Toward the definition of a pilot's physiological state vector through oculometry: a preliminary study in real flight conditions

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ABSTRACT
As long as the pilot is a key agent in charge of the flight, the definition of metrics able to predict his performance is a great challenge. Currently, online assessment of the aircrew performance relies on the aircraft state vector analysis. More recent approaches propose to refine this performance measurement by taking into account the pilots-aircraft interactions state vector (e.g. the pilot's actions on his user interface) or the pilot's physiological state vector. In this latter perspective, this preliminary study proposes to assess the benefits of using a standalone eye tracker in a light aircraft in real conditions. In spite of a sensitivity to light conditions and a definition of areas of interest limited to a part of the cockpit, the eye tracker has provided interesting behavioural (fixations) and physiological (pupillometry) measures in nominal (from take-off to landing) and degraded (provoke a simulated engine failure and plane down toward the airfield) conditions. The pilots spent less time glancing at the instruments, and focused less on instruments in the degraded condition. Moreover, the pupil size varied with the flight phases in the degraded condition, which reflected the variations of stress and attention levels. These encouraging results open promising perspective to online assess pilot performance through physiological vector.

Keywords
Eye tracker, pupillometry, psychological stress, pilot activity

INTRODUCTION
Flying aircraft presupposes intact cognitive and emotional capabilities for controlling the flight and anticipating correctly the evolutions of the environment (weather situation, traffic…) The cognitive capabilities support the rational process from the sensorial cues regarding the task. This process is based on the activation of a neural network, including in particular dorsolateral prefrontal cortex, that sustains executive functions like planning, working memory, focusing, shifting, inhibition [1]. This cognitive system interacts with the emotional system – also known as the limbic system – that plays a major role in decision making process, motivation, environmental evaluation, and in "flee or fight" ancestral reactions. These two systems maintain complex inhibition/activation relations and optimize human performance, provide accurate social reactions, and ensure survival. The disruption of the homeostasis [2][3] of these two systems may lead to inadequate cognitive [4], emotional and social responses such as the perseveration syndrome [5].

Therefore, a challenge of great importance is to define tools and metrics in order to assess and predict the pilot's performance. Classically, the pilot's performance is measured through the aircraft state vector analysis (e.g. an excursion out of the flight envelope may reveal a weak pilot's performance). A more refined approach focuses on behavioral data measured from the pilot/aircraft interactions (e.g. aircrew reactions time to alarm…) In particular, formal methods are developed to detect human errors thanks to aircraft/pilot behavior monitoring [6][7]. However, these methods which rely on the detection of the pilot's errors may intervene too late for coping with the situation degradation. Thus, a more predictive metrics is to assess the occurrences of conflicts in the flight management known as remarkable precursors of the pilot's situation awareness [5]: an approach based on particle Petri nets [8] is proposed to anticipate such pilot-systems conflicts [9] and to provide on line assistance.

Eventually, a last metrics based on the pilot's physiological states has to be considered: such data collected from the pilot's autonomous nervous system (ANS) give clues both on the cognitive activity and on emotional states and stress [10] [11]. Arousal, vigilance, emotional states, attentional demand can be derived from heart rate and blood pressure, theta and alpha brain waves, temperature variations, respiration, skin conductance and oculometry [12] [13].

All ANS devices though present practical drawbacks. They are sensitive to the operator's physical state (e.g. sweating perturbs skin conductance, fever changes temperature and heart responses ...) or to the environment (e.g. magnetic and electric fields may create artefacts on electroencephalograph responses), and they are too cumbrous to be easily adapted to a cockpit. For example, oculometry suffers the following limitations:

- As eye fixations "fill up" the total time, not all fixations are relevant to assess the pilot's visual demand. Moreover, a fixation does not necessarily imply perception [14];
- As the pupil diameter varies in function of light intensity to maximise visual capacity, pupillometry cannot be used to assess the level of stress of the pilot under changing light environments ;
- Electro-oculograms and most eye trackers are cumbersome devices and may disrupt pilots' activity since pilots have to wear an electrode close to the eye or special equipment like helmets.

