Introduction of a more automated environment in En-Route Air Traffic Control : Evaluation of impact generated on the operator by mental workload assessment

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Introduction of a More Automated Environment in En-Route Air Traffic Control

Evaluation of impact generated on the operator by mental workload assessment

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Abstract—**This article deals with the introduction of partial automation in the En-Route air traffic control working position. More precisely, it presents an experiment whose objective is to evaluate the generated impact on air traffic controllers by the use of a more automated environment, including a conflict aid services system (conflict detector and solver).**

This impact is evaluated through the assessment of air traffic controllers' mental workload. In this experiment, the evaluation of mental workload is carried out mainly through psychophysiological parameters, especially ocular data. This assessment is compared with subjective evaluation collected by questionnaire and assessment scale, and also with performance indicators analysis focused on communications between controllers and pilots.

Results achieved show that automated system proposed in the case of the SESAR project (W.P.4.7.2) seems to be promising because it generates a decrease of mental workload felt in comparison with a non-automated situation.

Partial automation, mental workload assessment, triple evaluation, questionnaire, eye tracker data, performance indicators

I. INTRODUCTION

Air Traffic Control (ATC) has limits [1]. For each controlled sector, the number of aircraft defines a maximum capacity threshold of airspace above which safety may be impaired. A major objective of the SESAR project is to increase the level of this threshold [2]. As a result, the air traffic control system capacity can grow and respond positively to the increase in the traffic announced in the coming years [3]. Moreover, it could permit to improve performance in terms of security, the environmental impact and therefore meeting expectations for tomorrow's ATC system.

Analysis of the control task has shown that several indicators affect the level of task involvement [4]. One of them is the presence of conflicts in the air traffic situation. A conflict is defined as a situation where several aircraft trajectories cross with a lower distance than the separation standards [5] (longitudinal: 5 nautical miles, vertical: 1000 feet). One of the operators' objectives is to detect and resolve these conflicts.

This part of the control task requires a significant level of the controller's cognitive resources. Increasing the management capacity of air traffic control could therefore be possible by providing assistance for conflict detection and management. Such a system would require less of the controller. The latter would then be able to handle more aircraft and sustain a high level of security, which would ensure increased airspace management capacity.

The automated tools considered in this project are able to detect conflicts that may occur in the traffic and solve some of them. Here, it is important to notice that this study is not the first of its kind. Indeed, several previous research projects have evaluated almost equivalent future prospects for ATC, as the EEE (ERATO Electronic Environment) project [6] and more recently the ERASMUS (En Route Air Traffic Soft Management Ultimate System) project [7]. Furthermore, it should be pointed out that some of these projects' results (especially concerning the way to inform controllers about automated system behavior) have been integrated in the concept of the present project.

The integration of these systems in the working position of en-route control, the object of this work, comes under the work-package 4.7.2 of the SESAR project. In this article, evaluation of the impact generated by the introduction of a more automated environment in control working position is studied by operator's mental workload assessment. We describe an experiment, which consisted of a multiple evaluation of controllers' mental workload in several experimental conditions, each reflecting a level of automation.

II. AUTOMATION IN THE FUTURE ATC WORKING POSITION: FUTURE PROSPECTS EVALUATED IN THIS PROJECT

This work, conducted as part of the SESAR project, considers the modification of the detection system and conflict management. Currently in air traffic control, this task is mainly based on the expertise of the working position operator, namely the controller. Here, the introduction of conflict detection and

solving system in the air traffic control working position is studied.

A. The project concept

The objective of the 4.7.2 work-package is to develop a concept that should be fully operational in the considered target environment: the 4DTRAD (Four Dimensional TRAjectory Data link). This service uses CPDLC (Controller Pilot Data Link Communication) for the provision of 4D clearances and ADS-C for acquiring trajectory data from the aircraft. The 4DTRAD service enables the negotiation and synchronization of trajectory data between ground and air systems. This includes the exchange of 4D clearances and intent information such as lateral, longitudinal, vertical and time.

The concept proposed in the work-package 4.7.2 of the SESAR project is based on a combination of two principal services:

- The Trajectory Control by Speed Adjustment (TC-SA) service. TC-SA is a strategic de-conflicting service that aims to adjust the 4D-planned trajectory in order to optimize the separation management for medium and/or long-term conflicts (e.g., next 20/30 minutes);

- Conflict Detection (CD) Aid to air traffic controllers. The CD aid service assists the controller in conflict identification and planning tasks. It provides an automated early detection and filtering of potential conflicts.

