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► To cite this version:

Maxime Reynal, Yvonne Colineaux, Andre Vernay, Frédéric Dehais. Pilot Flying vs. Pilot Monitoring during the approach phase: an eye-tracking study. International Conference on Human-Computer Interaction in Aerospace (HCI-Aero 2016), Sep 2016, Paris, France. pp. 1-7. hal-01682792

HAL Id: hal-01682792

<https://hal.science/hal-01682792>

Submitted on 12 Jan 2018

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To cite this version :

Reynal, Maxime and Colineaux, Yvanne and Vernay, Andre and Dehais, Frédéric Pilot Flying vs. Pilot Monitoring during the approach phase: an eye-tracking study. (2016) In: HCI-Aero, 14 September 2016 - 16 September 2016 (Paris, France).

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Pilot Flying vs. Pilot Monitoring during the approach phase: an eye-tracking study

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ABSTRACT

The adequate monitoring of the flight parameters in the cockpit is a critical issue for flight safety. However, little is known about how the crew supervises the flight deck. In this paper, the preliminary results of a project dedicated to analyze pilot flying and pilot monitoring eyes movements collected in full flight simulator during approach phases are presented. First analyses were conducted over 32 approach phases (8 different crews performing 4 approaches each). The results revealed that the pilot flying and the pilot monitoring exhibited similar ocular behavior during the approach. Moreover, the findings suggested that the pilot monitoring's attentional allocation may not be optimal especially during the short final with low percentage of dwell time on the speed indicator and high percentage of dwell time out of the window.

Keywords

Flight safety, Eye-tracking, Human error, Pilot activity.

INTRODUCTION

Operating an aircraft is a complex activity that requires efficient teamwork between the Captain and the First Officer (F/O). During flight operations, the two crewmembers can be alternatively either "Pilot Flying" (PF) or "Pilot Monitoring" (PM). Their roles as PF and PM are defined by the Standard Operating Procedures (SOPs) [18]:

- The PF is responsible for managing the aircraft flight path and gives orders to the PM.
- The PM is responsible for monitoring the current and projected trajectory, the status (e.g. flight path, energy) of the aircraft and all external hazards (e.g. cumulonimbus).

- The PM must inform the PF (or intervenes if necessary) of any deviation of the flight parameters, and executes the PF's orders.

This distribution of roles emphasizes on the adequate monitoring of the cockpit, thus challenging pilots' attentional abilities. However, it is well admitted that attentional abilities are bounded. Recent studies have shown that the occurrence of unexpected events is likely to capture human operator's attention on a single task to the detriment of the supervision of the flight [5] despite auditory alarms [6]. Operational fatigue and drowsiness may lead to the state of mind wandering, leaving the pilot's ill equipped to face complex and challenging situations when a problem arises [9]. As stated by [2]: "*Real-world monitors may be caught between a continuous vigilance approach that is doomed to fail, a dynamic environment that cannot be fully controlled, and what may be an irresistible urge to let one's thoughts drift.*" The National Transportation Safety Board (NTSB) and the International Civil Aviation Organization (ICAO) stated that poor monitoring issues were involved in most of major civilian accidents, such as Colgan Air Flight 3407 [15], Asiana Air Flight 214 [14], Turkish Airlines Flight 1951 [10], Air Inter Flight 148 or more recently the UPS Airlines Flight 1354 [13] to name a few [4]. The growing awareness of the need to better understand these events motivated the creation of the Active Pilot Monitoring Group. This group identified several contributive factors such as time pressure, human limitation, poor mental models, automated flight deck issues and a "*corporate climate that does not emphasis on monitoring*". This work resulted in the "Practical Guide for Improving Flight Path Monitoring" that proposes several countermeasures to crew's poor monitoring [11].

However, little is known on how the crewmember actually monitors the flight deck and cross-check the flight parameters especially during critical phases such as the approach [3]. To that end, measuring eyes movements with eye-tracking technique offers promising perspective to undercover pilots' voluntary or not attentional strategies. Several studies revealed the suitability of the eye tracking technique for understanding attentional vulnerabilities of pilots interacting with highly automated flight deck [7][17].

