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Towards eye tracking as a support tool for pilot training and assessment

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A key challenge in pilot training and performance assessment is the lack of insight into pilot visual behavior. Without this, it is difficult for an instructor to assess, e.g., whether pilots fail because they did not monitor the instruments or because they did not act on them, and whether pilots comply with monitoring aspects of the Standard Operating Procedures. Eye tracking provides the opportunity to measure where and how pilots look, thus offering an important window into pilot behavior that can address this challenge. An open question however is how to effectively present information about pilot gaze behavior to the instructor, such that it can be used to better guide trainees and improve performance and safety. In this paper, we review existing eye-tracking displays, set out a series of design principles for effective eye-tracking data visualization and propose example application areas for eye-tracking data visualization.

Keywords & Phrases: Eye tracking, visual behavior, gaze, performance, aviation, safety, training, assessment

1 INTRODUCTION

In multi-crew cockpits, there is a "Pilot Flying" and "Pilot Monitoring". These designations refer to the detailed choreography of work in the cockpit, where each member of the flight crew carries out their part in executing Standard Operational Procedures (SOPs). The SOPs cover almost every conceivable situation (including non-nominal, abnormal, emergency and non-routine procedures) but rely on pilots having good situational awareness [1], e.g. an accurate mental model of the aircraft and its state. It is important that pilots notice, recognize and process aircraft state information to enable them to monitor the flight envelope, notice problems early and deal with them effectively and, if needed, immediately. This paper discusses how eye tracking, the measuring of gaze, can be used to assess whether pilots display effective visual behavior, and how this knowledge can be used during the training and assessment of pilots.

In a visually crowded [2–5] environment such as a cockpit, it is difficult to process visual information that is not directly looked at. As such, effective gaze behavior of pilots is critical because the visual modality is the bottleneck for taking in the required information. That it is required to directly look at the relevant elements in the cockpit however also means that measurement of gaze behavior can provide significant insight into pilot behavior. Such insight will reveal whether pilots comply with monitoring aspects of the SOPs and in training can reveal deficiencies that need to be addressed in much greater detail than is possible with only subjective observation performed by an instructor.

To realize this potential, eye-tracking data must be easy to acquire. In the last decade, due to the work of companies such as Seeing Machines, Smart Eye, SMI and Tobii, it has become relatively

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Article №2 · Pages 17–28 · 10.3929/ethz-b-000407625

straight-forward to collect eye-tracking data in situ, enabling such data collection to be integrated into day-to-day training and performance assessment. The increased availability of eye-tracking data however does not automatically lead to useful analyses or applications for that data. Specifically, little work has been done to turn eye-tracking data into information that is useful for the trainee, instructor or assessor.

In this paper, we posit that eye tracking holds potential to augment pilot training and assessment, but that significant development work is required to unlock this potential. Below, we outline the hurdles that need to be overcome to turn eye tracking into a useful tool for day-to-day training and assessment practice. We focus on the challenge of how to present eye-tracking data such that it becomes useful information that can be used to improve performance. To address this challenge, based on the authors' academic and industry experience, we present proposals for design guidelines indicating how and when eye-tracking data is visualized to instructors to help bridge the gaps between theory, research and practice in industry. We furthermore highlight the open research questions around this issue.

2 WHAT COULD EYE TRACKING OFFER FOR PILOT TRAINING AND ASSESSMENT?

The work of the modern pilot is increasingly less focused on the traditional skill of maneuvering the aircraft, and more and more influenced by increasing automation, and the pilot's role of risk manager and systems operator. One example of the evolution of technology and automation can be found in the modern cockpit instruments, which compound information from previously mechanical instruments into an Electronic Flight Instrument System (EFIS), or more commonly a "glass cockpit". While representing an improvement supported by Human Factors and ergonomics research mostly carried out by the companies developing the technologies [see also 6, 7], this modern instrumentation has been implicated in many accidents and incidents since compounding a lot of information in a small space (e.g. the FMA) can lead to monitoring problems in high-cognitive demand situations. Aircraft manufacturers recommend visual strategies during aircraft handling and the carrying out of procedures in the form of visual-tactile flows, scan patterns, checklists and other directives of where it is critical to look at certain times. While some of these are based on experience and research [8, 9], some seem to come from tradition only, and many of the recommended practices have not been validated after the modern "glass cockpit" was introduced.

During training and assessment, the examiner or instructor sits behind the pilots and controls the simulator to provide the planned scenarios. This means that the examiner or instructor has to interact with a control panel, while watching the backs of the two pilots. In scenarios, the examiner plays the role of air traffic control, cabin crew, engineering and other possible operational partners that pilots interact with. Adding to that, some scenarios include high workload for the trainee pilots, and thereby also for the examiner or instructor. While this setup has a long tradition in aviation and has promoted increasing safety, it is not ideal for close observation of performance in that any aspect of visual performance can only be inferred from head movement and body position or from verbal or action cues [c.f. 10].