The service analyzed in this study can only modify the aircraft speed. It is not able to modify aircraft trajectory through others flight parameters such as flight level or heading.

The automated system proposed in this project has an operating cycle that can be divided into five steps (Fig. 1):

• Step 1: Data analyzed by the solver (system inputs) are the geographic points that define the trajectories of aircraft. From the forecast trajectories, the solver starts conflict detection. A comparison of predicted trajectories identifies the presence of crossing points between at least two aircraft trajectories, defining the presence of conflicts. This detection is performed within a 20 to 30 minutes time frame, which allows the identification of aircraft pairs involved in conflict.

• Step 2: This phase is named "clustering" of conflicts. It groups several conflicts as one when they possibly interact with each other. For example: If there are two conflicts involving aircraft A-B and B-C, only one cluster (group) of aircraft in conflict will be defined, namely cluster ABC.

• Step 3: The third phase of TC-SA operating cycle aims to analyze the conflict resolution. For this, the solver will compare for each conflict, the nature of the conflict with a set of solutions. It will then conclude with the appropriation of one of these to resolve the conflict. The solutions tested are small changes in the speed of at least one aircraft in the cluster (ranging from -6% to +3% from the expected speed).

• Step 4: The solver proposes a change of aircraft speed via the Flight Management System (navigation computer). This requires reaching a geographical point at a given time.

The pilot has to accept or reject the proposal made.

• Step 5: The list of aircraft handled by the TC-SA is known. The CD aid service deducts the list of conflicts which cannot be resolved automatically. These conflicts are called "residual conflicts" and require the action of controllers to solve them. Therefore, one of principal role of the CD aid service is to present over time the updated "residual conflicts" list to controllers, according to the changes made to the ATC situation.
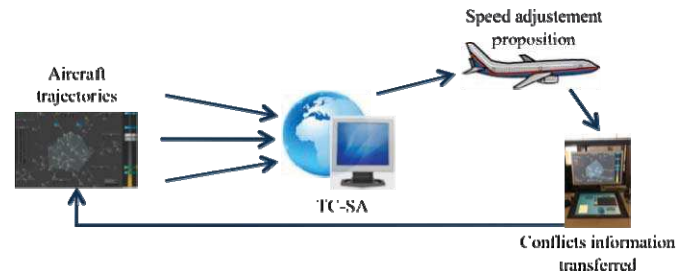

Figure 1. Illustration of automated system's operating cycle

In order to be usable by operators, the automaton needs to be included in the air traffic control working position. One solution to reach this prerequisite is to integrate this system in the HMI (Human Machine Interface) used by operators during their work activity. In the case of air traffic control, the radar display is one of the main sources of information used by controllers. The next part of this article focuses on the way the automaton is included in the radar display.

B. Introduction of the automated system in the ATC position

Modifying the actual ATC working position in order to add interactions with the automated system wasn't possible. A new generation of ATC working position has been created to fulfill the project objectives.

It is a 'full electronic' working position (no paper strips) composed of two screens, a big one (30") for the radar image and a Wacom 21" pen display which is being used to display information and interact with the radar image (refer to the paragraph III.F). The controllers have to inform the system about their actions (communication status with each flight, flight instructions provided…) in order to feed the automaton and the trajectory prediction involved in the project.

The integration of the automated system in the interface is essential in order to make possible a collaborative work between air traffic controllers and the automated system. Two types of information are shared with operators about the automaton state:

- Operator is informed of automaton's actions; more precisely, the aircraft handled by the automated system (speed adjustment validated) in order to resolve a detected conflict. On the radar display, a green clock (appearing gray on the figure 2) tags these aircraft and is located in the right-top corner of the aircraft label (Fig. 2).
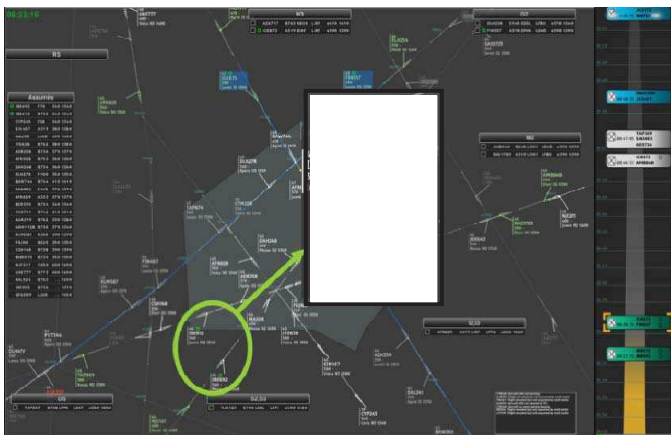
Figure 2. Screenshot of HMI with green clock tagging aircraft in conflict resolved by TC-SA