These considerations tend to restrict the utilisation of ANS devices to controlled studies in laboratory (i.e. flight simulator) [15] [16], although they have already been used in real flight conditions [17]. Eye tracking offers a fruitful perspective since visual perception is a key for pilot to control the flight and oculometry may provide both behavioural and cognitive/emotional physiological measures [11] to assess the pilot's performance:

- The visual-search strategy, or the selective attention to relevant visual stimuli is an index of information needs [18];
- The eye-scanning patterns of pilots in terms of frequency of fixations seem to be related to the instruments' importance. The length of fixations, however, is related to the difficulty in obtaining/interpreting information from instruments [19];
- An increase in workload is accompanied by increased fixation times [20] [21];
- The decrease of the duration and the number of eye blinks are strongly correlated to visual demand [22] [13];
- Low frequency "pupillary oscillations" are linked to fatigue [23];
- The pupillary response is related to mental workload [24] [25] [26];
- In many cognitive processes such as language processing, perception, memory, complex reasoning and attention, the pupil diameter grows with the difficulty of the task [27] [28];
- Pupillary responses also provide clues on the emotional state [29] [4] and pupil size may vary on a continuum according to emotional valence [30] or reflect the emotional activation or arousal [31].

Our long-term goal is to develop an onboard system able to predict the pilot's performance through the analysis of the aircraft state vector, the pilot-aircraft interactions state vector and the pilot's physiological state vector. However, the integration of this latter state vector implies to assess the feasibility and the acceptability of a non intrusive physiological device. Thus, this preliminary study proposes to assess the usability of an on-board eye tracker in real flights and aims at assessing the benefits of this tool for human factor concerns.

METHOD

Participants

A permit to fly was given by the European Aviation Safety Agency (number 856/2007 – EASA PTF.A07.0232) to conduct the experimentation with the restriction that ISAE flight instructors only were authorised to fly the airplane with the on-board eye tracker. Six ISAE flight instructors, all males, could participate to the experiment. Their mean age was 43 years (range, 35-58). Their mean flying experience was 5896 hours (range, 1480-13000). The six participants were qualified to fly the Aquila AT01 aircraft (two-seated light airplane, 100 horsepower).

Scenario

The flight scenario starts at nightfall at Lasbordes airfield and ends before the beginning of the aeronautical night[1]. It is divided into two consecutive sequences (cf. fig 1):

- The first sequence consists in a classical visual traffic pattern : take off (1) – cross wind leg (2) – down wind leg (3) - base leg (4) – last turn (5) – final leg (6) - touch and go (7) . This sequence is the nominal condition;
- The second sequences starts after the previous touch and go (7) and consists in flying back toward Lasbordes airfield at an altitude of 2500 feet. Once over the airfield, the pilot had to chop the throttle so as to perform an engine failure exercise (8) and then to plane down toward the airfield (9-12). This sequence is the degraded condition.

This scenario is presented to the pilot one hour before the beginning of the experimentation. During the briefing, it is clearly exposed to each pilot that he decides the moment of the

1 The aeronautical night begins in France thirty minutes after sunset.

engine failure exercise and that he may use the throttle at any moment if flight safety is altered.

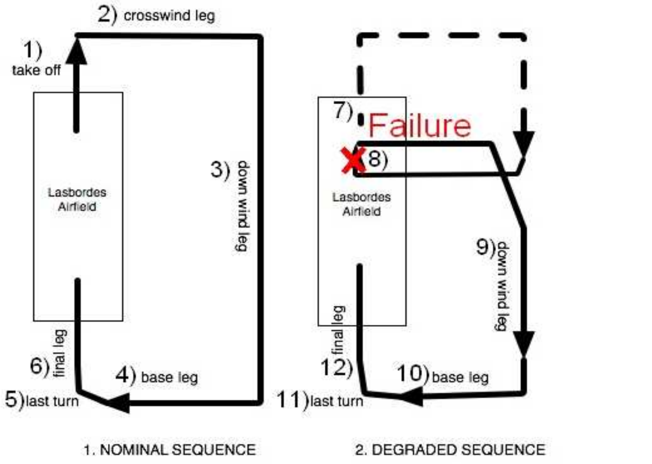

Figure 1: The two flight sequences: the nominal and the degraded one. The nominal sequence ends after the landing (6), the degraded sequence starts just after, with the take off (7)