In order to better understand why trained pilots fail sometimes to adequately monitor flight parameters, the DGAC/DSAC initiated the Pilot Vision project. This project aimed at analyzing eye tracking data collected by ISAE in different full flight simulators (Airbus-A330 and Boeing-777 full flight simulators) during approach phase preceding a go-around procedure.

In this paper, a first analysis conducted over 32 approaches is detailed. The aim of this study was to address the following questions: 1) In which proportion do the PF and the PM glances at the different areas of interests (AOIs) of the cockpit flight deck during the approach? 2) Does the monitoring in line with the SOPs? 3) Does the pilots' status (Captain versus First Officer) interfere with the pilots' role in the cockpit (PM versus PF)?



Figure 1 — Heatmaps examples of a Captain when he is PM (on top) and a First Officer when he is PF (at the bottom), between 1500 and 500 ft (the two pictures come from an Airbus A330 cockpit). The 'hot' zones where the users focused their gaze with a higher frequency are indicated by yellow/red colors whereas less attended zones are depicted in dark/blue colors.

MATERIAL AND METHOD

Participants

Eight voluntary French crews (i.e., one Captain and one First Officer) coming from different airlines, 16 pilots in total, took part to the experiment. The roles of the Captains and the First Officers (i.e., PM and PF) varied during the flight (see next section). PFs' mean age was 46.5 years ($SD = 7.7$) with a mean flight experience of 14450 hours ($SD = 2192$). PMs were on average 41.3 years ($SD = 4.3$), with a mean flight experience of 7991 hours ($SD = 2795$).

Eye-tracker and Areas of Interest

Eye tracking data were collected with two synchronized Perteck eye-trackers ($0.25^\circ - 0.5^\circ$ of accuracy). Head movements were corrected by an alignment of three infrared emitters to map participants' fixations on an image of reference (see Figure 1 for a graphical view). The 15 following AOIs were created (see Figure 2): 1) Airspeed (Speed), 2) Attitude indicator (AI), 3) Altitude indicator (Alt.), 4) Heading (HDG), 5) Flight Mode Annunciator (FMA), 6) Navigation Display (ND), 7) Electronic Centralized Aircraft Monitor (ECAM) for Airbus-A330 and Engine Indicating and Crew Alerting System (EICAS) for Boeing-777, 8) left Multipurpose Control Display Unit (MCDU), 9) right MCDU, 10) External view (Ext.), 11) Auto Flight Control Panel: Flight Control Unit (FCU) for Airbus-330 and Multi Control Panel (MCP) for Boeing-777, 12) Flaps control panel (Flaps), 13) landing gears control panel (Gears), 14) No Zone (NZ; i.e. all what is being viewed and which does not correspond to an AOI), and 15) Out of Zone (OZ; i.e. including all the data that was not captured by the device; this is not an AOI but a non-captured quantity of data).



Figure 2 — Example of Captain's AOIs delimiting flight deck instruments (Airbus A330).

Average percentage of dwell time on each AOI was calculated for each participant, for each approach.

Procedure

Data were collected during the ASAGA project (Aeroplane State Awareness during Go-Around) led by the Bureau d'Enquêtes et d'Analyses (BEA), the French safety board. This project was dedicated to the study of PM and PF's eye movements during go-around procedures (GA) in Boeing 777 and Airbus A330 full flight simulators, equitably distributed over the crews (please note that these two aircraft simulators were not equipped with a head-up display) [1]. During the experiment, the crews executed four different approach procedures: the first three leading to a GA during the short final and the last one leading to a landing. We unfortunately did not counterbalance the order of the landings across the participants due to implementation constraints in the full flight simulators. In

the present paper, we focused our analyses on the four approaches. Each approach was segregated into three phases: 2500 – 1500 ft, 1500 – 500 ft and 500 ft – TOGA or touch down (this last phase was temporally delimited when the PF put his hands and the thrust levers in order to execute the GA). In the two first scenarios, the Captain was PF and the First Officer was PM. In the last two scenarios, the Captain was PM and the First Officer was PF.

