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Pilot Flying versus Pilot Monitoring: Study of gaze allocation during dynamic and critical flight phases

Olivier Lefrancois\(^1\), Nadine Matton\(^2\), Vsevolod Peysakhovich\(^1\), and Mickaël Causse\(^1\)

\(^1\) ISAE-SUPAERO, Université de Toulouse, France
\(^2\) ENAC, University of Toulouse & CLLE, University of Toulouse, CNRS, UT2J, France

Abstract. Understanding pilots’ monitoring strategies is an important way to improve flight safety. We studied the gaze allocation of twenty pilots during sensitive flight phases in an Airbus 320 full flight simulator. Our objective was to characterize monitoring strategies regarding pilot’s status (Captain/First Officer) and pilot’s role (Pilot Flying/Pilot Monitoring). Monitoring strategies differed between Captain and First Officer during take-off and automatic landing. Monitoring strategies were also contrasted between Pilot Flying and Pilot Monitoring during go-around and warning events. When warning events occurred, suboptimal gaze allocation was characterized by an over-focus on primary flight parameters. Our results confirmed the importance of developing better training programs to enhance pilots’ monitoring skills and synergy in complementary monitoring.

Keywords: Cockpit Monitoring, Disjoint Attention, Eye Tracking, Flight Safety, Gaze Allocation, Go-around, Inter-individual Differences, Joint Attention.

Introduction

In aviation, human error is a major source of accident, and this cause remains constant over decades. The growing role of automation in modern cockpits allowed a drastic diminution of aircraft accidents and permitted to significantly lower crews’ workload. At the same time, it has introduced new challenges that necessitate research with regard to crew coordination, error management, and vigilance (Wickens, Fadden, Merwin, & Ververs, 1998). Automation is suspected to provoke a loss of hand-flying capabilities, an increased complacency (Endsley & Kiris, 1995; Haslbeck & Hoermann, 2016), and to reduce situation awareness (Parasuraman, Molloy & Singh, 1993). These automation drawbacks can be particularly problematic during highly dynamic flight phases, non-routine maneuvers, or in particular situations such as automation breakdown or when the crew needs to suddenly take over manual operations.

During their ab-initio training, pilots learn to fly in Instrument Meteorological Conditions (IMC), i.e., poor visibility conditions that require flying the aircraft by relying on cockpit instruments. During a flight in IMC, the control of the aircraft is largely based on the monitoring of the information available in the cockpit. This monitoring consists of different visual scans allowing a continuous and structured observation of flight instruments. The analysis of these visual patterns with eye tracking is frequent in human factor studies, in particular to gather information about monitoring strategies (Dehais, Behrend, Peysakhovich, Causse & Wickens, 2017; Haslbeck, & Bengler, 2016; Haslbeck, Schubert, Gontar, & Bengler, 2012; Peysakhovich, Lefrançois, Dehais & Causse, 2016; Reynal, Colineaux, Vernay & Dehais, 2016; Sarter, Mumaw, & Wickens, 2007).
**Monitoring strategies in the cockpit.** Monitoring consist of adequately watching, observing, and cross-checking. A methodical and efficient visual scan of cockpit instruments is necessary to build an up to date situation awareness or to make accurate changes in aircraft flight parameters (attitude, altitude, speed etc.). Monitoring also involves a cognitive comparison against the expected values, modes, and procedures. Surprisingly, most of ab-initio pilots are rarely trained on how to make an efficient and appropriate visual scan on modern glass cockpits. Thus, each pilot develops its own monitoring strategies, with more or less efficiency. A previous study of Lefrancois, Matton, Gourinat, Pey sakovich, and Causse (2016) suggested that pilots’ scanning strategies had an impact on hand flying performances. This study highlighted a high variability in visual scanning skills and its impact on flying performances. Yet, during highly dynamic phases (such as take-off and landing) or non-routine maneuvers, pilots have to constantly monitor instruments in order to be able to make fast and appropriate decisions. Thus an efficient monitoring strategy is vital (Kasarskis Stehwien, Hickox, Aretz & Wickens, 2001; Spady, 1978).