- The second type of information concerns the list of potential residual conflicts that are to be resolved by the controller. Each residual conflict is illustrated by labels of the cluster (at least two aircraft), which figure in a "dynamic" timeline (Fig. 3 – right part). Depending on the time, labels are moved to the bottom of the timetable in order to illustrate the time available to resolve conflict before its occurrence.
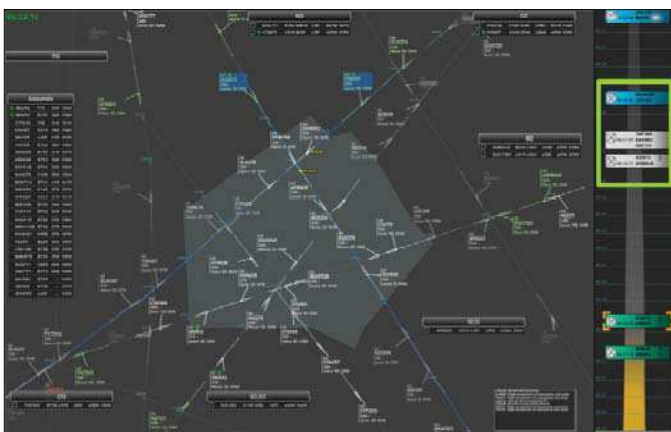

Figure 3. Screenshot of HMI with the timetable showing residual conflicts

In the case of automation introduction in a working position, some changes have to be anticipated. Two main risks may occur: one deals with the nature of the air traffic control task, the other is focused on air traffic controllers. The following two parts will detail the consequences of partial automation in air traffic management.

C. Changes in the control task

The integration of an automated system in the control working position will modify the nature of the control task performed by operators. This kind of impact has been observed or can be predicted in any automation project [8]. In air traffic control, it concerns the amount of time allocated for each subtask of an air traffic control task. Here, it is central to highlight that two subtasks can be distinguished in the principal control task: Firstly, the air traffic situation monitoring which allows the controller to order and manage the air traffic; secondly the detection and the resolution of conflicts guaranteeing air traffic situation safety.

Here, the dreaded effect is a reduction of controller's attention in conflicts detection and resolution. The first subtask of air traffic situation monitoring however, may increase with a higher number of aircraft under the controller supervision. This change may also have an impact on the behavior of air traffic controllers during task execution.

D. Consequences on the air traffic controller

As said before, conflicts can be used as an indicator of air traffic control task requirements [4]. The modification of air traffic control working position studied in this project aims at decreasing the number of conflicts that the controller has to detect and to resolve. With the introduction of an automated system, the level of task requirements imposed on the operator may change. Moreover, the use of a new working position may ask the operators to define a new work method.

At the same time, mental workload is defined as the level of cognitive resources that the operator will need in order to meet the control task requirements [9]. This argument justifies a modification in mental workload felt by controllers with the introduction of an automated system in the control working position. The next part of this article describes the experiment carried out in order to evaluate the magnitude of the impact that the introduction of this kind of automated system could generate on the controllers.

III. METHOD

In air traffic control, safety is essential; this is why we cannot test a change in the working position during real controllers' activity. Nevertheless, experiment carrying out in realistic conditions is a way to obtain an idea of the impact generated by working position changes on the controller.

A. Assumptions of the experiment

The principal objective of the experiment carried out in this project is to evaluate the effect of automation integration on the system. This evaluation was carried out in a futuristic air traffic control environment designed for the SESAR project.