It is exactly here where eye tracking holds great promise for training and assessment, because it can provide the direct insight into the visual behavior of pilots that is currently missing from these settings. Recently, across research fields ranging from medical and technical diagnosis [11–15] to educational science [16, 17], the question of whether eye tracking can augment training and performance assessment has been studied. Here we extend this discussion to airline pilots. Specifically, eye tracking in the cockpit allows for: 1) determination of successful and unsuccessful gaze patterns in different scenarios [18] to build databases of expert gaze behavior [19, 20] which can then be used as training targets; and 2) providing instructors and assessors with enhanced insight into pilot actions, thereby enabling better and more personalized guidance to individual trainee pilots, and enhanced insight into whether experienced pilots perform procedures correctly (augmenting checks on procedural compliance). Specifically, when failure occurs, eye tracking allows assessing whether pilots did not visually acquire the required information (either did not notice a warning, or did not check requirements on aircraft state before initiating a maneuver), or did look at this information but did not act on it correctly (either did not respond to a situation that required intervention, or responded inappropriately). It furthermore allows identification of instances of suboptimal visual strategies that did not lead to eventual overt failure but can still be identified and corrected to improve safety.

3 CURRENT USE OF EYE-TRACKING TECHNOLOGY FOR PILOT TRAINING AND ASSESSMENT

For aviation, eye tracking has been used to develop an understanding of the performance of pilots and air traffic controllers, which has led to new design solutions as well as development of work procedures. As the literature studying pilot visual behavior has been recently comprehensively reviewed [see 18, 21], this will not be further discussed here. The promise of eye-tracking research in aviation has been that it could be used more regularly in operations and training to provide data, feedback and guidance for safer and more efficient operations. Development of eye-tracking applications that can be used to support operational flying situations such as single-pilot operations or pilot monitoring support is ongoing [e.g., 22, 23], but deployment of these techniques to day-to-day operations remains distant, also because new hardware would be required in the aircraft to support these applications.

Eye tracking is of interest to the airline industry because it can improve safety by improving pilot monitoring, an important factor in safe aircraft operation [24]. It can furthermore help make training more effective, which can increase efficiency in use of expensive training resources. At this point in time, Qantas has acquired a Boeing B787 full flight simulator with integrated eye-tracking capability, with the focus to be used for pilots transitioning on the B787 type and specifically for them to be trained effectively on the use of the Head-Up Display (HUD). Other airlines – such as Air France and Emirates – have worked on developing eye tracking to become a tool in regular flight training. Similar development work is ongoing at other airlines, simulator manufacturers and eye-tracking equipment manufacturers.

There are at least three ways in which eye tracking could support learning, not all of which have been applied to pilot training, to the best of our knowledge. First, if the objective of a training program is to guide the viewer to specific locations in the cockpit at specific times, e.g. to aid trainees in acquiring the gaze behavior of an expert, a replay of gaze behavior may be an appropriate choice of learning material. In this eye movement modeling examples paradigm (EMME, [14, 16, 25, 26]), the eye-tracking data takes on a cueing or signaling function [27–29], giving trainees the opportunity to "look through the expert's eye" by means of following an attention marker that indicates where the expert is currently looking. This not only directly models the gaze behavior of an expert, but also helps disambiguate verbal explanations of the behavior they are modeling—especially in visually complex environments [16, 30].

Second, the insight of pilots into their visual strategies may be enhanced by viewing gaze replays of their own recorded scan path. As discussed by [31], this can aid meta-cognitive reasoning, i.e., reflection about their own behavior, which enhances learning. For instance, [32] showed that visualizations of eye tracking data can foster meta-cognitive processes directly: they found that when people re-watched their own performance on a task, they make more meta-cognitive statements about what they did when they also see a replay of the eye movements they made during task execution, compared to when they were not able to see their eye movements.

Third, gaze replays of students may also support the insight of an instructor or assessor into pilot behavior, e.g., since these replays "would allow the pointing out of attentional errors by pilots, such as an excessive focus on a particular flight parameter or, on the contrary, its disregard" [22]. We like to add to this that live views of pilot gaze may also enhance training and assessment scenarios as they enable the instructor or assessor to provide in-situ guidance instead of only after-the-fact feedback, which may aid learning for instance by providing the opportunity for co-construction [33, 34]. In the last forty years, a series of studies have explored this use of gaze displays [35–41] but found mixed results, possibly due to sometimes unintuitive, distracting and delayed visualizations offered by these tools. Nonetheless, questionnaires showed that instructors found access to pilot scan patterns helpful.