**One cockpit, two distinct and complementary roles.** On multi crew jet aircraft, the status of the two pilots is well known: There is the Captain and the First Officer. The Captain is higher in the hierarchy and generally owns significantly more experience than the First Officer on the specific aircraft. In addition, each pilot has a dedicated role: flying or monitoring.

The Pilot Flying’s primary responsibility is to control and monitor the aircraft’s flight path (including monitoring the flight guidance automated systems, if engaged). The Pilot Flying is secondarily responsible for monitoring non-flight path actions, such as aircraft systems and other operational activities. The Pilot Monitoring’s primary responsibility is to monitor the aircraft’s flight path (including automation systems, if engaged) and to immediately bring any concern to the Pilot Flying’s attention. The Pilot Monitoring is secondarily responsible for accomplishing non–flight path actions, such as radio communications and aircraft systems (Flight Safety Foundation, 2014).

During a flight, the two pilots can be alternatively either Pilot Flying or Pilot Monitoring. However, for some specific maneuvers, the Captain must be the Pilot Flying, such as during the rejected take-off maneuver or the automatic landing in low visibility. Specificity of this organization supposes an active “complementary monitoring” and a cross checking of all actions by the other crew member (call-out). This repartition also requires predictive monitoring to anticipate future aircraft attitude, and to rapidly detect potential visual alarms or deviations of the flight parameters. For example, the pilot in charge of monitoring the take-off should produce a specific gaze allocation including flight mode annunciator, thrust, and speed, while keeping some attention toward some other channel of information. A similar description can be made for other dynamic phases of flight such as landing. Besides, non-routine maneuvers like go-around are particularly interesting because this “normal” procedure commonly produces a high mental workload, creates a strong segregation of the tasks, and a “disjoint monitoring” in the cockpit between the Pilot Flying and the Pilot Monitoring (Adam and Condette, 2013). This cockpit disunion commonly results in a poor management of automatism and a lack of teamwork.

**Objectives of the study.** In this work, we had several objectives. First of all, we examined pilots’ specific gaze allocation according to their role during take-off, potential go-around, sensitive maneuvers (e.g., low energy recovering), and warning events (e.g., sink rate alerts) in standard visibility. Moreover, we studied gaze allocation during take-off and landing in low visibility conditions as the role of the Pilot Monitoring is particularly critical in these conditions. Indeed, low visibility conditions require the Captain acting as Pilot Flying. This procedure is complex because it requires frequent transitions between external visual references and cockpit instruments from the Pilot Flying. Moreover, for the Pilot Monitoring, timely detection of
abnormal parameters is critical because the flight crew has no external references except the runway centerline. We hypothesized that during all studied phases of flight, cockpit should be markedly split due to different task allocations. Moreover, we assumed that gaze allocation should strongly differ between the Pilot Flying and the Pilot Monitoring during low visibility procedures. In addition, we hypothesized that a sub-optimal gaze allocation could be observed during go-around, sensitive maneuvers, or warning events, with the Pilot Flying over-focusing on primary flight instrument (specifically the attitude indicator) to the detriment of other flight parameters. The Pilot Monitoring might also mainly focus on the primary flight instrument instead of short-term trajectory, flight mode annunciator (FMA), or on the evolution of aircraft total energy. In order to validate these hypotheses, twenty pilots (10 crews) performed two flight scenarios, facing standard and poor weather conditions in a full flight simulator. Pilots’ ocular movements were recorded with two head mounted eye-trackers.

Method

Participants. Ten crews consisting of twenty pilots were recruited (10 Captains and 10 First Officers) to perform the flight simulator experiment. They were all qualified on Airbus A320. All pilots were males, with a mean age of 42.3 years (SD = 3.8 years) for Captains and of 29.2 years (SD = 2.7 years) for First Officers, with a minimum of 1000 flying hours (FH). They totalized an average of 11500 FH (SD = 1300 FH) and 3500 FH (SD = 340 FH), respectively. All were volunteers, signed a consent form, and provided demographic information. They were not rewarded for their participation. Participants were randomly assigned to compose each of the ten crews and were not informed about the purpose of the study. Pilots were only briefed with all relevant flight parameters and context, but they were not introduced to the scenario, and purpose of research.