Indeed, the air traffic sector (Fig. 4) used during the experiment is a generic one, that is to say a sector where the future air traffic rules and procedures could be applied (for example, the business trajectories).
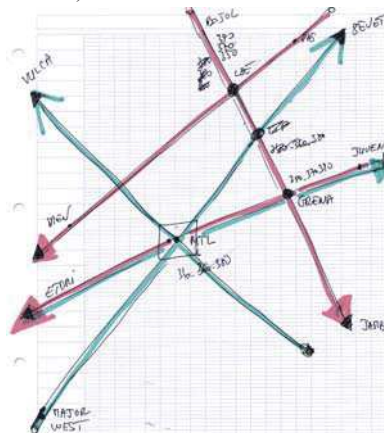

Figure 4. Sketch map representing the main features of the air traffic sector

The second characteristic of future air traffic control environment taken into account during the experiment is focused on air traffic density. SESAR project based its study on a significant increase of air traffic level in the future; this is why the level of air traffic density chosen for the experiment is 130% of the current air traffic level.

Finally, the last characteristic of the experiment, which illustrated the futuristic aspect of its environment deals with the working position used. An all-electronic air traffic control working position has been chosen for the experiment because it allows the integration of tools like a conflict solver.

During the experiment, several indicators have been recorded to determine the "air traffic control system state". Their principal functions are to determine automaton behavior, task performance reached and the operators' feedbacks. This article is focused on the evaluation of operators' feedbacks and more precisely on the mental workload they experienced during experimental task achievement.

B. The experimental task

The experiment principle was to ask qualified air traffic controllers to handle two hours of air traffic samples in a future air traffic control working position (Fig. 5 & 8).
Participants had to achieve the experimental task in pairs (binomial) as they do for the time being. One had the role of the planner controller; the other was the tactical controller. After one hour, the two participants exchanged their roles between planner and tactical controllers.

The evaluation of changes in the working position validity requires the comparison of operator's feedback between two main conditions: with or without the use of automated systems. This pre-requisite justifies the need of several experimental conditions.

To avoid learning effects, a preliminary phase of training has been carried out with the participants of the experiment. This training has been divided in two phases: the first one lasted three days during which participants had an initial and significant training on the concept of the project, the air traffic sector used during the experiment (geographical characteristics, rules and procedures to apply) and mostly on the air traffic control simulator and the HMI they had to use during the experiment. During the first phase of training, participants had several air traffic control simulations in order to accommodate themselves to the experimental conditions. The second phase of training was conducted the day before the beginning of the experiment and acted as reminders. During this phase, participants had again a significant time of air traffic control simulations.

C. Participants

There were 12 participants, grouped into 6 binomials of planner and tactical controllers. All the participants of the experiment were En-Route Air Traffic Controllers qualified in European air traffic control centers. 50% of participants were females, 50% males. The average age of participants was 34.83 years and the average ATC experience was 8.41 years.

D. Experimental conditions

As said before in order to evaluate the impact of automation introduction on the controllers it was necessary to assess their behaviors in several conditions, notably with or without automated systems. Two experimental conditions have been added in order to evaluate the impact of each service proposed separately.

Therefore, four experimental conditions have been defined as shown in the following table (Fig. 5). The first condition corresponds to the case of the new air traffic control HMI used without automated systems which corresponds to the baseline. The second condition is similar to the first one except that it uses the TC-SA automaton (i.e., the detection and resolution of a part of conflicts). Condition three uses only the CD aid service which shows to the controller the conflicts he or she has to solve. The last condition includes the TC-SA and CD aid duet in HMI which shows to the controller the solved and residual conflicts. Each experimental condition has been played with similar air traffic samples.

Condition 1	Condition 2	Condition 3	Condition 4
Reference situation (Without automation)	Partial automated situation 1 (Only use of CD aid)	Partial automated situation 2 (Only use of TC-SA)	Partial automated situation 3 (Use of TC-SA & CD aid duet)

Figure 5. The four conditions of the experiment

E. Air traffic samples

For each experimental condition, a two hours' air traffic sample was used. Each air traffic sample took place in the same air traffic sector.

An air traffic control expert built air traffic samples. This insures that scenario meet experimental criteria, and are equivalent in terms of difficulty (number and configuration of conflicts). Five air traffic samples have been created including one as a "spare scenario". This scenario could be used in case of technical problem, which would justify another experimental run.

In order to avoid any effect on the statistical results, experimental conditions and air traffic scenarios have been crossed between participants' binomials.