Oculometry

A non intrusive eye tracker Tobii x50 was used for the purpose of the experimentation. This device has 0.5 degree of accuracy and a 50 HZ sampling rates. It also provides instant re-acquisition after extreme head motion. It had to be adapted to be easily set in the Aquila aircraft without any modification of the airplane and without provoking any disturbance for the pilot (e.g. no visual scanning disturbance).

The eye tracker was placed below the left part of the instrument panel in front of the pilot's seat (cf. Fig 2). A scene camera was centrally placed under the fix part of the canopy. Data synchronization and processing was done via an analog/numerical video converter, a Tobii external card and a Sony Vaio laptop. These three light devices were situated in the luggage compartment.

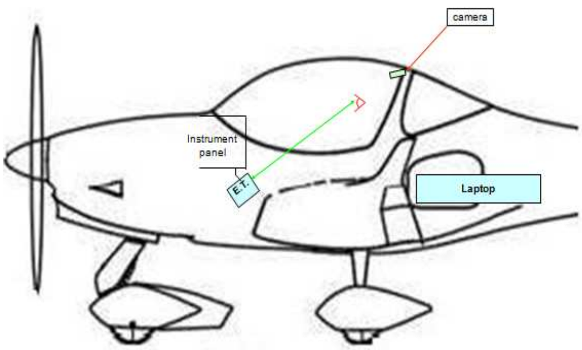

Figure 2: The eye tracker (ET) was fixed under the instrument panel and the data processing system was placed in the luggage compartment. This latter processed and surimposed in real time both the eye tracker data and the video data coming from the scene camera.

The technical characteristics of the x50 eye tracker and its particular location allowed to track the pilot's eye gaze on the left part of the instrument panel where are the primary flight beacons (i.e. airspeed, altimeter, horizon…) As shown in the figure 3 and 4, it is not possible to determine the pilot's eye gaze out of this area (i.e. the eye gaze out of the cockpit, the eye gaze on the beacons situated on the right part).

Figure 3: The blue dot represents the gaze fixation. Note that the pilot is focusing on the airspeed instrument to check the rotation speed (Vr), just before taking-off

Area of interests

A dedicated analysis software provides in real time data such as the timestamps, the (x,y) coordinates of the pilot's eye gaze on the left instrument panel and the pupil diameter. Moreover it is possible to determine the number and the duration of fixations in specific "areas of interests". In this sense and in order to study the pilot's ocular behaviour, fourteen areas of interest corresponding to the fourteen beacons of the left instrument panels have been respectively defined: (1) outside temperature, (2) compass, (3) manifold pressure, (4) alarm, (5) airspeed, (6) horizon, (7) altimeter, (8) tachymeter, (9) bank and turn indicator, (10) directional gyroscope, (11) vertical speed, (12) VOR, (13) switches (14) flaps (cf. fig 4).

Figure 4: The fourteen rectangles define the different area of interests.

Pupil diameter variations

As the eye gaze, the pupil size is recorded continuously. In practice, establishing mean physiological values for a group of subjects for an entire task is meaningless because of inter-individual variability. We use delta values (differences between the mean pupil diameter during the concerned flight sequence and the one calculated on the whole experiment) for measuring the pupil variations.

