of negative answers (11 out 20) and the uncertainty of the PNF (4 answers "don't know" out of 5). This shift is mainly due to the different and independent tools that are used by ATCOs and aircrews, e.g. time shift between STCA and TCAS. This leads to a lack of common perception of the situation which may interfere in the communication and cooperation between ATCOs and aircrews in these demanding situations.

		No	Yes	Don't know
To the aircrew: *Do you think you had a common perception with ATCO?*	PF	1	0	4
	PNF	5	0	0
To the ATCO: *Do you think you had a common perception with aircrew?*	ATC1	3	1	0
	ATC2	2	0	3

Table 2. *Feeling of a common representation by ATC an aircrew*

The Aircrew-ATCO Communications

In this section, the main results regarding the communications between ATCOs and aircrews are reported. The results are presented both for the messages from aircrew to ATCO and from ATCO to aircrew.

Aircrew notification The only way for the ATCO to be informed of a TCAS resolution is through the notification of the RA by the PNF. The airline procedure provides only 2 messages, whatever the RA issued: "TCAS climb" or "TCAS descend". In this study, for simple RA such as Climb or Descend, the observed messages are consistent with the procedure which is, in this case, clear and appropriate. For the other RA a large variability of phraseology is used, with sometimes some ambiguous. For example, some pilots used the message "TCAS descend" to report an Adjust Vertical Speed RA, although this RA always means a decrease of vertical speed that may occur while the aircraft is climbing. This raises the issue of the alert "Adjust vertical speed" which does not give directly the sense of the RA and, as a consequence, the way the pilot can report it to the ATC.

ATCO instructions Since the accident of Uberlingen (BFU, 2004) both aircrews and ATCOs are aware that aircrews must follow their RA and that ATC should not give any clearance to the aircrew. However, on the 5 scenarios that have been played where the ATCOs were involved, 2 ATC clearances have been given to aircrew who followed these clearances. In these two cases, the ATC clearance was given because the ATCO was trying to avoid a conflict with another aircraft. In one case, the clearance happened while the ATCO thought that the conflict is solved, for the other, the clearance was compatible with the RA TCAS. The critical aspect is that the initial RA could be followed by another RA which may be incompatible with the clearance.

Discussion and Conclusion

The results obtained in this study show that even a partial simulation of tasks was able to reproduce TCAS events, stress and behaviors that raise several human factors issues that could not be revealed in incident reporting. The simulation conditions enabled producing the temporal pressure and stress that is inherent in the TCAS sequences. The assessment method that was developed for this study, gathering physiological recordings, observations, verbalization and questionnaires showed its strength to detect and analyze the critical human factors issues to be addressed in the future. These issues have to be considered in the aircrew-ATCO relation and not only at one level. To summarize these issues, the TCAS sequences can be represented as a "parenthesis" in the normal aircrew-ATC communication and cooperation (figure 2). This figure depicts the several events and sequences that follow one another. The upper part represents the TCAS events occurring in the cockpit, the lower part the ATC side and in-between the air-ground communications. As it is shown, the effects of TCAS occur before the TA, when a traffic is displayed on the ND. This leads to a change in the communication with potential interferences and disruptive effects as it was reported earlier (Benhacène, 2001 ; Walsh, 1997). The subsequent sequence starts when a TA occurs. This period is critical for the aircrew as it is intended to prepare them for a potential RA. One of the main issue related to this period that was revealed by the study is the very large variability of the timing of the sequence: from very short (even in one case, with no TA) - which does not allow the crew to apply the expected procedure and be mentally prepared to react- to long periods where the preparation can diminish progressively. As airborne and ATC systems are independent, additional interferences can occur at this moment due to the STCA triggering which may induce actions from the ATCO. When the RA occurs, a critical period is starting (T1). As long as the aircrew has not reported the RA, the ATC has no means to be informed that the TCAS has issued an alert.

This creates a very sensitive situation where ATC may still give clearances that can be very disruptive for the aircrew. The reporting of the RA by the aircrew is expected to open the parenthesis in the aircrew-ATCO communications. However, as demonstrated by our results the reporting is sometimes inexistent, late or ambiguous. The "Clear of Conflict" (CoC) message from the TCAS starts another critical period (T2). As for T1, as long as it is not reported by the aircrew, the ATCO is ignorant of the end of the RA. This raises a transfer of liability issue between the aircrew and the ATCO: who is responsible for the separation of aircraft? The report of the CoC by the aircrew to the ATC closes the parenthesis, the aircrew normally returning to the initial clearance, and resuming normal navigation (auto-pilot ON, flight director ON). As it was shown in the results, these tasks and a potential slack in attention due to the stress experience during the RA may have potential impact in this period reducing the attention on subsequent TA.

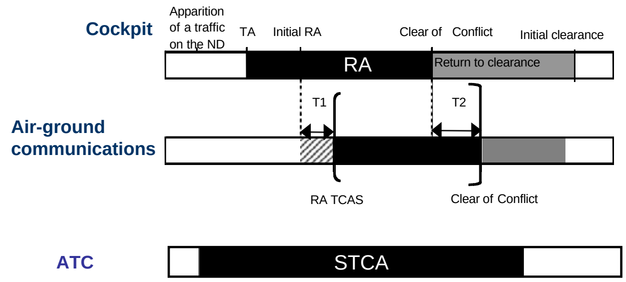

Figure 2. *The parenthesis in the aircrew-ATCO communications in the TCAS sequence*

Most of participants (pilots and ATCOs) stated that this type of simulation and common debriefing allowed them to better realize the operational issues and difficulties in these time-critical situations: some had a clear understanding of TCAS and associated procedures but no operational experience. They were surprised to have performed away from their understanding under time pressure and they noticed the consequences of their action on the other's job (ATCO or aircrew). So this represents a step forward as far as training is concerned into practice for the training process. Further analyses of the data are currently conducted in order to get a systematic analysis of errors.

A second round of simulations was conducted in autumn 2004: some changes were applied to scenarios in order to keep the ATCOs in their operational role. This led to some new situations and opened some new issues about these very short intensive periods. From the whole results and discussions of both sessions, some solutions will be suggested, which may reinforce or question present studies related to TCAS improvement. One of the most encouraging outputs is the method that was used to tackle the human aspects of the air-ground integration and could be use for the evaluation of solutions such as the RA downlink (Broker, 2004): it is a valuable complement to other approaches that have already been conducted: incident analysis, simulations involving only one side (RADE1, 2004), or field evaluations (Walsh, 1997). It may also be a valuable complement to present training methods, which does not require outstanding technical means.

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