It is important to note that when trainees view an expert's eye movements or review their own, they do so with their full attention and are thus able to devote maximal processing capacity to the task of following and understanding the gaze display. In a highly time-constrained activity such as commercial pilot simulator training, it is questionable that time would be available for reviewing gaze recordings, and what the cost-benefit balance of such an approach would be. In addition, we question whether direct gaze displays are an appropriate tool for the instructor or assessor in this scenario [see also 37, 42]. Gaze replays or live views likely do not present pilot visual behavior in an easy-to-understand way for an instructor or assessor who already has high workload. Specifically, we think that the following problems with gaze displays should be considered:

1. Humans change their gaze location at a rate of three or more times per second [43]. As such, gaze displays show a series of gaze locations at a rate that is hard to keep up with.
2. Using gaze displays to judge, e.g., whether a pilot has looked sufficiently often at an instrument entails high memory load. We consider it unlikely that an instructor or assessor is able to mentally aggregate all the rapid fixations a pilot makes into a tally of gaze per cockpit element.
3. Interpreting the task someone is performing from gaze displays has been shown to be difficult [44, 45]. As such, even if the instructor or assessor is able to follow the gaze display, they are unlikely to derive insight into pilot behavior from it.

The above factors make interpreting a gaze display not only time-consuming, but also too cognitively demanding to be translated to effective learning or coaching in limited time. Similar critique holds for static visualizations of gaze behavior, which, we posit, are also frequently demanding to interpret (see, e.g., the visualizations in [46, 47]).

Besides the above limitations, bringing academic research results to day-to-day operations comes with other issues. First, while in academic settings data collection and analysis often take a long time and are performed on an aggregate level, to apply eye tracking in pilot training and assessment, the analysis and feedback needs to be (nearly) instantaneous and the results need to be specific and targeted. Second, parameters useful in research are not necessarily useful to assess and develop pilot competencies. The development of simple, relevant and useful parameters for use by pilots, instructors and assessors remains a challenge. These metrics must be reliable and presented in a simple interface that makes them understandable and convincing enough to be useful at 03:00 AM in a discussion after a simulator session.

4 DASHBOARDS: TURNING EYE-TRACKING DATA INTO INFORMATION

As argued above, we think that gaze replays are unlikely to be of use in most training and assessment applications, and research into what constitutes effective visualization of eye-tracking data for pilot instructors is only just beginning [48]. In this section, we therefore propose methods and design guidelines for aggregation and visualization of eye-tracking data such that it can effectively contribute to assessment of pilot performance. Specifically, we propose that when assessing whether pilots display situationally appropriate gaze behavior, instructors and assessors would benefit from dashboards that provide insight into gaze behavior at a higher level of abstraction than gaze replays. In our opinion such dashboards should adhere to the following design principles:

1. Aggregated: To overcome the workload associated with viewing gaze displays, the dashboard should aggregate the gaze behavior over time and space, and present it at an appropriate level of spatial and temporal detail. The aggregation level should be user-configurable and linked to simulator events, so that the user can easily generate task-specific data views (e.g., gaze distribution between primary flight display and runway in the last 90 seconds before touch-down).

2. Relevant: The presented data should be relevant to the task at hand and contain as little extraneous information as possible. This is achieved through adapting the dashboard to specific situations. E.g., when performing a maneuver where looking at the PFD is critical, to reduce complexity all gaze to other elements can simply be grouped in a category "other", rather than specified per instrument panel.

3. Simple: The dashboard should display data in an intuitive manner such that the relevant information can be picked up in a single glance [c.f. 49]. Thereby instructors can use insights from eye tracking for real-time feedback to pilots, or use it to direct scenario evolution.

4. Timely: The dashboard should provide aggregated data in real-time so that it can be used by the instructor during the training session. When used for debriefing, it should be available immediately without causing wait times due to transcoding or processing.

5. Transparent: Some visualizations of eye-tracking data can suggest a higher level of certainty about measured gaze position than can actually be obtained due to the inherent inaccuracy and imprecision of the equipment and calibration, and due to the functioning of the human visual system. The dashboard should make the level of uncertainty about actual gaze position (and inferences about attended location) obvious to avoid misinterpretation.

6. Explanatory: Without a background in eye tracking, it can be difficult to understand what certain gaze metrics mean, how they are defined, and how they are measured (e.g., dwell vs. fixation). It should be easy to understand the meaning of the metrics presented in the dashboard, ideally through means of user interface but otherwise by documentation.