Luminosity measurements were performed. Indeed the pupil regulates the amount of light that enters the eye, and thus, its size variations are highly sensitive to the luminosity changes. Thanks to a lux-meter the ambient luminosity was continuously recorded in order to identify the flight sequences where the light remains reasonably constant. In accordance with Gupta's work [32] on pupil size variations in function of the ambient luminosity, we have limited the pupil variations analysis to sequences where the visible light was inferior to 25 luxAll material on each page should fit within a rectangle of 18 x 24 cm (7 x 9.44 in.) centered on an A4 page, beginning 1.5 cm (.39 in.) from the top of the page, with a 1 cm (.39 in.) space between two 8.5 cm (3.4 in.) columns. Right margins should be justified, not ragged.

RESULTS

The data were filtered to eliminate artifacts. The baseline was defined with a sample of 10 seconds before the beginning of the flight. The delta values were obtained thanks to the difference between measured and baseline data. As the sample size was small and the data did not follow normal distributions, nonparametric statistical methods for dependent sample were used. Overall analyses were performed with the Friedman Anova. Wilcoxon signed rank test was used for paired-samples tests. The analyses were performed with Statistica 7.1 (© StatSoft).

Behavioural results

The figure 5 shows the percentage of time spent on the various instruments regarding to the total time for the six pilots. The take off (including the initial climb) and the down wind leg are the flight phases with the greater percentage of time fixations on the instruments; in third position comes the final leg.

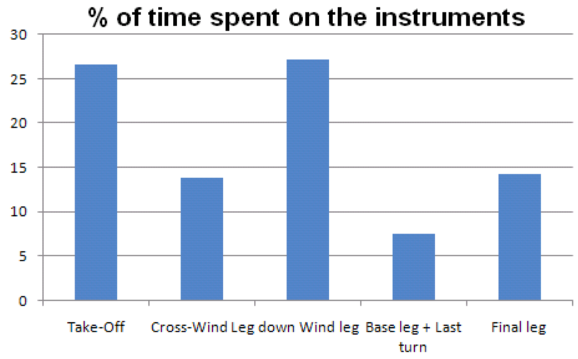

Figure 5: Percentage of time spent on the various instruments regarding to the total time acorrding to six flight phases for the 6 pilots: (1) – Take off + initial climb (2) – Cross-Wind leg (3) – Down-wind leg (4) – Base leg + Last turn (5) – Final leg.

In the same manner, the figure 11 shows, for one subject, the fixation times, (in milliseconds), spent on his instruments during six defined flight phases of a nominal flight.

The different fixation times, expressed in percentage of the total time spent on the 14 defined instruments during the nominal landing sequence vs. the landing sequence with the simulated failure (the degraded landing sequence), are presented in figures 6 and 7.

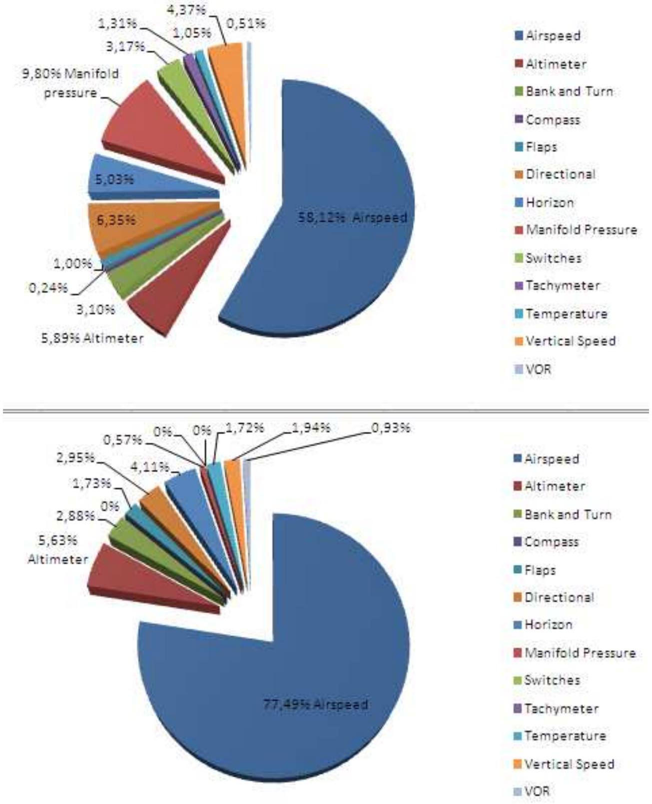

Figure 6: Mean fixation durations in percentages on the areas of interest of the six pilots during the nominal and the degraded landing, from base leg until the flare