Approach 1) GA requested from ATC (Captain = PF, First Officer = PM): While the crew began an approach on runway 18 at Lyon airport, ATC announced a change in the selected runway then requested an Instrument Landing System (ILS) break in 36 left under radar guidance to occupy the crew during approach. Under 200 ft, runway was occupied and ATC requested for an unexpected GA. This first GA was ordered by ATC and disrupted by a change in the aimed altitude.

Approach 2) GA due to tailwind conditions (Captain = PF, First Officer = PM): The crew had to change aircraft course to Marseille airport in accordance with the flight record. They had to execute a standard ILS 31 right Z

approach, with tailwind will increase from 15 to 20 kt. ATC effectively announced this wind conditions change only during short final approach. The crew was expected to perform a GA.

Approach 3) GA due to IMC (Captain = PM, First Officer = PF): Still above Marseille airport, the crew had to make a breakthrough LOC DME 13 left under radar guidance. However, poor visibility led the crew to execute a GA.

Approach 4) and landing (Captain = PM, First Officer = PF): After the third GA, the crew managed to land on Marseille Airport.

RESULTS

Descriptive analysis

The next figures illustrate our descriptive results. We first merged AOIs related to the primary and secondary instruments for both PF and PM (see Figure 3). Then, the average percentage of dwell time on the different AOIs in two different ways was plotted to highlight the possible interactions between pilot's status and role (see Figure 4).

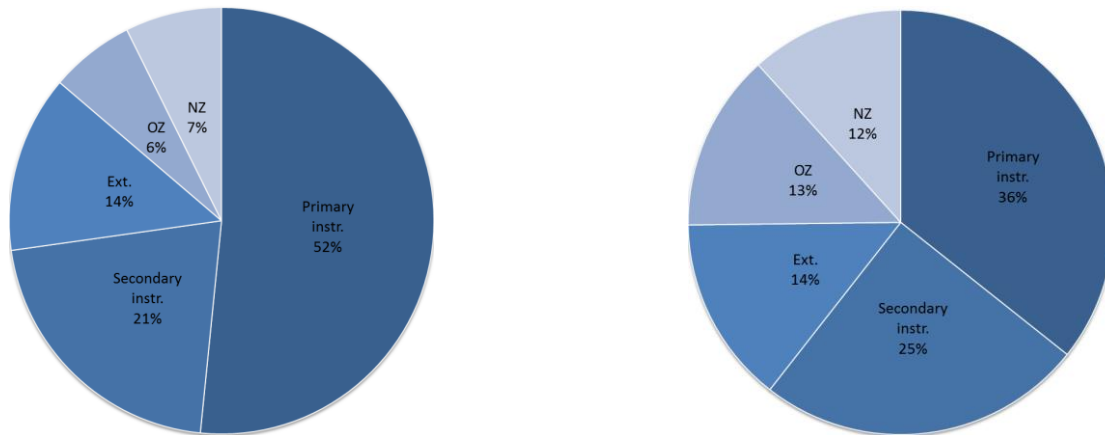


Figure 3 — Average dwell time for PF (on the left) and PM (on the right), regarding Primary instruments (i.e. Airspeed, Heading, Attitude and Altitude indicators), Secondary instruments (i.e. FMA, ND, ECAM/ECAIS, FCU/MCP, MCDUs, Flaps panel, and landing Gears), External view, Out of Zone (OZ) and No Zone (NZ).

