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TAPAS project: facilitating cooperation in hybrid combat air patrols including autonomous UCAV

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Abstract

This paper deals with a return of experience on TAPAS project. It aims at presenting the method and the tools developed for analyzing and assessing the different flight collaborative configurations by looking at their effects on pilots. The resulting classification of the different collaborative activities in terms of mental workload level is then used to design new mechanisms so as to ease and unlock some of these critical collaborations.
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Keywords: Human-human and human-machine cooperation; Task analysis; Physiological activity; Mental workload; Common ground

1. Introduction: industrial and scientific context

The current evolution of aircrafts towards unmanned solutions opens the way for thinking new configurations of collaboration in combat air patrols. The fighter squadrons could become hybrids, composed of more and more autonomous and adaptable drones and manned aircrafts. The new interactions and collaborations between fighter pilots, drone pilots and semi-automated Unmanned Combat Air Vehicle (UCAV) must therefore be completely designed to optimize the performance and the reliability of these systems of systems and to maintain the Common Ground (CG) between the different agents of the patrol (Klein, 2005).

In this outlook, the French National Research Agency-funded TAPAS project aims at developing a method and tools for analyzing and evaluating different configurations of Human-Human and Human-Machine collaboration according to their impacts on human operators (workload viewpoint). This project, involving Dassault Aviation and Lab-STICC research laboratory, starts from the study of the collaboration between two fighter pilots, and then looks for transposing the results of this analysis to help the design of the future hybrid squadrons including UCAV.

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The method presented in this paper identifies and classifies the collaborative tasks threatening the performance and the reliability of the current configuration of a combat air patrol (composed of two Rafales). This identification of "critical" collaborative tasks is performed with the study of the physiological activity of the patrol leader and the quality of intra-patrol communications, as explained in sections 2 and 3. The analysis of the "AS-IS" intra-patrol collaboration (*i.e.* the current configuration with manned vehicles) results then in pointing out key markers for assessing the online quality of the Common Ground and alerting to its potential degradation. These markers are i) the *a priori* critical nature of a collaborative task, combined with ii) the detection of a decrease of communication quality and iii) the detection of an increase of physiological activation. In those cases, a new role can be imagined to facilitate the combat air patrol collaboration (cf. section 4). An observer, external to the patrol, human or artificial, could monitor and regulate the communications, when a degradation of the CG is detected. These new facilitation mechanisms could be implemented to the"AS-IS" configuration (two Rafale pilots) or to a "TO-BE" configuration (i.e. a future configuration with both manned and unmanned vehicles, e.g. one fighter pilot collaborating with a drone operator, or even with an "autonomous" drone).

2. Method to analyse pilots collaborative activity

The TAPAS method is founded on a task and physiologically based activity analysis, and has been applied to the study of current squadron configuration. It is composed of two main steps, as depicted on Figure 1 and detailed in the following paragraphs.