Flight simulator. Experiments were conducted in a full flight Airbus 320 simulator (Thomson), used for the regular training of professional flight crews provided by Air France group ©. Eye movements were recorded during the entire scenario duration, from thrust application during the take-off up to the roll out after the landing (when aircraft speed diminished below 50 knots). Eye data analysis was focused from “brake release” to “positive rate call-out” for the take-off, and from an altitude of 2500 feet up to the touchdown for the landing phase. This choice was made for the landing phase because the lower the altitude, the more accurate the Instrument Landing System (ILS) beams have to be flown and more visual attention is solicited. We recorded five flight parameters in order to characterize performance during the approach: Localizer and glide slope deviations, the speed (target value = 138 knots), the height above the runway threshold at landing (target value = 50 ft.) and the touchdown point (target values = between 300 and 600 meters from the runway threshold).

Eye tracking. Two synchronized 50Hz Pertech head-mounted eye trackers (0.25 degree of accuracy) have been used to record eye movements of the two pilots. Acquisitions were performed thanks to EyeTechPilot © software from Pertech. Post-processing has been conducted thanks to EyeTechMotion ©, and EyeTechLab © software, also from Pertech. Video and audio streams were also collected to analyze interaction and the communication within the flight crew. For post-processing purposes, flight displays were divided into nine areas of interests (AOIs; see Figure 1). The nine areas of interest corresponded to several information on the primary flight display, 1) speed indicator, 2) attitude indicator(AI), 3) heading-localizer deviation scale (HDG/LOC), 4) altitude-vertical speed-glide slope deviation scale (ALT/GS/VS), 5) the flight mode annunciator (FMA), 6) the navigation display (ND), 7) the electronic centralized aircraft monitor system (ECAM, including engine thrust display N1), 8) the system display system (SD), 9) and finally the outside world via the windows.
Procedure. All pilots performed two flights, from take-off (Toulouse runway 32 right threshold) to landing at Toulouse airport (LFBO) on runway 32 Right, one approach as Pilot Flying and one as Pilot Monitoring in a random order. After take-off, flight crews were requested to climb to 5000 feet, turn left, and intercept the localizer and the glide slope at this altitude on the same airport, then, they were cleared to the approach.

Each pilot performed as Pilot Flying and as Pilot Monitoring a full manual approach (without flight directors and without auto-thrust engaged) in standard visibility conditions (runway visual range of 550 meters).

Stabilization criteria were as per operator manual. If the approach was unstabilized, pilots had to decide whether a go-around had to be performed or not. The scenario ended when the aircraft was fully stopped on the runway. If there was remaining time at the end of the experiment, pilots performed an automatic landing (with flight directors and auto-throttle engaged up to the roll out) in low visibility conditions (runway visual range between 75 and 400 meters). In this type of approach, the Captain always acts as Pilot Flying. Due to time restrictions, only six out of ten crews performed this scenario.

Analyses. We only achieved statistical variance analyses for take-off scenario in standard visibility because this procedure has been made by all pilots, unlike the one in low visibility which has been made by only six flight crews due to lack of time at the end of the experiment. For all other procedures or maneuvers, we performed qualitative analyses as they were performed by only two different crews.
Results

Take–off: Standard visibility. Hereafter are presented gaze allocations during the take-off in standard visibility for both the Captain and the First Officer as Pilot Flying and Pilot Monitoring (see Figure 2 and Table 1). ANOVA showed a significant main effect of AOI ($F(8, 144) = 196.70, p < .001, \eta^2_p = .92$). In particular, the window was the most gazed AOI (LSD, $p < .001$ in all 8 comparisons), with an average of 46.6% of the percentage of dwell times. ANOVA also showed a significant AOI x Status interaction ($F(8, 144) = 3.13, p = .003, \eta^2_p = .15$). Captain and First Officer visual circuits were quite similar (no significant main effect of the status, $F < 1, p = 0.75$), except for the speed, the ECAM, and the window (LSD, $p < .001$ in all 3 comparisons). For example, the Captain spent 12.3% of the take-off roll gazing at the ECAM whereas the First Officer spent only 5.8% on it. The AOI x Role interaction was also significant ($F(8, 144) = 44.16, p < .001, \eta^2_p = .71$). When acting as Pilot Flying vs. Pilot Monitoring, pilots spent in average considerably more time gazing the window, respectively 64.7% vs. 28.5% (LSD, $p < .001$), probably because visual cues are primary means to track the runway centerline. Time spent gazing Speed and ECAM also differed as a function of the pilots’ role (LSD, $p < .001$ in the two comparisons). Pilot Flying was less focused on these two AOIs. Finally, the AOI x Role x Status interaction was also significant ($F(8, 144) = 3.26, p = .002, \eta^2_p = .15$). When pilots acted as Pilot Monitoring, ECAM was the most gazed instrument with 30.3% of the time for the Captain and 24.2% for the First Officer. A significant difference was also noticed concerning the speed indicator, it was monitored 25.7% of the time during the roll phase by the “First Officer monitoring” whereas it was consulted only 15% of the time by “Captain monitoring”. Other main effects and interactions were not significant ($p > .05$).