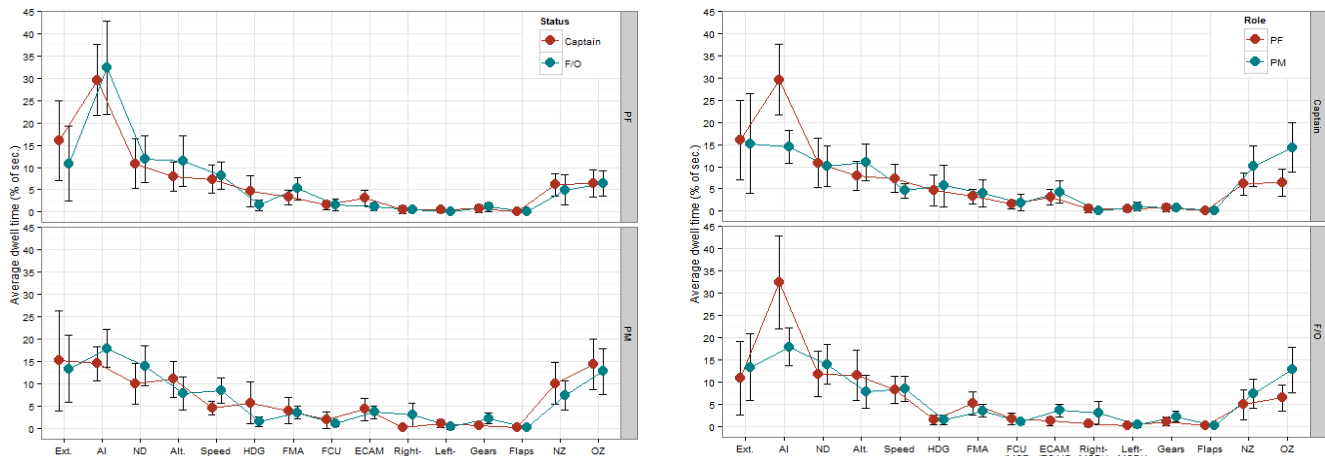


Figure 4 — Average dwell time per AOI, per role then per status (on the left), and per status then per role (on the right), for all the four approaches.

Eventually, the last figure illustrates PF and PM average percentage of dwell time during the three segments of the approach.

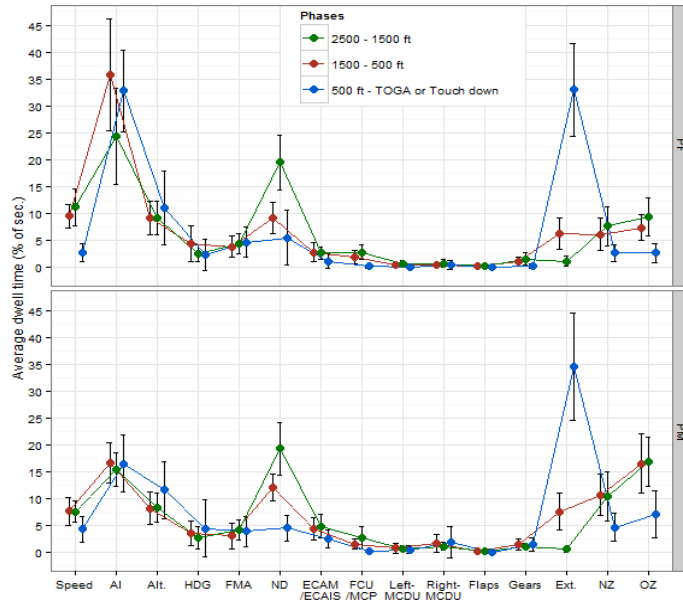


Figure 5 — Average dwell time per AOI, per phases and roles, over all approaches.

Statistical analyses

Primary vs. secondary instruments

Approaches 1 and 2 were averaged into a first single situation in which Captain was PF and First Officer was PM, and approaches 3 and 4 were averaged into a second single situation in which Captain was PM and First Officer was PF.

AOIs were first merged into two main groups, which are Primary instruments and Secondary instruments (see Figure 3). These two groups were taken as grouped AOIs then compared with External view, NZ and OZ.

A first inferential analysis was performed using Statistica 10. A general mixed $5 \times 2 \times 2$ (Grouped AOIs [Primary instruments, Secondary instruments, Ext., OZ, NZ] \times Role [PF, PM] \times Status [Captain, First Officer]) analysis of variance (ANOVA) with both Grouped AOIs and Role implemented as within factors and Status implemented as between factor.