F. The experimental position

The Air Traffic Control simulator used during the experiment was composed of two main parts:

- The upper part of the working position: the radar screen. That 30'' screen displays the radar picture and the scenario of the experiment. In this graphical representation of the air traffic situation, five main types of information are displayed: the clock, the flights lists, aircraft illustrated by radar plots associated to a label, menus and functions (displayed on demand), and the information provided for residual conflicts (a timeline right of the radar image).

- The lower part of the platform, a 21'' Wacom pen display, is being used as a display and interaction tool.

It is composed of two areas: The first one is a touchpad zone used to interact on the radar image (move the pointer, make a data entry) with a stylus. The second one gathers the rest of the platform's tools like configuration of the radar image (zoom in/out, pan, speed vector configuration) or flight plan information for the selected aircraft.

Figure 6. Control working position used during the experiment

G. Assessment tools chosen to study mental workload

Assessing mental workload felt by operators during task execution can be done by several approaches. Three main categories are distinguished:
- Performance analysis, which is commonly studied through a double task technique or as well through performance indicators evaluation (different according to the studied task);
- Subjective methods that require operators to specify their experienced mental workload by mean of a questionnaire;
- Objective approach, which refers to psycho-physiological measures. Several physiological indicators have been already used in previous studies to evaluate mental workload like heart rate, skin resistance or ocular data [10]. The latter can be eye fixations, saccades, eye blinks or pupil diameter.

The use of only one mental workload assessment has been defined insufficient [11; 12], this is why in this experiment, a multiple assessment composed of a performance, a subjective and an objective evaluation has been chosen:

- Performance indicators analyzed deal with controllers' communications. In fact, communications have been defined in previous researches as linked to the mental workload felt [13]. More precisely, we analyzed the number of clearances given to the aircraft, as the duration of radio frequency occupation for each experimental condition.

- The subjective assessment carried out during the experiment is twofold. At the end of each experimental condition, participants were asked to fulfill the AIM-s test (Assessing the Impact of Automation on Mental Workload). It is a standard validated questionnaire developed by EUROCONTROL to assess the task-associated workload of a controller. The test proposes 16 questions, corresponding to 16 controlling tasks, to be assessed from 0 (no effort) to 6 (extreme effort).

At the end of the questionnaire, a score is defined. So, four AIM scores have been obtained during the experiment, one per experimental condition.

Moreover during the experiment, participants were asked to answer, every five minutes, to the ISA (Instantaneous Self-Assessment) scale. This scale is composed of four values (1 to 4), the lowest value representing the lowest value of workload. In detail, controllers had to select on a 10-inch touchscreen integrated to the experimental control working position divided in four colored parts (from 1.green to 4.red), the value reflecting their instantaneous level of mental workload.

Figure 7. The ISA interface used during the experiment

- The objective evaluation is based on the eye tracking method which consists in recording ocular data in real time. To make it possible two Tobii X-120 eye-trackers were integrated to the experimental control working position (cf. Fig 8) and a calibration phase preceded each simulation. This tool made possible the recording of four ocular parameters (eye gaze, pupil diameter value, eye blinks, and saccadic eye movements) with a 60Hz frequency (a data every 16.7 ms). Two of these data have been analyzed in detail during this study. In fact, eye fixations repartition is used to assess attention repartition [14]. The study of pupil diameter maximum aims to assess mental workload felt by operators [15; 16]. The analysis of eye data has been preceded by a pre-analysis of raw data in order to filter incorrect data. In a first time an eye fixations data sorting has been carried to in order to delete of data file, all the non-significant fixations defined by duration value less than 100 milliseconds [17]. Once this first sorting out done, the ocular data have been linked to the air traffic scenario data (aircraft positions). Thus, the significant eye fixations have been divided into the several categories of AOI, Areas Of Interest (as the aircraft on the radar screen, parts of the interface…).

Figure 8. Participants during experimental task execution

H. The experiment hypothesis

The main hypothesis of this study is summarized as follows: Mental workload felt by air traffic controllers during control task execution is lower when automated system(s) is/are integrated in ATC working position and that for an equivalent level of air traffic. Such a result could permit to confirm that these automated tools represent a real aid for air traffic controllers. Moreover, a complementary hypothesis deals with the comparison between the several indicators of mental workload, object of this study.