The results showed a reduction of the number of instruments gazed during the degraded sequence in comparison to the nominal one. During the nominal sequence, all the instruments were looked (except for the alarm panel) whereas only 10 instruments were looked during the degraded sequence. More precisely, compass, switches and tachymeter weren't gazed. Moreover, there was an increase of the relative fixation time on the airspeed during the degraded sequence regarding to the nominal (77.49% vs. 58.12%).

Finally, the time spent on instruments appeared to be lower during the degraded sequence (cf. Fig 8), showing that pilots focused more on external information.

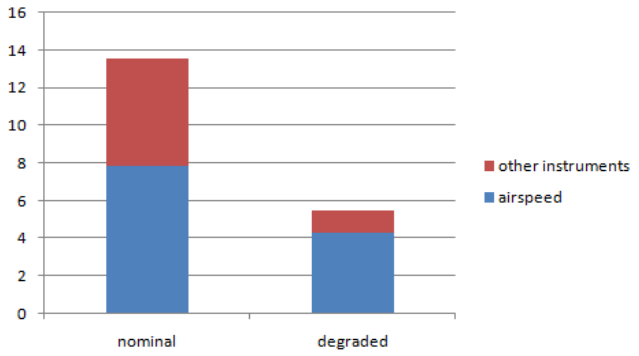

Figure 7: Mean fixation time on the airspeed instrument and all other instruments during the nominal landing and the degraded landing (time in sec)

Below is presented the official “cruise checklist” [33] of the Aquila AT01 (table 1) and the fixation times in percentages (fig. 9) obtained during the cruise check list (generally performed at an altitude of 2000 feet).

TABLE 1: AQUILA ATO1 OFFICIAL “CRUISE CHECKLIST” [33]

Trim	set
Chronometer	Top and estimated
Altimeter	set
Directional	Checked
GPS	Use & Stby state
Engine instruments	Checked
Manifold pressure	25 inches
Tachymeter	2000 RPM

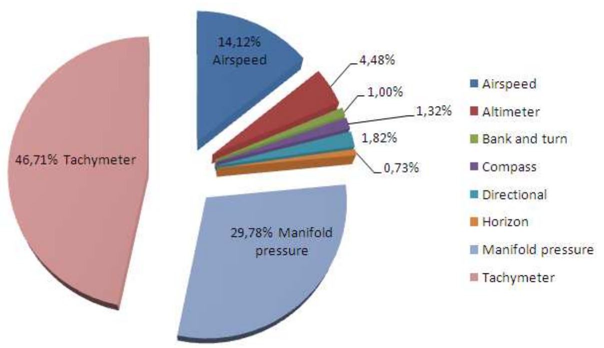

Figure 8: Mean fixation times in percentages on the 14 zones of interest during the “cruise checklist”. Note that “airspeed” stands for “airspeed indicator”, “directional” stands for directional gyroscope, “horizon” stands for gyro horizon and “bank and turn” stands for “bank and turn indicator” (mean total duration = 7.27 sec)

The analysis shows that the tachymeter is the most looked instrument (46.71%), and then comes the manifold pressure (29.78%) and the airspeed (14.12%).

Pupillary response

In spite of the fact that all the experiments were conducted at nightfall, the luminosity variation did not allow to analyze pupil diameter variations during all the sequences (cf. table 2).

Considering this pitfall, only the degraded sequences of four pilots (pilot ID: 1 to 4) were included in the pupil diameter variation analysis. Indeed, mean luminosity variations during the considered sequences were only of 5.75 lux for the four pilots.