This first ANOVA revealed a main effect of the AOIs, [$F(4, 56) = 115.00, p < .001, \eta^2_p = .89$], and a Role \times Grouped AOIs interaction [$F(4, 56) = 17.00, p < .001, \eta^2_p = .55$] (see next Table 1 for a summary of the results).

General ANOVA (with grouped AOIs)				
Variable	ddl	F	p	η^2_p
Grouped AOIs	4, 56	115.00	< .001*	.89
Role	1, 14	1.00	.29	.08
Status	1, 14	1.00	.44	.04
Role \times Status	1, 14	1.00	.30	.08
Role \times gr. AOIs	4, 56	17.00	< .001*	.55
Status \times gr. AOIs	4, 56	1.00	.43	.07
Role \times gr. AOIs \times Status	4, 56	1.00	.60	.05

Table 1 — Results from 5 AOIs (Primary instruments, Secondary instruments, Ext., OZ and NZ) \times 2 Roles \times 2 Status ANOVA.

Tukey's HSD post hoc analysis for Role \times Grouped AOIs interaction showed that PF ($M = 51.59, SD = 12.11$) fixed more at primary instruments than PM ($M = 35.74, SD = 7.09, p < .001$). No other significant result was found.

Considering all AOIs separately

A second general mixed $14 \times 2 \times 2$ (AOIs [Speed, Attitude indicator, Altitude indicator, Heading, FMA, ND, ECAM/ECAIS, FCU/MCP, left MCDU, right MCDU, Flaps, External view, NZ, OZ] \times Role [PF, PM] \times Status [Captain, First Officer]) ANOVA with both AOI and Role implemented as within factors and Status implemented as between factor, was performed (see Table 2 for the results). Data collected for Gears AOI being not balanced because they were missing for one session, the study does not integrate them into the statistical analyses.

This ANOVA showed a main effect of the role [$F(1, 13) = 46.24, p < .001, \eta^2_p = .780$]. The analysis revealed a second main effect of the AOIs, [$F(13, 169) = 66.27, p < .001, \eta^2_p = .84$] and a Role \times AOIs interaction [$F(13, 169) = 15.23, p < .001, \eta^2_p = .54$].

General ANOVA				
Variable	ddl	F	p	η^2_p
AOIs	13, 169	66.27	< .001*	.84
Role	1, 13	46.24	< .001*	.78
Status	1, 13	.14	.72	.01
Role \times Status	1, 13	.36	.56	.03
Role \times AOIs	13, 169	15.23	< .001*	.54
Status \times AOIs	13, 169	1.75	.06	.12
Role \times AOIs \times Status	13, 169	1.52	.12	.11

Table 2 — Results from 14 AOIs \times 2 Roles \times 2 Status general ANOVA.

To simplify statistical analyses, twelve different mixed ANOVAs were launched, one per AOI (i.e. Airspeed,

Attitude and Altitude indicators, Heading, FMA, ND, ECAM/ECAIS, FCU, MCDUs, Flaps panel and External view).

For each AIO, a mixed 2×2 (Role [PF, PM] \times Status [Captain, First Officer]) ANOVA was run with Role implemented as within factor and Status implemented as between factor. Tukey honest significant difference (Tukey's HSD) was used for post hoc testing.

Airspeed. The analysis revealed a main effect of status [$F(1, 14) = 5.60, p < .05, \eta_p^2 = .29$], with Captains ($M = 5.96, SD = 1.42$) glancing significantly less at the Airspeed indicator than First Officers ($M = 8.38, SD = 2.53$). A trend was found for the role, [$F(1, 14) = 4.03, p = .06, \eta_p^2 = .22$], with PF ($M = 7.79, SD = 6.17$) having high values for this AOI than PM ($M = 6.55, SD = 4.96$). The analysis showed a significant Role \times Status interaction [$F(1, 14) = 6.14, p < .05, \eta_p^2 = .31$]. Post hoc analyses revealed that Captains gazed more at the airspeed when they were PF ($M = 7.35, SD = 6.24$) than when they were PM ($M = 4.57, SD = 3.07, p < .05$). When endorsing the role of PM, First Officer glanced significantly more at the Airspeed indicator ($M = 8.53, SD = 5.68$) than Captains ($M = 4.57, SD = 3.07, p < .05$). Finally, no difference on this AOI where found when First Officers acted as PF or PM.