IV. RESULTS

A. The performance indicators evaluation

As previously mentioned, the analysis of participants' communications carried out deals with the number of clearances and the occupancy of radio frequency.

Analysis of the clearances shows lower values for experimental conditions including conflict aid services (Fig. 8) and especially for the conditions including the TC-SA service. The CD aid condition, for its part, has a number of clearances almost equivalent to that arising from the reference condition.
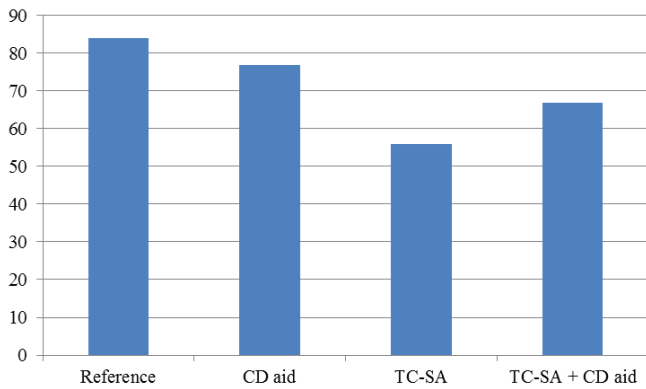

Figure 9. The average number of clearances given per experimental condition

The results made from the analysis of radio frequency occupancy are almost equivalent. Again, experimental conditions including the TC-SA service are linked of the lower durations of occupancy. Same observation can be made than in the clearances analysis concerning the CD aid condition which has an equivalent result than the reference condition.
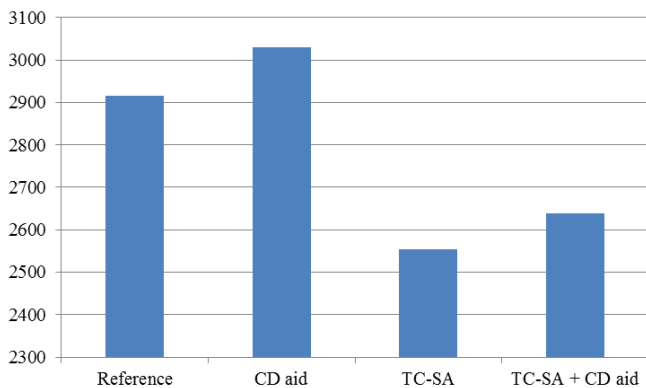

Figure 10. The average occupancy of radio frequency per experimental condition (seconds)

To resume about the analysis of performance parameters, we can highlight two principal results. The TC-SA appears as a real spare of time and requests for controllers. However, concerning the CD aid service, the picture is a more mixed because results for this condition do not differ from the reference condition.

B. The subjective assessment

This part of the analysis deals with results obtained through the AIM questionnaire and the ISA scale.

Scores obtained to the AIM questionnaire (Fig. 10) show that the reference condition has the highest score. It can be therefore defined as the more costly condition for participants. The CD aid condition has an intermediated score, while the two others experimental conditions (including the TC-SA service) obtained the two lowest and almost equivalent scores.
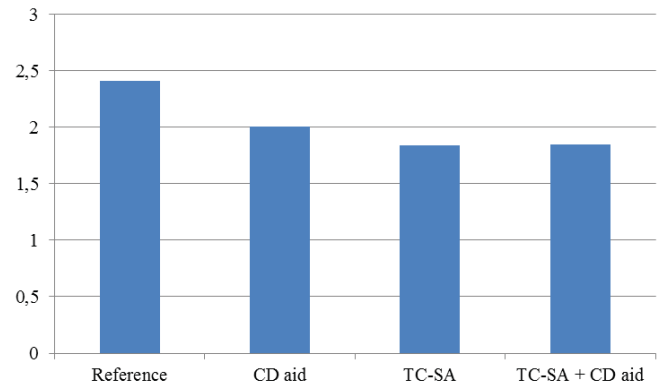

Figure 11. The score of AIM questionnaire defined for each experimental condition

