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Flight Crew Visual Scanning Techniques on Transport Category Aircraft

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16. ABSTRACT

Aviation incidents and accidents have often been linked to inadequate monitoring of flight deck information. Still, to date, limited data and guidance exist on how pilots should, and how they actually do allocate their attention to various flight deck displays. This project aims to help fill this gap with the goal to inform design and training interventions that better support flight crews in monitoring their flight path, automation status, and associated behaviors. First, a review of the scientific literature, regulatory documents, and guidance material related to visual scanning on modern transport category aircraft was conducted. Building on the findings from the literature review, three focus groups were held with twelve aviation professionals to learn about (1) current needs and approaches to scan training, (2) factors that lead to breakdowns in monitoring, and (3) the effect of flight deck design on visual scanning. Finally, publicly available documents were examined, and virtual meetings were held with airline representatives to learn about plans and ongoing efforts to introduce eyetracking to pilot training as a tool for assessing and improving pilots' scanning behavior. In combination, the above research activities highlight that, despite widespread agreement on the need for improving pilots' monitoring strategies and performance, significant gaps still exist in our understanding of what effective scanning behavior, training and procedures look like for individual pilots, in their role as PF or PM, for entire flight crews, and across flight phases and events. Existing guidance and recommendations tend to be rather broad and focus on desired outcomes rather than describing the specific means of achieving those goals. Eyetracking has emerged as a promising tool to fill these gaps, but more work is needed to develop the hardware, processes and interfaces needed to deploy the tool for those purposes.

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ACRONYMS

A(D)I	Attitude (Director) Indicator
AC	Aircraft
AFM	Airplane Flight Manual
ALT	Altitude
AOI	Area of Interest
AP	Autopilot
AQP	Advanced Qualification Program
AR	Augmented Reality
AS	Airspeed
ATC	Air Traffic Control
BEA	Bureau Enquêtes-Accidents
CAA	Civil Aviation Authority
CARS	Crew Awareness Rating Scale
CDU	Control Display Unit
CFIT	Controlled Flight Into Terrain
CMF	(NASA's) Cockpit Motion Facility
COVID	Coronavirus Disease
CP	Center Pedestal
CRT	Cathode Ray Tube
DBF	De-Briefing Facilities
ECAM	Electronic Centralized Aircraft Monitor
EFIS	Electronic Flight Instrument System
EICAS	Engine Indicating and Crew Alerting System
EV	External View
FAA	Federal Aviation Administration
FCU	Flight Control Unit
FD	Flight Director
FFS	Full Flight Simulator
FMA	Flight Mode Annunciation
FMC	Flight Management Computer
FMGC	Flight Management and Guidance System
FMS	Flight Management System
FO	First Officer
FPM	Feet-Per-Minute
GA	General Aviation
GRACE	Generic Research Aircraft Cockpit Environment
HDG	Heading
HF	Human Factors
HFES	Human Factors and Ergonomics Society
HSI	Horizontal Situation Indicator
HUD	Head-Up Display
IATA	International Air Transport Association

ICAO	International Civil Aviation Organization
ICP	Instrument Control Panel
IFR	Instrument Flight Rules
ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions
ISA	Instantaneous Self-Assessment
LCA	Line Check Airman
LCD	Liquid Crystal Display
LGHCD	Landing Gear Handle Control and Display
LOC DME	Localizer Distance Measuring Equipment
LOSA	Line Operations Safety Assessments
MCDU	Multi-Function Control and Display Unit
MCP	Mode Control Display
MEL	Minimum Equipment List
MFD	Multi-Function Display
MIDAS	Air Man-Machine Integrated Design and Analysis System
MSL	Mean Sea Level
NASA	National Aeronautics and Space Administration
ND	Navigation Display
NTSB	National Transportation Safety Board
OP	Overhead Panel
OTW	Out-The-Window
PARC CAST	Performance Based Operations Aviation Rulemaking Committee - Commercial Aviation Safety Team
PDT	Percentage Dwell Time
PF	Pilot Flying
PFD	Primary Flight Display
PI	Principal Investigator
PM	Pilot Monitoring
PNF	Pilot Not Flying
POH	Pilot’s Operating Handbook
POR	Point of Regard
RAF	British Royal Airforce
RFD	(NASA’s) Research Flight Deck
SEEV	Salience, Effort, Expectancy, Value (Model)
SID	Standard Instrument Departure
SIP	Standby Instruments Panel
SOP	Standard Operating Procedure
SPO	Single-Pilot Operations
STAR	Standard Arrival
UM	University of Michigan
VFR	Visual Flight Rules