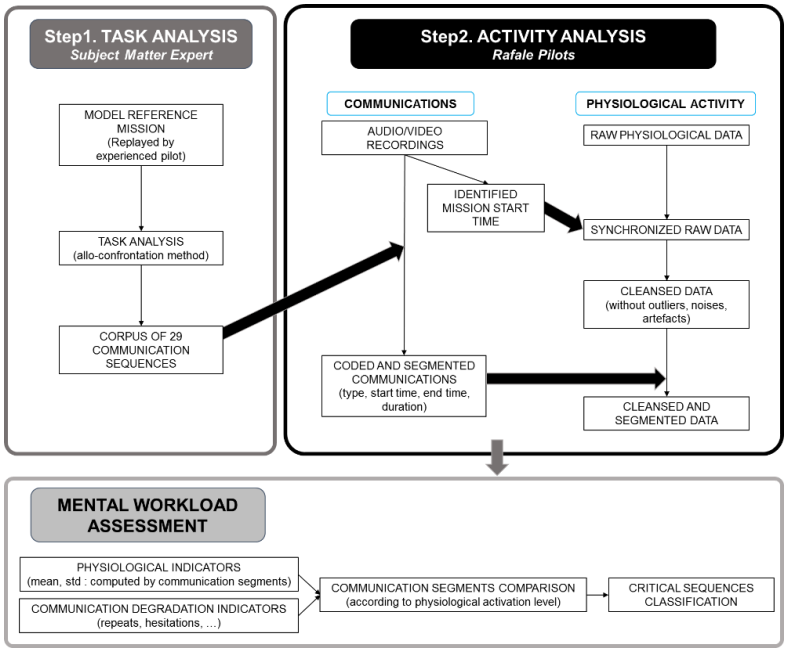

Figure 1: the two-steps TAPAS Methodology

2.1. *First step: collaborative tasks identification*

The first step (Guerin *et al*., 2014) has consisted of distinguishing and determining a typology of different collaborative tasks or situations along a mission, based on the communications between two or more agents: two Rafale pilots (patrol leader and wingman) and controllers. These communications were extracted from the intra-patrol radio conversations of an air-to-air mission run by experienced pilots at the simulation center. A communication is defined by at least two sentences transmitted through the radio frequency system aiming at one or more temporary

mission/safety goals. This exchange of information, order or clearance (in addition to other devices and networks) allows the different agents to collaborate.

The task analysis, using allo-confrontation method (Mollo & Falzon, 2004), had been led with the help of Subject Matter Expert (Lt.-Col., French Air Force attached to Dassault Aviation). As a result, twenty-nine typical collaborative mission tasks or situations have been distinguished. Collaborative tasks were identified in terms of significant communication sequences: target assignment, self-protection, take-off, *etc*. For example, before the patrol crosses the enemy line, the leader will order on the radio frequency to configure the aircraft in combat mode. During landing, several communications can appear between the tower and the patrol depending on the type of approach or the weather.

2.2. Second step: study of the effect of collaborative tasks with pilots' physiological patterns

The second step (Lassalle *et al*., 2014) aims at determining if some of these typical collaborative situations threaten the performance and the reliability of the system of systems, here composed of two Rafales and their pilots. The previous identified collaborative tasks were assessed and classified according to their effects on the physiological activity patterns of the pilots during the different flight phases (*i.e*. the collaborative tasks increasing mental workload could be considered as critical for the success of the mission). This step is supported by the implementation of an experimental setup dedicated to the on-line recording of pilot physiological activity and communications within a highly realistic and very constrained simulation environment.

Indeed many studies pointed out the relevance of physiological measurements to monitor pilot activity and interpret them as mental workload (Karavidas et al., 2010; Lehrer et al., 2010; Veltman & Gaillard, 1998; Veltman, 2002; Wilson, 2002a; Yao et al., 2008; Ylonen et al., 1997) The study of the increase of respiratory rate (RR) and heart rate (HR) or the decrease of heart rate variability (HRV) is used to detect an increase of the pilot's mental workload (Casali & Wierwille, 1984; Hankins & Wilson, 1998; Karavidas et al., 2010; Lehrer et al., 2010; Veltman, 2002; Wilson, 2002; Wilson et al., 1994). However, very few works, studying simulated or actual flight, report skin conductance (SC) or pupil diameter (PD) measurements although they are widely used to study individual mental workload. This lack is often explained by strong operational constraints, and integrating devices to measure these signals in a highly realistic flight simulation is currently a real challenge.

Nevertheless, it would be very useful to monitor these signals and integrate adapted sensors in the experimental setup to obtain the most accurate picture of pilot activity during flight. The following section presents how these sensors could be integrated in an experimental apparatus. It also explains how the resulting signals could be used to study pilots 'collaborative activities and to identify critical collaborative tasks.