The results of the ISA scale data show that the reference and the CD aid conditions lead to the highest scores. The TC-SA and TC-SA+CD aid conditions have on the contrary the lowest scores.
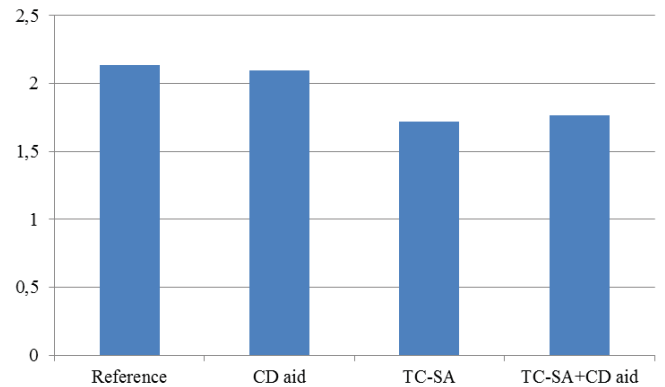

Figure 12. The average value of ISA scale determined for each experimental condition

All the results achieved through the subjective assessment seem to point out a real aid for controllers from the TC-SA service. CD aid service is more controversial with positive trend in the AIM questionnaire but very little, if any, impact on ISA results in comparison with the reference situation.

C. The objective evaluation

The analysis of eye data deals only with eye fixations on the conflict aircraft, and more precisely on their graphical representation on the radar screen (radar plots). This choice is justified by the concept of the project which is focused on the conflict detection and the resolution. Therefore, the use of TC-SA and CD aid services is expected to have an impact on the level and the repartition of attention and cognitive resources deidcated to the aircraft involved in conflict situations.
In terms of the results obtained with regard to the eye fixations number on conflictual aircraft (Fig.12), it should be noted that the highest value in the reference condition.

For others experimental conditions including conflict aid services, number of eye fixations recorded are in the same order of magnitude. Value is slightly larger in the TC-SA condition, while it is the lowest in the TC-SA + CD aid condition.
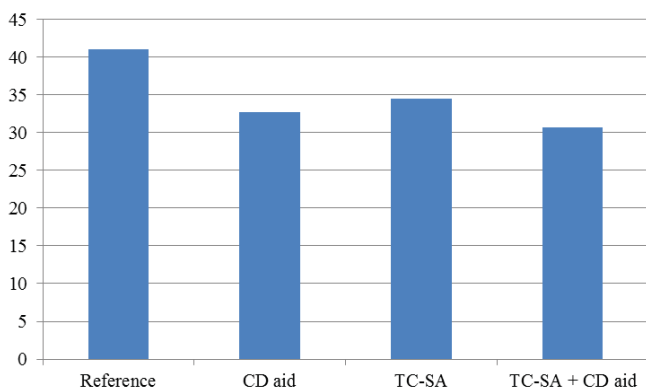

Figure 13. The average number of eye fixations on conflict aircraft according to experimental condition

The analysis of eye fixations duration (Fig. 12) shows a significant higher values for the reference and TC-SA conditions. The two others conditions including the CD aid service have lower average duration and especially for the TC-SA + CD aid condition.
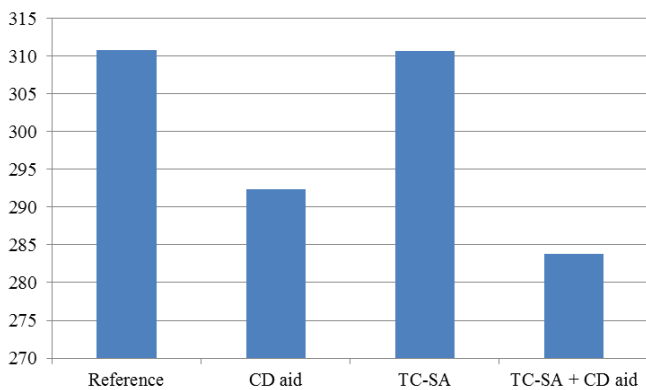

Figure 14. The average duration of eye fixations on conflict aircraft according to experimental condition

Analysis of attention repartition through the eye fixations highlights two principal results:

- First, it can be pointed out that the conflict aid services decreases the number of eye fixations allocated to the conflict aircraft.

- Secondly, it must be noticed that the CD aid service seems to reduce significantly the part of attention allocated to the conflict aircraft especially in terms of eye fications duration. Here, it has to be recalled that in these experiment conditions, an "Agenda" graphically presents the cluster of conflict aircraft and also a complementary representation of conflicts. Therefore, this part of interface may require as well a significant part of attention (longer eye fixations) dedicated to the "conflict detection and analysis". So, it can be deduced that the effect of CD aid service on attention repartition is in fact not fully confirmed.