TABLE 2: LUMINOSITY MEASUREMENTS FOR EACH PILOT AT THE BEGINNING AND THE END OF THE TWO FLIGHT SEQUENCES (E.G. PILOT ID 1 STARTED THE FIRST FLIGHT SEQUENCE WITH 127 LUX AND ENDED IT WITH 40 LUX ; HE THEN STARTED THE SECOND SEQUENCE WITH 20 LUX AND ENDED IT WITH 7 LUX)

	Luminosity variations (in lux)	
Pilot ID	first sequence	second sequence
Subject 1	**127-40**	**20-7**
Subject 2	**82-36**	**8-4**
Subject 3	**90-35**	**10-6**
Subject 4	**93-33**	**10-12**
Subject 5	**473-230**	**220-91**
Subject 6	**610-600**	**520-380**

The Friedman’s ANOVA showed a strong significant difference (p=0.001) concerning the delta pupillary diameter among the four flight phases (fig. 10). However, Wilcoxon post hoc paired-samples analysis didn’t show any difference.

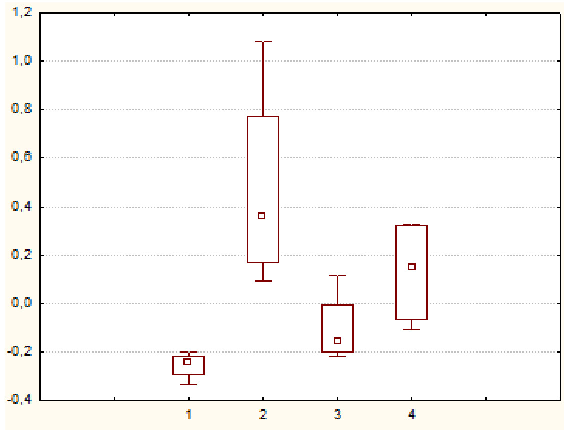

Figure 10: Pupillary diameter changes (in mm) regarding the four flight phases during the second flight sequences, respectively one minute before the failure (1), the failure and the crosswind (2), the base leg (3), from the last turn to the final touch (4)

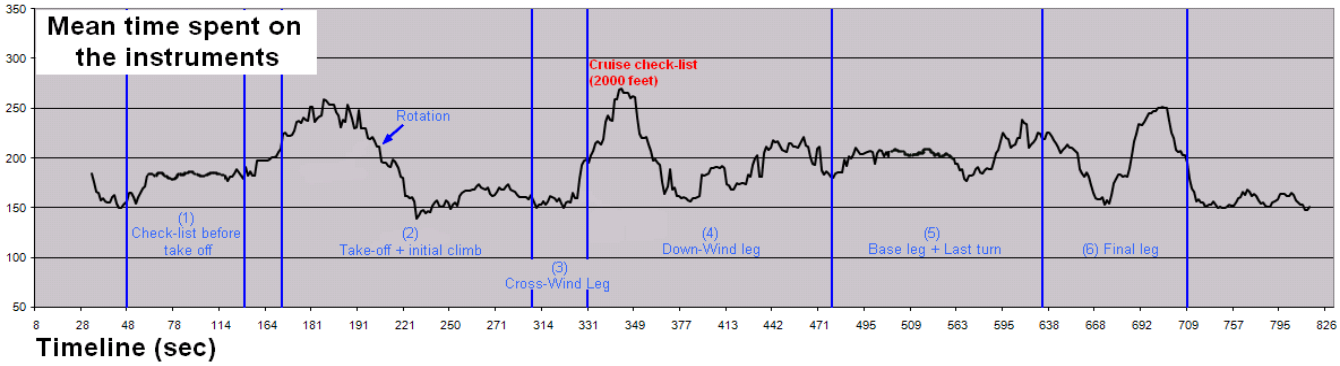

Figure 11: Example of mean time spent on the various instruments according to six flight phases for one subject: (1) – Check-list before take-off (2) – Take off + initial climb (3) – Cross-Wind leg (4) – Down-wind leg (5) – Base leg + Last turn (6) – Final leg. A cross indicates the rotation time, the 2000' check-list is also mentioned.