Attitude indicator. The statistical analysis revealed a main effect of role [$F(1, 14) = 31.42, p < .001, \eta_p^2 = .69$], with PFs spending more time staring at the attitude indicator ($M = 30.96, SD = 18.57$) than PMs ($M = 16.19, SD = 8.14$). No effect of the status, nor Role \times Status interaction were found.

Altitude indicator. The analysis revealed a significant Role \times Status interaction [$F(1, 14) = 11.61, p < .01, \eta_p^2 = .45$], but the post hoc analysis revealed no significant differences. No PM/PF difference and no effect of the status were found.

Heading. The analysis revealed a significant main effect of status [$F(1, 14) = 10.33, p < .01, \eta_p^2 = .43$], with Captains glancing more ($M = 5.19, SD = 2.92$) at the Heading indicator than First Officers ($M = 1.53, SD = 1.37$). The analysis revealed no significant effect between PM and PF, or Role \times Status interaction.

ECAM/ECAIS. The statistical analysis for this AOI revealed a significant main effect of role [$F(1, 14) = 14.55, p < 0.1, \eta_p^2 = .51$] with PFs ($M = 2.18, SD = 2.98$) glancing less at the ECAM/ECAIS than PMs ($M = 3.92, SD = 4.03, p < .01$). No effect of status nor Role \times Status interaction were found.

Right MCDU. The statistical analysis revealed a main effect of role [$F(1, 14) = 5.04, p < 0.5, \eta_p^2 = .27$], with PM ($M = 1.60, SD = 4.01$) spending more time on it than PF ($M = .53, SD = 1.36, p < .05$). A significant main effect of status was found [$F(1, 14) = 5.80, p < 0.5, \eta_p^2 = .29$], with Captains ($M = .34, SD = 1.13$) glancing less at it than First Officers ($M = 1.79, SD = 4.02, p < .05$). A significant Role \times Status interaction was also found [$F(1, 14) = 8.99, p <$

$0.1, \eta_p^2 = .39$]. Post hoc analysis revealed that First Officers glanced more at it when they were PM ($M = 3.04, SD = 5.30$) than when they were PF ($M = .53, SD = 1.16, p < .05$). Moreover, First Officers glanced more at right MCDU ($M = 3.04, SD = 5.30$) than Captains ($M = .16, SD = .34, p < .01$) where they were both PM.

No statistical result was found for the following instruments: **FMA, ND, FCU/MCP, Left MCDU, Flaps panel and External view.**

To summarize, these statistical analyses revealed that:

- (i) PF fixed more the Primary instruments (Attitude and Altitude indicators, Speed and Heading) than PM (see Table 1);
- (ii) PF and PM exhibited almost similar average percentage of dwell time on the Airspeed, Altitude indicator, Heading (i.e. three out of four primary instruments), FMA, ND, FCU/MCP, left MCDU, Flaps panel (the most part of secondary instruments), and moreover External view AOIs;
- (iii) The PF glanced more at the Attitude Indicator than the PM;
- (iv) The status of the pilot led them to glance differently at primary instruments Airspeed (more fixed by First Officers) and Heading (more fixed by Captains);
- (v) There is also a Role \times Status interaction on Airspeed: with PM–First Officers glancing more at the Airspeed than PM–Captains.

DISCUSSION

The objective of the present paper was to present the preliminary findings conducted over eight crews performing four stabilized approaches (i.e. 32 analyses). The main motivation was to investigate PM and PF's ocular behavior (in terms of dwell times) with regard to SOPs. To the authors' knowledge, this study was the first to measure both PM and PF's eye movements in the context of realistic operational scenario, with multi-crew environment in full flight simulator and during approach phases.