In this study, the mental workload is evaluated trough the pupil diameter analysis. We remind that this choice is justified by the fact that pupil diameter is defined as a reflector of congitive activity and especially the peaks reached in the pupil diameter signal [16]. In order to include this characterisitc in our data analysis we chose to analyze the maximum of pupil diameter reached during eye fixations on conflict aircraft.

The maximum of pupil diameter analysis shows two principal results. The first result defined two experimental conditions as more costly for the participants because of higher value of pupil diameter : the reference and the CD aid conditions. TC-SA and TC-SA + CD aid conditions obtained a lower level of mental workload associated, and especially the TC-SA+CD aid condition.
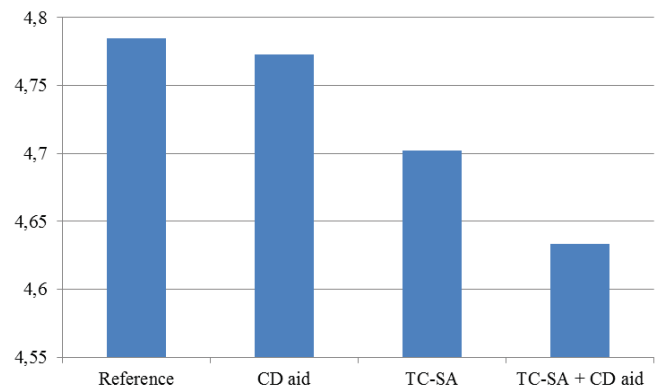

Figure 15. The average maximum value of pupil diameter during eye fixations according to experimental condition

To summarize, we can say that the mental workload analyze through eye characteristics (pupil diameter data) highlights a significant decrease of mental workload dedicated to conflicts with the use of the TC-SA service. Nevertheless, using only the CD aid does not seem to have an impact on controllers' mental workload in comparison with a non-automated situation (reference condition).

V. CONCLUSIONS

The study introduced in this article has permitted to evaluate the controllers' mental workload through several complementary approaches. In the assessment center is the mental workload evaluation reached through the pupil diameter analysis. Indeed, this method has made possible to quantify objectively the evolution of mental workload felt by controllers, depending on the level of automation integrated in an air traffic control situation.

This part of data analysis has shown that the integration of a conflict solver (the TC-SA service) permits to decrease significantly the level of mental workload felt by air traffic controllers. Moreover, it has shown that this decrease is more important when the solver is coupled to a "residual" conflicts detector (CD aid), system which does not have an impact on mental workload when it is used alone.

Supplemental analyses carried out during this experiment and which were focused on performance indicators analysis (communications) and subjective evaluation of mental workload seem to confirm the result of the objective evaluation. Indeed, these complementary analyses highlight that the TC-SA is a real help for air traffic controllers. Moreover, the CD aid service is also defined as a non-significant help when it is used as the only automaton, contrary to the situation where it is coupled to a conflict solver (the TC-SA service). Indeed, in this situation performance indicators and subjective assessment of mental workload show positive results in terms of impact generated on air traffic controllers' mental workload.

If we compare results achieved with the hypothesis, we can say that the principal hypothesis of the study, "mental workload felt by air traffic controllers during control task execution is lower when automated system(s) is/are integrated in ATC working position and that for an equivalent level of air traffic" is partially confirmed. Indeed, it has been shown that the introduction of TC-SA service or TC-SA + CD-aid generated a significant decrease of mental workload felt by air traffic controllers. The complementary hypothesis wondering about the consistence of results achieved through the performance, subjective and objective evaluations is fully confirmed. More than consistent, it has been observed that these several approaches were complementary to each other.

This experiment carried out within the context of the SESAR project has permitted to deduce several significant results concerning the introduction of a partial automated system, and on the impact that could be generated on the air traffic controllers' mental workload. Nevertheless, many issues are still open about the CD aid service. Even if it has not been defined as a significant help for controllers, we noticed during experiment that the availability of such a system (conflict detector) would be really useful for controllers and especially for the planner controller.

Therefore, one of the main perspectives of this project will consist in proposing a new version of the CD aid service that takes into account specific planner controllers' needs.

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