3. Analysis of the effects of collaborative tasks on the mental effort of leader pilot

3.1. Experimental context

Subjects and simulator:

Experiments were conducted during tactical flight training of five male French Navy fighter pilots, ages 29-32, who pass a section lead test. The total piloting experience of participants ranged from 700 and 1100 h with an average of 870 h and between 150 and 500 h with a mean of 338 h regarding Rafale flight hours. Experiments were performed on a tactical Rafale simulator located at the Rafale Simulation Center at Landivisiau Navy Air Base, France. The cockpit simulator was identical both in appearance and functions to a real Rafale aircraft (real flight instruments and G-seat). Eight retro-projected facets arranged in a pseudo-sphere provide a high visual definition. During simulation, the cockpit was placed in the pseudo-sphere allowing a large field vision. The leader pilot communicates during the session with his wingman (installed in the same simulator, in a side room) and controller (instructor's room). These communications were specifically studied to segment the pilot activity according the typology of collaborative tasks (cf. section 2.1).

Apparatus:

Pilot activity was studied using a set of physiological signals continuously recorded along the training session, as shown on Figure 2. Heart rate (HR), breathing rate (BR), skin conductance (SC) and pupil diameter (PD) were

collected, with the respective sampling frequencies: 250 Hz, 25 Hz, 32 Hz for SC and 60 Hz. The cardiac and respiratory activities were measured from a BioHarness3™ belt worn directly on the skin around the rib cage just below the chest. The belt integrates a set of sensors for measuring heart rate (electrocardiogram) and respiratory (pressure sensors that detect the expansion of the chest related to respiratory activity). To fit with experimental field constraints, the SC measurement was achieved by using the Q-Sensor tool (V2) from Affectiva™. The measurement was performed by applying two Ag/AgCl electrodes on the wrist (internal distal face) held by a strap (wristband). All sensors (belt and wristband) were installed on pilots prior to the simulated training mission, and all the data were locally recorded on computer or on sensors (without wireless transmission).

Audio recording (microphone fixed on the pilot's flight suit) and video recording (webcam attached to each side of the cockpit seat) were also collated throughout the training session. These data were required for the subsequent synchronization of physiological and eye data with the flight session timeline. Synchronization is obtained by deleting all the sensor data before the start time of a training mission.

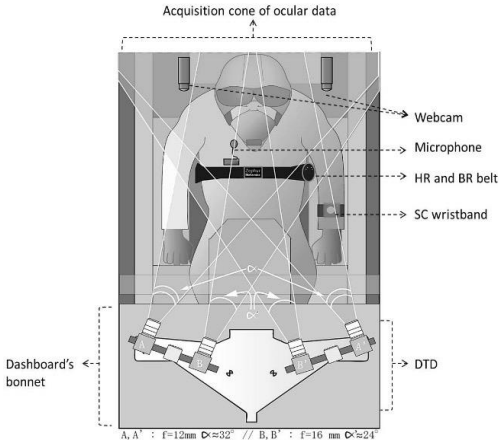

Figure 2. Experimental setup for measuring pilot's physiological activity during flight

The main innovation of the proposed experimental protocol is based on the sensors measuring pupil diameter, which aim at reducing the number of sensors affixed to the same subject and device intrusiveness. One of the main difficulties was to obtain and guarantee a maximal coverage area over the flight to ensure tracking maintenance despite the pilot's head movements. For this, a Double-Tracking Device (DTD) was elaborated. The DTD consisted in the association of two faceLab™ eye trackers (two optical pairs) mounted on a specific support to be easily attached or removed, directly behind the head-up display inside the cockpit (see fig.3). The device (support and DTD) was thought to integrate a simulation environment without causing any inconvenience for the pilot. Furthermore this configuration was supported by the software FaceLab™ Link that generates a virtual tracking device from the two physical eye trackers by merging their data.

3.2. A first resulting sequences differentiation based on pupil diameter variations

It is important to note that pilots' activity was observed in a highly realistic simulation environment throughout pilot training session in order to achieve a section lead test. Missions were chosen but detailed scenarios were not predefined, so experimental conditions were not set up by the experimenters.