DISCUSSION

The introduction of a new onboard device for human factors purposes must fulfill three requirements: 1) the device does not disturb the pilot's activity, 2) the device is able to work correctly in real flight conditions, 3) the device improves significantly the human-machine interface, and therefore the flight safety. This preliminary work gives some clues about the capabilities of an eye tracker as a device onboard a small aircraft. The observation of the six pilots showed that no perturbation was generated by the eye tracker that remained totally unnoticed after the preliminary set up phase. However, this must be confirmed on non expert pilots and on other types of aircrafts.

Concerning the usability of the eye tracker in real flight conditions, the results are more equivocal. Because of light issues, we weren't able to compare pupil dilation during the nominal sequence vs. the degraded one in all pilots. Moreover, AOIs can be only defined at places that are constrained by the eye tracker's location in the plane. This can be overcome by helmet eye trackers, however with an intrusiveness of the device in the pilots' activity. Technological progress must thus be accomplished to allow the generalisation of onboard eye tracking experiments.

In spite of these drawbacks, the preliminary results highlight the possibility of deriving interesting measures of the pilot's activity from eye tracker data.

Firstly the analysis of the time fixation during the nominal flight offers interesting assessment of the visuo-attentional demand in function of the flight phases (fig. 5). For instance the take-off *per se* is characterized by an intense visual demand, as a critical decision to abort the take off could be taken, through the aircraft parameters, before the rotation speed (fig. 11). The other noticeable increase also observed corresponds to the down wind leg where a precise check-list has to be performed (c.f. next section). Finally, the final leg requires an important monitoring of the airspeed that explained the observed raised of fixation time.

Analysis of the areas of interest captured by the eye tracker is a way to assess its accuracy in real conditions. In particular, analysis of critical events such as the in-flight checklist sequences is a key to evaluate the reliability of this tool:

- The visual scanning is codified by an official procedure in the flight manual than can be used as a model of reference;
- These sequences are very short (less than ten seconds) and flight parameters to be checked by the pilot are vital.

Such constraints lead the pilots to relevant eye fixations during these periods and allow assuming that the areas of interest observed are also a priori the result of a real voluntary attentional activity.

In this perspective, the analysis of the areas of interest during the "cruise checklist" (cf. Fig 5) shows that the visual scanning of the six pilots is limited to eight flight instruments. More precisely the pilots have focused on the tachymeter, the manifold pressure, the airspeed indicator, the altimeter, the directional gyroscope, the compass, the bank and turn indicator and the gyro horizon. These areas of interest are consistent with the ones defined in the official Aquila "cruise checklist": the tachymeter and the manifold pressure have to be set to particular values and the results of these adjustments have to be implicitly checked on the airspeed indicator, the altimeter has to be checked as the "cruise checklist" starts at an altitude of 2000 feet, and the value of the directional gyroscope has to be checked, which is done thanks to a quick comparison with the value of the compass.

Though it is not explicitly expressed in this checklist, it is totally consistent that flight indicators such as gyro horizon and turn and bank indicator are supervised by the pilots in order to be stabilised perfectly on the three axes (roll, pitch and yaw) to perform an optimal checklist. One may notice that some actions of the checklist are not detected by the eye tracker but:

- The chronometer and GPS settings were not performed as the pilots were not engaged in a complex navigation task but stayed close to the airfield;
- The trim or the engine instruments (e.g. oil pressure indicator) are located on the right part of the instruments panel where no eye tracking could be established due to the limitation in angle of the Tobii x50.