![Gaze allocation during take-off in standard and low visibility conditions](image)

Figure 2. Mean percentages of dwell time for each AOI during take-off for both standard and low visibility conditions. Dash boxes represent gaze allocation for the Captain acting as Pilot Flying (Captain is necessary Pilot Flying for a take-off in low visibility conditions) and the First Officer acting as Pilot Monitoring during low visibility. Intervals represent standard deviation from the considered subgroup.
Table 1. Mean percentages of the most gazed main areas of interest during take-off on standard visibility. Standard deviations in parentheses.

<table>
<thead>
<tr>
<th>Pilots’ status and role</th>
<th>Speed</th>
<th>Attitude Indicator</th>
<th>ECAM</th>
<th>Windows</th>
</tr>
</thead>
<tbody>
<tr>
<td>Captain Flying (n=10)</td>
<td>11.6%</td>
<td>9.1% (4.7)</td>
<td>12.3% (3.8)</td>
<td>60.3% (15.1)</td>
</tr>
<tr>
<td>First Officer Flying (n=10)</td>
<td>12.9%</td>
<td>8.5% (8.8)</td>
<td>5.8% (2.8)</td>
<td>63.76% (9.9)</td>
</tr>
<tr>
<td>Captain Monitoring (n=10)</td>
<td>15%</td>
<td>3.8% (5.4)</td>
<td>30.3% (3.8)</td>
<td>34.2% (9.1)</td>
</tr>
<tr>
<td>First Officer Monitoring (n=10)</td>
<td>25.7%</td>
<td>10.4% (8.4)</td>
<td>24.2% (4.4)</td>
<td>21.5% (17.9)</td>
</tr>
</tbody>
</table>

**Take-off: Low Visibility.** Due to lack of time at the end of the experiment, only six crews performed the take-off in low visibility condition. Thus, we only present qualitative results here (we did not perform any ANOVA). Gaze allocation for the Captain Flying and the First Officer Monitoring are presented Figure 2 and Table 2. The largest differences between visual patterns with standard and low visibility were observed for the “First Officer Monitoring”. Indeed, with low visibility, the Pilot Monitoring spent more time gazing at the ECAM and less time gazing outside the windows. More precisely, dwell time increased by 57.8% at 38.2% of the total duration on the studied phase, unlike windows which decreased by 122% at 9.7% of total time.

In addition, for the “First Officer Monitoring”, dispersion of the gaze duration on the windows was lower in low visibility vs. standard visibility conditions, 5.1% vs. 17.9% respectively (see Table 2). This is the same for the Captain Flying with a dispersion of 0.9% vs. 8.0%, for low visibility vs. standard visibility conditions, respectively.

Table 2. Mean percentages of time in main areas of interest during take-off on low visibility. Standard deviations in parentheses.