Signal processing and data reduction:

First pre-tests were conducted on the five pilots, on heterogeneous missions (e.g. navigation, night flight, or fighting mission), so as to assess the quality of the recorded signals and the robustness of the proposed experimental apparatus (cf. Lassalle *et al*., 2014). A good quality of data acquisition was observed, except for skin conductance sensors, which was too sensitive to hand moves. Then specific missions were chosen, with homogeneous missions, involving several

air-to-air or air-to-ground fight phases. Finally, the deployment of the proposed method has resulted in the data collection of eight missions achieved by two different pilots.

Each of the eight missions has generated data from the experimental apparatus (physiological, ocular and audio/video data), but also communications from the simulator recorder (used to replay, analyze and debrief training sessions). The data from simulator recorder were transcribed and coded with the typology of collaborative tasks (corpus of 29 communication sequences). Communication quality was also coded, by counting the different "errors" occurring in the very standardized exchanges between the two pilots. This work, achieved in circa 100 hours, resulted in about 2000 communication segments for the height missions, with start and end times and communication quality. This coding has therefore used to synchronize the different physiological and ocular data with communications. The physiological and ocular data were also processed so as to remove outliers (cf. Lassalle et al., 2014, Storm et al., 2000, Sami et al., 2004) and signal noise. For instance, pupillary diameter signal was cleansed of all light reflexes by using the routine proposed by Marshall (2002), so as to keep only the cognitive dimension of pupillary response. Temporal means were then calculated for each segment of communication sequences (*i.e.* for each of the 2000 communication segments). Means were calculated considering a time window including five seconds before and after segments, because the communication sequences are only markers of collaborative activities and can occur just after the beginning of the collaborative tasks, and because there can be residual effects on measures. A last step has consisted in converting data to z-scores to reduce inter-individual variability.

To illustrate the proposed method, results on Pupil Diameter (PD) are given in this paper. These ocular data, as well as physiological data and communication quality indicators, were segmented and processed with the aid of online communications exchanged over flight activity, coded according to typical communication sequences. Analyzed data set contains a total of 1991 communication segments grouped into twenty-one different communication sequences (based on the previously defined corpus of sequences).

Statistical treatments:

A Kolmogorov–Smirnov test showed that pupil diameter data fits the Gaussian distribution ($p>0.2$), thus parametrical statistical tests can be applied. A repeated measure of ANalysis Of VAriance (ANOVA) was performed with 95%-confidence intervals. The study of the influence of pilot activity, in terms of communication sequences, on pupil diameter changes is carried out using this analysis. Only the main results will be presented in the following section.

Results:

Figure 3 shows PD mean, and associated 95%- confidence intervals, for each communication sequences. ANOVA was conducted on individual PD measures considering the fixed factor « Communication Sequence » and a random factor « Pilot ». It reveals a significant effect of « Communication Sequence » factor on pupil diameter ($F(20, 1949)=3.52$, $p<0.01$).

A Duncan post-hoc test mainly indicated a significant difference between the communication sequences "Handover", "Join Up" and "Radio frequency change" and the sequences "SA acq." (Situation of awareness acquisition), "Targetting", "Threat", "Commit", "Interception", "Engagement", "Self-protection" (with $p <0.05$). A decrease of pupil diameter can be observed for the former group compared to the latter. The Duncan post-hoc test also revealed a significant difference between "Landing" sequence and all other communication sequences ($p <0.05$) except four of them ("Fence-in", "Handover", "Join up" and "Radio frequency change"). The size of the pupil diameter was significantly smaller in landing than in other sequences.

As expected, results showed that pupil diameter tends to increase during the communication sequences related to tactical phases (interception, engagement, self-protection, *etc.*) compared to more routine communication sequences such as handover, radio frequency change, *etc*. This could mean an increase in mental workload over tactical phases. On the whole, results have brought critical communication sequences to light from physiological point of view. As a consequence, proposed method can be used for classifying communication sequences and detecting, in *a posteriori* or real time way, high mental workload collaborative sequences. These sequences can potentially be detrimental to the mission achievement and should therefore require more vigilance.