The analysis of the fixation times on the areas of interest during this checklist showed that the pilots focused particularly on the tachymeter (46.71 % fixation time on this instrument during that checklist), the manifold pressure (29.78 %) and the airspeed indicator (14.12 %). Interviews with the six pilots have confirmed that the engine management during this checklist requires a certain amount of attentional demand: very accurate and careful adjustments were needed on the tachymeter, manifold pressure and the speed. The pilots spent less time on checking instruments as the altimeter (4.48%), the directional gyroscope (1.82 %) or the compass (1.32 %). Indeed, discussion with the pilots revealed that the altimeter was rapidly looked to check that a 2000 feet altitude was reached (i.e. to start the cruise checklist). They also just glanced at the directional gyro and the compass: as the pilots were not about to perform a navigation task, the cross-checking of these two indicators were of less importance. In this sense, these findings are consistent with research conducted on the correlation between attentional demand and time fixations [19] [20] [21]: important information implies longer time fixations.

The analysis and the comparison of the pilots' areas of interest during the landing in nominal and degraded conditions (cf. fig 6 and 7) have revealed different ocular patterns. First of all, the total duration of fixations in nominal conditions was more than two time higher to the total duration of fixations in degraded conditions (13.59 seconds vs. 5.53 sec). This suggests that in degraded conditions, the pilots spent more time looking outside the cockpit to assess and adapt their trajectory in reference with the airfield. Another major difference between the two landings relied on the fact that the pilot's areas of interests were less distributed in the degraded conditions than in the nominal one with a particular focus on the airspeed indicator (77.49% of total fixation times in degraded landing vs. 58.12% in nominal landing). A first consideration is to take into account the fact that in the degraded condition, the pilots had no more interest to supervise the tachymeter and the manifold pressure due to the engine failure. Another consideration is given by the pilots who all agreed that in the degraded condition they had faced troubles to manage their speed as they were surprised by the high lift-to-drag ratio of the Aquila. In this sense, this led them to focus especially on the airspeed indicator and particularly to take a key decision: maintaining the landing or going around.

The analysis of pupil diameter variations shows some evolutions according to the different flight sequences. More precisely, mean delta pupil diameter was of -0.25 mm before the simulated failure, +0.47 mm during the failure and the cross wind leg, -0.10 during the base leg and +0.12 from the last turn to the final touch. These results are consistent with the pilots' interviews that report a high anxiety and cognitive demand due to the management of the aircraft during the few early minutes of the simulated failure, a lower anxiety during the base leg because of the successful stabilization of the aircraft, and finally another increase of anxiety and cognitive demand during the landing sequence because of the required precision and the potential go-around in case of unsafe approach. Furthermore, the literature classically reports a high cognitive demand and a high ANS arousal during the landing [34], which is consistent with the increase of pupil diameter observed during the last turn and the final touch.

During the flying activity, pilots are confronted with numerous stressors that can deplete their performance, such as time pressure, increased anxiety, and unexpected failure. Whereas a growing literature [35] [36] sheds light on the effect of complex flight scenarios or anxiety on pilots' performance and physiological parameters, real flight experiments remain extremely rare. Therefore, on-board eye tracking offers promising perspectives in term of real condition monitoring of both pilot's actions and physiological states, although this ecological approach shows some technical limitations. Firstly, the analysis of the areas of interest shows the reliability of the tool and its capability to predict behaviours. Indeed, during a takeoff, it has been possible to link the absence of visual scanning on the flaps with an omission of a required action on them later. Moreover, the AOI analysis allows bringing to light differential visual behaviours according to the landing condition (nominal or degraded). Secondly, the measurement of the pupil dilation gives clues on the pilot's emotional state and/or cognitive workload. The pupil response seems to evolve differently during the four flight phases. The pupil diameter appears to be higher just after the simulated engine failure. This observation is coherent with the increase of mental demand and/or anxiety during this particularly critical flight phases. In addition, the occurrence of differential patterns during the failure phases vs. the nominal ones seems to emphasize pupil diameter results. Further work should be conducted by night to totally get rid of the luminosity variations and to attempt to produce more results, in particular concerning the comparison of degraded and nominal conditions.

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