<table>
<thead>
<tr>
<th>Pilots’ status and role</th>
<th>Speed</th>
<th>Attitude Indicator</th>
<th>ECAM</th>
<th>Windows</th>
</tr>
</thead>
<tbody>
<tr>
<td>Captain Flying (n=6)</td>
<td>8.5% (0.9)</td>
<td>12.5% (0.7)</td>
<td>11.9% (6.3)</td>
<td>58.8% (7.0)</td>
</tr>
<tr>
<td>First Officer Monitoring (n=6)</td>
<td>18.2% (2.2)</td>
<td>11.9% (3.0)</td>
<td>38.2% (3.9)</td>
<td>9.7% (5.1)</td>
</tr>
</tbody>
</table>

**Go-Around: Standard visibility.** As only five crews performed a go-around, we only present qualitative results here (we did not perform ANOVA). We found differences of gaze allocation between the Pilot Flying and the Pilot Monitoring as seen on Figure 3: It appeared that Pilots Flying were highly focused on the attitude indicator (30.8%). Moreover, the Pilots Monitoring were more focused on the couple Vertical Speed / Altitude indicator (12.3%) and the flight mode annunciator (16.3%).
Moreover, considering main instruments, gaze dispersion was considerably lower for this manoeuver compared to take-off during standard visibility (see Table 3). For the Pilots Flying, standard deviation on the attitude indicator was 2.2 % during go-around for the while it was 4.7 and 8.8 % for the Captain and the First Officer, respectively, during the standard take-off.

**Table 3.** Mean percentages of time in main zones of interests during go around manoeuver. Standard deviations are in parentheses.

<table>
<thead>
<tr>
<th>Pilots’ status and role</th>
<th>Attitude Indicator</th>
<th>Localizer</th>
<th>Vs./Altitude</th>
<th>ECAM</th>
<th>FMA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pilot Flying (n=5)</td>
<td>30.8 % (2.2)</td>
<td>5.4 % (2.4)</td>
<td>2.5 % (3.2)</td>
<td>2.1 % (1.7)</td>
<td>16.2% (1.7)</td>
</tr>
<tr>
<td>Pilot Monitoring (n=5)</td>
<td>12.1 % (2.5)</td>
<td>3.4% (2.5)</td>
<td>12.3 % (2.1)</td>
<td>6.7 % (2.4)</td>
<td>116.3%(2.0)</td>
</tr>
</tbody>
</table>

**Automatic Landing: Low visibility.** As only six crews performed low visibility scenarios, we only present qualitative results here (we did not perform ANOVA). Considering the gaze allocation during the final stage of the approach, it appeared that the Pilot Flying (necessarily the Captain) spent more time gazing the “Windows” (72.4%), and the attitude indicator (15.7%) as illustrated Figure 4 (see Table 4 for summary descriptive statistics).

**Figure 3.** Mean percentages of dwell time in the different zones of interests during go-around manoeuver, Pilot Flying and Pilot Monitoring. Red boxes represent gaze allocation of the Pilots Flying, blue one of the Pilots Monitoring, and intervals represent standard deviation from the considered subgroup.

**Figure 4.** Mean percentages of time in main zones of interests during automatic landing, Pilot Flying and Pilot Monitoring.
The Pilot Monitoring (necessarily the First Officer) spent more time gazing the attitude indicator (26.6%), the speed (19.1%) and the ECAM (18.8%).

Table 4. Mean percentages of dwell time in main zones of interests during automatic landing for the pilot flying, and monitoring. Standard deviations are in parentheses.

<table>
<thead>
<tr>
<th>Pilots’ status and role</th>
<th>Attitude Indicator</th>
<th>Localizer</th>
<th>Vs. / Glide</th>
<th>ECAM</th>
<th>Windows</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pilot Flying (n=6)</td>
<td>15.7% (4.2)</td>
<td>0.2% (0.2)</td>
<td>4.5% (1.8)</td>
<td>2.9% (3.1)</td>
<td>72.4% (16.7)</td>
</tr>
<tr>
<td>Pilot Monitoring (n=6)</td>
<td>26.6% (5.8)</td>
<td>3.4% (2.7)</td>
<td>11.3% (1.8)</td>
<td>18.8% (2.1)</td>
<td>2.4% (1.3)</td>
</tr>
</tbody>
</table>

As shown in Table 4, dispersion is particularly low considering the Pilot Flying gazing the localizer (0.2%) and the glide (1.8%) compared to results published in a previous study on these instruments by (Lefrancois and al., 2016). A similar remark can be made for the Pilot Monitoring gazing ILS deviation scale, the ECAM (2.1%) and the windows (1.3%).