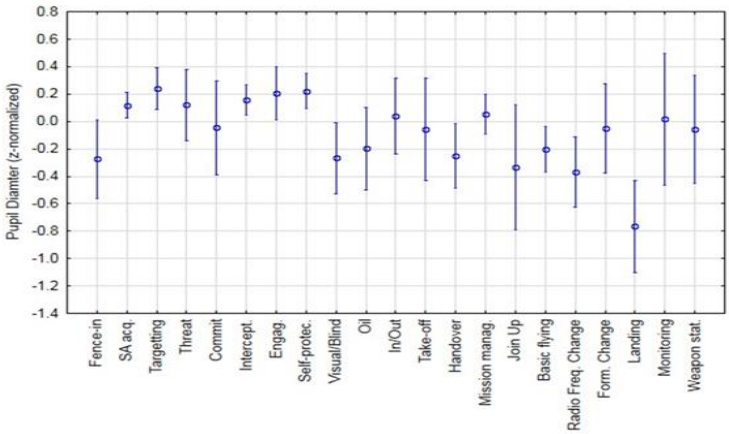

Figure 3. Effect of pilot activity (according to communication sequences) on Pupil Diameter.

4. Towards the facilitation of collaborative tasks

4.1. The importance of dialog management in teams

The importance of dialog management and collaborative communications has been proved many times to be of higher importance in human cooperative critical system. Elaborating and maintaining a common ground (CG) between the members of a group represents an important part of their cooperative activities (Hoc, 2000). A bad elaboration of a CG and/or its degradation may lead to coordination surprises (Klein *et al*., 2005). These reactions of surprise mean ruptures in the coordination amongst team members. Ruptures are defined as differences between the expectations of an agent about the behavior of another agent and the actual behavior of the later agent or of the controlled process elaborated by this second agent (Patterson et al., 1998). These coordination problems usually do not severely spoil the process but provoke a certain level of inefficiency. However, the degradations and ruptures of CG that lead to coordination surprises may, in some cases, cause severe consequences, especially when considering critical contexts such as squadrons of fighters jets or UCAV.

Former studies (Chauvin *et al*. 2010) proposed to describe team cooperative communication along several parameters, such as the nature of the communication activity (elaboration or maintenance of CG for instance), the nature of the exchange (question or answer) and the characteristics of the « loops » within the exchange (a loop corresponding to the acknowledge of understanding of one actor of the dialog, so that the common ground should have been upgraded or more generally maintained). The existence and the time duration of loops have been proved to reflect the coherence and consistency of the team (Chauvin *et al*. 2010) in its collaborative activities.

The same approach could underlie the present work, where two pilots should be perfectly synchronized, especially when handling dialogs related to critical tasks. The identification of a priori critical sequences (potentially related to a degradation of CG) as well as the detection of singular physiological patterns with the apparatus described in section 3 could be completed by a deeper analysis of online communication sequences. This complementary analysis would be based on the detection of errors in communication protocols that shows that the Common Ground becomes deficient, due to situation mis-definition, mental workload and stress pressure.

4.2. Managing a dialog with an autonomous system

When the communication has to be set between a human operator (or pilot) and an autonomous system, there is no easy way - in the current state of progress about dialog manager - to properly address the synchronization and adaptation of information exchanges that two human operators can achieve naturally in unpredictable and critical contexts.

Where some corrections, complements of information or expressions of intent can be exchanged between two pilots, especially when one or two of them detect inconsistencies due to a degradation in their common ground, there needs to be an external assistant and dialog manager that will be devoted to the checking of communication protocol and that will help in maintaining a correct level of shared knowledge between the two actors.