VMC	Visual Meteorological Conditions
VNAV	Vertical Navigation (mode)
VNAV ALT	Vertical Navigation Altitude (mode)
VSI	Vertical Speed Indicator

Flight Crew Visual Scanning Techniques on Transport Category Aircraft

Abstract

Aviation incidents and accidents have often been linked to inadequate monitoring of flight deck information. Still, to date, limited data and guidance exist on how pilots should, and how they actually do allocate their attention to various flight deck displays. This project aims to help fill this gap with the goal to inform design and training interventions that better support flight crews in monitoring their flight path, automation status, and associated behaviors. First, a review of the scientific literature, regulatory documents, and guidance material related to visual scanning on modern transport category aircraft was conducted. Building on the findings from the literature review, three focus groups were held with twelve aviation professionals to learn about (1) current needs and approaches to scan training, (2) factors that lead to breakdowns in monitoring, and (3) the effect of flight deck design on visual scanning. Finally, publicly available documents were examined, and virtual meetings were held with airline representatives to learn about plans and ongoing efforts to introduce eyetracking to pilot training as a tool for assessing and improving pilots' scanning behavior. In combination, the above research activities highlight that, despite widespread agreement on the need for improving pilots' monitoring strategies and performance, significant gaps still exist in our understanding of what effective scanning behavior, training and procedures look like for individual pilots, in their role as PF or PM, for entire flight crews, and across flight phases and events. Existing guidance and recommendations tend to be rather broad and focus on desired outcomes rather than describing the specific means of achieving those goals. Eyetracking has emerged as a promising tool to fill these gaps, but more work is needed to develop the hardware, processes and interfaces needed to deploy the tool for those purposes.

1. Introduction

Breakdowns in pilot-automation interaction, and resulting incidents and accidents, have often been linked to inadequate monitoring[1] of flight deck systems and interfaces. In 1994, the National Transportation Safety Board (NTSB) stated that, "in their view, more than 80% of accidents were happening as a result of inadequate monitoring." Based on a review of 24 Controlled Flight Into Terrain (CFIT) accidents, the International Civil Aviation Organization concluded that in half of those cases, the "crew did not monitor properly" (ICAO, 1994). Two years later, the FAA Human Factors report titled 'The Interfaces between Flight Crews and Modern Flight Deck Systems' (FAA, 1996) similarly expressed the view that "incidents demonstrating deficiencies in flightcrew monitoring and awareness of autoflight system modes, airplane energy state, terrain proximity, and airplane systems' status are occurring to an unacceptable extent." And another 17 years later, concerns about pilot monitoring were raised yet again in a report by the Performance Based Operations Aviation Rulemaking Committee

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[1] Note that this document adopts the definition of monitoring by the Civil Aviation Authority (CAA) Loss of Control Action Group (2013): "The observation and interpretation of the flight path data, configuration status, automation modes and on-board systems appropriate to the phase of flight. It involves a cognitive comparison against the expected values, modes, and procedures. It also includes observation of the other crew member and timely intervention in the event of deviation." Visual instrument scanning is considered one element of monitoring.

(PARC) Commercial Aviation Safety Team (CAST) Flight Deck Automation Working Group, titled ‘Operational Use of Flight Path Management Systems’ (FAA, 2013).

To date, limited data exist concerning pilots’ monitoring behavior (i.e., how they allocate their attentional resources to various sources of information over time) and performance (how effective their monitoring is). This project aims to help fill this gap which is critical for developing training interventions that better support flight crews in monitoring the flight path and in tracking automation status and behavior. Improved insights into visual scanning will also help determine the acceptability of proposed designs for new flight deck displays and layouts.