Non-Normal Maneuvers: Standard visibility. One crew experienced a low energy alarm and another one experienced a sink rate alarm during the approaches (thus we only present qualitative results here). The first one was a warning enhanced by the airplane. In fact, the aircraft flight augmentation computer computes the aircraft energy level, and issues an aural low energy alert to warn the pilots when the energy level becomes too low. In the situation presented in Figure 5, pilots where in turn, about to intercept the localizer at 5000ft. Only one crew faced this situation.

Figure 5. Percentages of dwell time in main zones of interests during speed recovery manoeuver, Pilot Flying and Pilot Monitoring (one crew).

It appears that during final turn, at constant altitude, both pilots were significantly gazing the attitude indicator during respectively 44.3 % and 44.4% of the event (6.21 seconds). Gaze allocation of the Pilot Flying has been focused during 26.3% of the manoeuver on the localizer deviation scale, and dwell time of the Pilot Monitoring was also focused on this instrument during 15.2%. In addition, they under-focused the speed and the ECAM, where thrust is displayed.

The second warning was a sink rate triggered by the ground proximity warning system during the final stage of the approach. One crew faced this situation. Considering the rate of descent in feet/minute when the radio altimeter becomes alive, the system may issue first a sink rate alarm followed by a pull up maneuver request if there is a no action from the flight crew.
Concerning this alarm, gaze allocation was recorded between 100 and 50 ft. Both Pilot Flying and Pilot Monitoring were strongly focused on the aiming marks during 88% and 71% of the selected approach time, respectively, as appreciated on Figure 6.

![Gaze allocation during sink rate alarm](image)

Figure 6. Percentages of dwell time in main zones of interests during path recovery manoeuvre, Pilot Flying and Pilot Monitoring (one crew).

**Discussion/Conclusions**

The objective of the study was to characterize monitoring strategies regarding pilot’s status and pilot’s role through different highly demanding maneuvers. To this aim, twenty operational pilots qualified on Airbus A320 were recruited to perform two scenarios in a full simulator experiment.

**Take-off on standard and low visibility.** According to Boeing’s statistics (2010), from 2001 to 2010, 13 % of fatal accidents occurred during take-off. This part of the flight is very sensitive since visual attention is highly solicited in order to detect potential abnormalities in the parameters. Time pressure is high, and decisions to abort take-off have to be performed very fast in order to avoid dangerous events such as tire blowout or runway excursion. The take-off is a particular phase of the flight because only the Captain can make the decision to reject the take-off or not. The rejected take-off (RTO) is a maneuver performed during the take-off roll if the Captain estimates that the take-off should not be continued before reaching the decision speed $V_1$, maximum speed at which the RTO maneuver can be initiated, and the aircraft stopped within the remaining field length. If an engine failure (or a wind-shear or an unsafe or unable to fly state) is recognized at or after decision speed, the take-off must be continued within the remaining take-off distance.

Regarding pilots’ role, we observed that the Pilot Monitoring allocated his attention more on speed and ECAM, and less to the windows, compared to the Pilot Flying. Regarding pilots’ status, time devoted to each area of interest was globally similar for Captains and First Officers except for the ECAM, which was more gazed by the Captain when flying or monitoring. This high visual allocation on the ECAM by the Captain can be explained by the fact that the decision to reject take off is mainly associated with engine parameters, and alarms. These are essentials parameters during take-off roll, to make fast and appropriate decision regarding its possible abortion.

A deeper analysis revealed that speed indicator and ECAM display were differently gazed depending on both pilots’ role and status. Indeed, the “First Officer Monitoring” spent more time gazing the speed indicator than the Captain Monitoring, and the Captain Monitoring allocated more visual attention to the ECAM than the First Officer Monitoring.
We could initially expect a different gaze behavior regarding role and status on airspeed because the Pilot Monitoring announces speed during roll and the Pilot Flying crosschecks and confirms the speed indicated at 100 knots: at this moment, the Pilot Monitoring addresses its attention to monitor systems, and particularly engine parameters. When pilots were monitoring, the ECAM was frequently gazed, and differences between roles on this instrument were substantial. In chronological order, ECAM became the most gazed instrument around 100 knots because below this speed, the Captain may decide to abort the take-off depending on the circumstances. Above this speed, rejecting take-off is a more serious matter that is why this speed is a turning point from a monitoring point of view.