Firstly, the results confirmed that both pilots glanced more at the primary flight parameters than the secondary ones. This is consistent with the SOPs as it is mandatory for pilots to particularly monitor the parameters such as the aircraft attitude, the speed, the altitude and the heading. We also note that the rank ordering of the different AOIs is closely correlated with the scan data of PF observed by [17], for commercial PF and for pilots [7].

Secondly, the results showed that the PF and the PM exhibited the same ocular behavior at the exception of the Attitude indicator. Indeed, the PF glanced more at the Attitude indicator than the PM. Though this latter result is

consistent with the SOPs (i.e. the PF is in charge of monitoring the trajectory), one could have expected more pronounced differences between the PF and the PM's ocular behavior. Indeed, these two pilots are supposed to behave differently as defined by the SOPs. We found no effect of the status on the pilots' behavior to the exception of the speed indicator. That is, whatever their status and experience (i.e. Captains are more experienced than First Officers), all PMs and PFs behaved the same way. Only the Captains, when they were PM, glanced more at the airspeed indicator than when they were PF. However, Captains fixated less this critical AOI than First Officers.

Thirdly, results suggested that PMs' visual behavior was not optimal regarding the prioritization of the flight parameters. For instance, PMs spent few time monitoring the speed during the three sequences of the approach. PMs progressively redistributed their attention across the three segments to particularly focus on the external view. This was particularly true during the last sequence (500 ft to GA/touch down) when PMs spend approximately 35% of the time on the external view. This finding is surprising as long as PMs are supposed to keep their head down to monitor critical flight parameters related to the aircraft state. This possible misallocation of attention could find two explanations. The first one is that the pilots can monitor the speed using peripheral vision/covert attention thanks to the "speed trend vector" [7] (i.e. an arrow indicating the speed value in the next 10 seconds). This indicator can lead to less eye movements to integrate "trends" of the speed rather than the exact value of the speed itself. A second explanation may rely on automation bias issues [16] leading the pilots to over rely on the auto-thrust to manage the speed, and thus to pay less attention to this parameter. These issues on the speed indicator could provide explanation to recent accidents such as Asiana Air Flight 214 for example, when the pilots failed to identify a critical drop of the speed [14].

Eventually a last result concerned the right MCDU: the PMs glanced more at it compared to PFs, and the First Officers fixated more this AOI when they were PM than when they were PF, and they also glanced more than Captains in general. This has to do with the fact that the PM used this user interface to check wind conditions during approach 3.

CONCLUSION, PERSPECTIVES AND LIMITATION OF THE STUDY

We believe that these first results demonstrate the need to conduct eye tracking studies to undercover both PM and PF eye movements during critical phases such as landing. These first findings show that there is a need to establish standards on visual pattern especially for PM and PF to be consistent with SOPs. These eye tracking results are consistent with pilots' training purposes recently recommended by the Federal Aviation Administration (FAA), stated that "by March 2019, air carriers must

include specific training pertaining to improve monitoring".

However, this study has several limitations that need to be considered. First, the eye tracking results have to be taken with care. Indeed, our sample was composed of only 16 pilots (eight crews) and the accuracy of eye-tracking techniques still remains a challenge, especially in ecological conditions. Secondly we did not counterbalance properly the order and the design (i.e. PF, PM) of the four approaches. This design was imposed by the ASAGA project and the complexity of using full flight simulators. Thirdly, this study was conducted with French pilots and thus it does not take into account cultural effect. Actually, it's known that several differences exist between countries concerning the conduct of checklists and procedures [12].

Eventually, our study will continue with the analyses of the remaining data collected during the ASAGA project (i.e. four more crews – 16 approaches), and other data collected during unstabilized approach (4 landings × 28 PFs) in Boeing-737 full flight simulator.

Focus should be placed on the analysis of pilots' ocular dynamics via their scan path, and other eye metrics such as saccades, number of fixations, or time duration between two fixations, for example [8].

ACKNOWLEDGMENTS

We would like to thank Guillaume Adam (BEA), leader of the ASAGA project, and all the pilots who took part in this experiment.

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