7. Embedded: To the greatest extent possible, the dashboard should be embedded in the training infrastructure, specifically in regards to output of simulator data. That means for instance that flight data (e.g., air speed, landing gear deployment, etc.) are accessible to the dashboard and can be shown on the timeline alongside gaze data, and that information from the dashboard can be archived in the training assessment system.

5 APPLICATIONS OF EYE-TRACKING DATA

Below we discuss three specific applications where we think that eye-tracking data that can provide better insight into pilot behavior than would be possible without having knowledge about where the pilots are looking.

1. Assessing instrument monitoring behavior: is the scan pattern adopted by the pilots appropriate (and according to training) for the current situation? Do the two pilots correctly synchronize their gaze behavior as expected by the choreography of procedures they carry out, or are specific instruments left unmonitored between them? A suitable interface to answer these questions may be a recency map indicating for each instrument in the cockpit of relevance to the current flight phase when it was last looked at by each of the pilots. Instructor interaction with a specific instrument on this dashboard may either cue the pilots to monitor that instrument, or initiate an unexpected event that can only be detected using that instrument.

2. Assessing decision making: gain insight into whether visual behavior is appropriate during a certain situation and whether information looked at is taken in and responded to appropriately.

When an unsafe situation/error occurred that could have been discovered from the instruments, was the information not looked at or not acted upon? If it is looked at, how long until it was acted upon? As an example, a situation can be taken in which multiple instruments are critical once a failure condition is initiated. Latency until first look on these instruments and time spent looking at these instruments are displayed on the dashboard, along with the state of the relevant control inputs. Instruments not looked at are flagged saliently to cue the instructor.

3. Procedural compliance: Is the right information about aircraft state acquired before making a given decision (e.g., looking at air speed before selecting flaps)? A dashboard can be envisioned in which a timeline of specific flight operations is provided. Upon selecting a specific event, gaze data leading up to that event is classified into looks at various relevant instruments and an "irrelevant" category. During normal operation, the dashboard could automatically display this information for the current or last-undertaken flight action.

We think that such situationally-relevant aggregation and visualization of gaze data would allow an instructor or assessor to see what the pilots see instead of only staring at their backs, providing a significant increase in insight into pilot behavior. This insight may help resolve many questions in current debriefs, allowing to focus on where improvement or retraining is needed. These dashboards would allow Evidence-Based Training regarding situationally appropriate gaze behavior to take a big step forward, improving training efficiency and safety in line operations.

6 CONCLUSIONS

In this position paper, we have discussed the challenges that instructors and assessors face in developing insight into pilot behavior, and have articulated a way forward for how eye-tracking technology could augment their ability to do so. We discussed why direct replays or live views of pilots' gaze data are likely to be of little use to instructors and assessors, especially since they usually have many other tasks to manage during a simulator session and thus do not have the requisite cognitive resources available to process such information. We therefore proposed that eye-tracking data should be presented at a higher level of abstraction and aggregation in the form of smart, contextually sensitive dashboards, and suggested novel applications of eye-tracking data in pilot training and assessment using these dashboards.

While we believe that these dashboard interfaces can improve flight training efficiency and effectiveness, it must be recognized that this field is in its infancy and significant research work is required before such tools can be deployed in daily practice. First, automatic gaze analysis is required [e.g. 50] and integration of these systems with flight simulator data needs to be developed. Second, attainable data quality with eye trackers [51, 52] in the simulator setting must be evaluated. Third, an effort needs to be made to systematically evaluate the SOPs together with expert instructors to identify expectations about pilot visual behavior and determine which elements in the cockpit should be targeted by the dashboards in which flight scenarios [c.f. 38, 39]. Fourth, significant work is required to determine effective eye-tracking data visualizations [c.f. 48] and to validate and refine the dashboard concept as posited here. Furthermore, integration with other sensor data, such as voice analytics, would enable a complete procedural compliance training system that is able to automatically score sequences such as {**look** (airspeed) – **speak** ("flaps 20") – **other pilot look** – **act** (change flaps) – **look** (confirm flaps in right position)} [c.f. 53]. We think these items offer interesting research potential for the future, as well as opportunities for strong collaborations between academia and the aviation industry.

Lastly, while this paper has focused on pilot training and assessment, it should be noted that similar techniques and principles would apply also to training and assessment of other personnel in the aviation industry, such as air traffic controllers [54–57] and operation control center staff. Furthermore, the techniques developed are likely to find application in other fields where the acquisition of visual skills is an important part of training, such as driving instruction [12], teachers managing classrooms of students

[58, 59], medical personnel in diagnosis or surgery situations [15, 44], and even fashion designers [60, 61]. While we believe that the aviation industry presents an ideal seedbed for developing eye-tracking dashboards, we think that the potential to generalize this research, the derived techniques and the findings to other domains makes it all the more worthwhile to carry out.

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