During low visibility procedures, for many airlines, the Captain is mandatorily the Pilot Flying for the take-off but this policy may change according to visibility, and operator manual. Comparing take-off on low visibility with standard one, dispersion of gaze durations was lower for First Officer Monitoring, specifically for the windows. This was also the case for the Captain as Pilot Flying, specifically for the speed and attitude indicator. These differences with take-off on standard visibility conditions can be associated to the criticality of any alarms or failures that may happen in low visibility, and particularly runway excursion.

**Go-around procedures:** During the session, five out of the 20 pilots had flown an unstabilized approach, and decided to go-around. The Pilots Flying over-focused the attitude indicator (explained by the necessity to fly the aircraft first with the appropriate path), the FMA and the speed, unlike the pilot monitoring that over-focused the FMA, the altitude indicator and the navigation display. Hereafter, it can be conjectured that the cockpit seemed divided between the pilot who deals with the trajectory and the pilot who deals with the configuration and the navigation (This segregation corresponds to the standard manoeuvre, which consists in flying the correct path, and ensure that automatisms are correctly engaged), that is why, even if the procedure is classified as normal, recurrent training is necessary because crew resource management is of the most important parameter. Our results are consistent with those published by (Adam and al., 2013).

Reasons of the unstabilized approach have been explained in a previous study (Lefrancois and al., 2016): Gaze allocation analysis of pilots who pulled up vs. the most accurate pilots of the experiment revealed that gaze allocation of primary flying instruments were at least twice as large than for most accurate pilots. These pilots over, and under-focused different primary instruments to the detriment of others in this dynamic phase of the flight.

Study of visual attention during go-around is also similar to (Dehais and al., 2017): During go-around, pilots spent less time on the outside world, redistributing gaze allocation on the airspeed indicator due to pitch concern during full thrust application, and on the navigation display to strictly follow the missed approach trajectory on busy airport environment.

**Automatic landing during low visibility:** Low visibility procedures exist to support low visibility operations at aerodrome when either surface visibility is sufficiently low to prejudice safe ground movement without additional procedural controls or the prevailing cloud base is sufficiently low to preclude pilots obtaining the required visual references.

Landing the aircraft into low visibility conditions requires automatic landing. In this specific phase of flight, crew duties are clearly specified: Captain is always the Pilot Flying, First Officer the Pilot Monitoring. This phase of flight requires the Captain to monitor flight parameters up to the final stage, during which he has to look outside for visual references. At the same time, the First Officer has to monitor all flight parameters inside the cockpit up to the roll out, looking for any abnormal parameters, glide deviation or automation malfunction.
It clearly appears that a specific repartition was required to deal with this type of approach. First of all, captains were particularly looking outside searching for visual references to complete the approach whereas the Pilot Monitoring supervised all systems, particularly glide path deviation and the ECAM in order to detect a failure.

**Sensitive maneuvers:** Two different crews experienced unstabilized approach but some of them faced procedures that required particular attention: “Speed”, and “Sink rate” wake-up call resulted from an incorrect path, and an irrelevant monitoring by these crews: These events were the results of an inadequate gaze allocation for each basic flying instrument during the approach for both Pilots Flying and Monitoring roles. Both pilots were considerably focused on the pitch attitude to maintain altitude in turn and the ILS interception regarding the “speed” alarm.

Concerning sink rate alarm, a result of this over-focalization was a decrease of the pitch attitude in very short final (minus four degrees on approach compared to a mean value of two degrees considering the aircraft weight, and configuration), and consequently an increase of the vertical speed without thrust adjustment. In fact, it appears that the Pilot Monitoring did not take into consideration parameters inside the cockpit during the final stage of the approach (Speed, vertical speed and pitch attitude) when the pilot was flying the path and under focusing the attitude indicator also. Both pilots were strongly focused on the aiming mark during the “sink rate”.

**Crew reactions facing unstabilized approaches:** Despite these remarks, 100 % of unstabilized approach ended up by a decision to go-around; the experiment did not record any “procedure violation”. In fact, continuation of an unstabilized approach is regularly observed (Causse and al., 2013), and has been found to be a causal factor in 40 % of all approaches and landing fatal accidents (Flight Safety Foundation, 2009). Therefore, our sample of pilots was really aware of stabilization requirements and did not hesitate to make the decision to go-around when necessary. Moreover, the experimentation was conducted in marginal weather conditions (that is to say minimum visibility, and strong crosswind) compatible with a manual landing, so the rate of unstabilized approached does not seem to be particularly high according to visibility conditions and crosswind values.