We propose to design a first prototype of assistance based on the insertion of a new human operator, acting as the communication regulator and facilitator. The role of such an operator is to decide about catching up communication failures or biases through requests for repeating, explaining or making accurate some information that were detected as missing or out of the cooperation communication protocol (cf. figure 4).

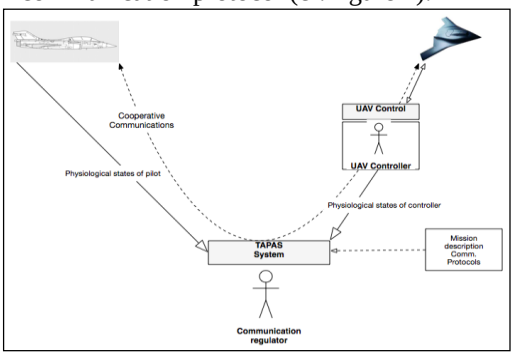

Figure 4. A prototype for regulating and facilitating communications

This operator should be provided with:

- the mission schedule and current positions, marked with the a priori critical collaborative sequences (identified with the aid of the methods described in sections 2 and 3, and depicted by black ovals in figure 5),
- the real-time physiological status of the two pilots involved (when the communication concerns an usual combination of two fighters) or of the pilot and the UAV operator (when the communication concerns an hybrid configuration) acquired with the same instrumentation than proposed in section 3 (monitoring alerting principles are shown on figure 5),
- the cooperative communication protocols and patterns, that could be analysed online in terms of question/answer communications or opened/closed loops as proposed by Chauvin *et al.* (2010), and in terms of degradation with the communication quality indicators mentioned in section 3 (number of errors occurring in the very standardized exchanges between the two pilots)

From these information, the operator is expected to have an adequate understanding of communication status, failure, biases, and to be able to proceed with recovery actions when necessary to maintain the CG.

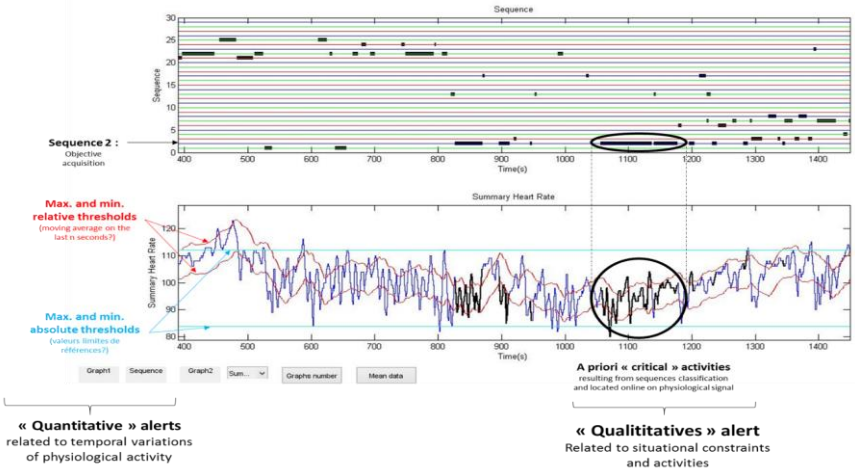

Figure 6. Online monitoring of mission sequences, physiological status and communication patterns

5. Conclusion

This presented work proposes a method to analyse collaborative tasks and to identify the critical ones with the aid of physiological monitoring and communication analysis. The first outputs of this method seems promising: tactical flow sequences (where pilots are involved in fighting) are considered more critical than routine sequences (when pilots change radio frequency for example) for indicators based on pupillary response. The analysis of other indicators is still ongoing.

Moreover, this proposition opens new perspectives, by using this identified critical tasks and some physiological and communication-based markers, to externally monitor online and to improve the collaborative activity of different agents (pilots, drone operators, autonomous UCAV). A new role of facilitator was introduced, and a prototype is currently developed so as to study the future interactions between this facilitator and the different supervised agents.

6. Acknowledgements

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