**Limits of the study:** Furthermore, due to well-known accuracy limitations of the eye–tracking system, it was not possible to differentiate between the heading and the localizer; a similar statement has been made for the altitude which could not be differentiated from the glide / vertical speed couple. Nevertheless, it can be hypothesized that radio altimeter keeps the pilot aware of the height of the aircraft above the runway, so this differentiation was not essential for the study.

Another limit is the sample size of the study. Only five flight crews performed a go-around and two experienced warning events. It might be interesting to study gaze allocation and visual pattern during these procedures on a more significant number of pilots.

**Perspectives of the study**

It should be interesting to know if pilots would appreciate that manufacturer published monitoring strategies for some procedures or maneuvers to help them being more efficient, and increase awareness of the crew. The question should be asked for each specific role, as Pilot Flying or Monitoring, because during these procedures, the Pilot Flying is responsible for attitude changes, and the Pilot Monitoring supervises flight path, automation engagement or weather condition. For example, during a wind-shear escape maneuver, we could expect a monitoring pattern which enhanced the wind direction and the rate of climb (with specific call out to bring any concern to the other pilot attention), the automatism engagement and the flight mode
annunciator. This scan flow could help Pilots Monitoring to check all relevant parameters through optimized visual patterns.

Concerning the study of the take-off, it could be interesting to perform an analysis of take-off roll with a failure associated to a specific environmental context (such as contaminated runway or flock of bird mentioned in the ATIS) to study visual patterns approaching decision speed, and associated decision making. It could help to design interacting systems assisting the pilots to make an appropriate decision in this dynamic context.

According to present findings, it would be interesting to develop a short training about the different maneuvers discussed on this work, and measure differences after a second experiment with similar scenarios. It could be interesting to study monitoring strategies development if pilots whose gaze allocation is sub optimal take into consideration dwell time of pilots who detect discrepancies efficiently. It can be assumed that, if less efficient pilots take into consideration tactics and visual patterns of the more reliable pilots, rate of unstabilized approached, and alarm would probably decrease. Another development currently under researches is to associate gaze allocation and transition between the different flying instruments to study kinematic of visual patterns during these specific phases of flight and maneuvers. We are currently working on a reeducation program to improve flight performance through visual pattern strategy and gaze allocation monitoring.

Another question is to know if the gaze allocation of the Pilots Monitoring during automatic approaches should be the most efficient way to detect any deviation during the approach, particularly if a manual landing is performed. In fact, their gaze allocation is evenly distributed between all flying instruments and aircraft systems up to the flare, with a minimum time spend on the outside world though the windows. We could assume that if all Pilots Monitoring would have applied these gaze allocation strategies during unstabilized approach, rate of go-around would have decreased, and alarms issued by the aircraft would have not been recorded. A similar conclusion has been made by (Reynal and al., 2016). They suggested that Pilots Monitoring visual behavior was not optimal regarding the prioritization of the flight parameters. During final stage of the approach, they noticed that Pilots Monitoring were spending approximately 35 % of the time on the external view, but they should keep their head down to monitor critical flight parameters. This finding could be explained by the automation confidence leading the pilot to over rely on automation to deal with thrust adjustments and attitude computation through the flight directors.

Main problem remains that monitoring is never taught during initial and recurrent training. Even if some visual patterns are depicted during initial training, and during the first flight into IMC, scanning strategies are no more taught during the pilots' career. Some studies, (Adam and al., 2013) also concluded that it should be necessary for manufacturers, and operators to define together a visual scan that would optimize crew teamwork during some phases of the flight, particularly the go-around procedure. These patterns could help pilots to manage time spent on each instrument during the approach and associated cinematic. In this context, eye-tracking technology could be very useful in recurrent training to increase consciousness of pilots.
References


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**Contact Information**

LEFRANCOIS Olivier, DCAS, ISAE, University of Toulouse, France
olivier.lefrancois.60@gmail.com