We first conducted a review of the scientific literature, regulatory documents, and guidance material related to visual scanning on modern transport category aircraft. This review highlights findings from empirical, mostly eyetracking-based studies on flight crew monitoring behavior which are summarized in a report titled “Flight Crew Visual Scanning Techniques on Transport Category Aircraft” (Sarter and Thomas, 2021). Building on the findings from our literature review, we next conducted three focus groups on visual scanning with aviation professionals to gain a better understanding of current practices in the commercial aviation sector. Participants in the focus groups included active commercial airline pilots, instructor pilots and check airmen, safety and human factors experts, and flight deck designers. The main goal of these focus groups was to learn (1) what current training needs and approaches are, (2) what factors lead to breakdowns in monitoring, and (3) how flight deck design affects visual scanning. We prepared a technical report for the FAA titled “Flight Crew Visual Scanning Techniques on Transport Category Aircraft: Findings from Focus Groups with Aviation Stakeholders” (Sarter and Thomas, 2023) that documented the key insights from the three focus groups. Finally, publicly available documents were examined, and virtual meetings were held with airline representatives to learn about plans and ongoing efforts to introduce eyetracking to pilot training as a tool for assessing and improving pilots’ visual scanning behavior.

This final technical report provides an overview of findings from the above research activities and includes revised and updated versions of the first two technical reports that were prepared as part of this effort. It starts with a historical perspective on how instrument flying and visual scanning evolved since the early days of aviation.

2. A Historical Perspective on Instrument Flying and Visual Scanning on Flight Decks

2.1 Before the Introduction of Flight Instruments

Over the last century, the design, equipment, and layout of flight decks have changed considerably. As late as the early 1920s, many passenger and military aircraft were still flown with open flight decks due to a lack of material needed to make windows that were sufficiently safe and light-weight and did not discolor. Enclosed flight decks became the norm only during the Second World War. Also, the value of flight instruments was greatly underestimated until the 1920s. A common misconception at the time was that pilots were able to maintain awareness of the movement and position of their airplane without any assistance.

This misconception was challenged as early as 1918 by Colonel William Charles Ocker who became a huge proponent of flight instruments (Wolverton, 2008) after becoming disoriented himself while flying through a cloud as he was testing an early turn indicator. Also, around that time, before the end of WW1, systematic research began on how to recover from a spin which commonly followed the disorientation pilots experienced when, without guidance from instruments, they had to climb through clouds or enter clouds to escape interception in combat operations. The first documented case of an intentional spin and recovery is that of Harry Hawker who, in 1914, demonstrated that the use of the rudder to oppose rotation was a critical component of spin recovery. Hawker did not rely on instruments, however. This approach was championed three years later by the English physicist Frederick Lindemann who conducted a series of experiments that led to an early understanding of the aerodynamics of a spin and the importance of instrument flying skills. Like Lindemann, Ocker who is often referred to as the "Father of Instrument Flying" realized "that instinct is worse than useless in the clouds, that it can induce deadly spirals, and that as a result having gyroscopes is not enough, that pilots must learn against all contradictory sensations the difficult discipline of an absolute belief in their instruments" (Langewiesche, 1998).

Ocker's proposal to introduce flight instruments was met with skepticism from the aviation community which still believed in 'flying by the seat of their pants'. To prove to pilots that their senses were easily tricked and to demonstrate the advantage of using flight instruments, Colonel Ocker and Captain David Myers (at the time the flight surgeon at Crissy Field, CA - a former U.S. Army airfield) conceived of an experiment. Pilots were blindfolded and placed in a Jones-Barany chair (a device still used for aerospace physiology training; see Figure 1). They were spun around the vertical axis and then stopped and asked to perform tasks such as determine their direction of rotation or attempt to point at a stationary object after the chair was stopped.

Figure 1. Jones-Barany Chair 1919
(from https://goflightmedicine.com/aerospace-medicine/history-of-flight-medicine/)

Pilots were unable to perform those tasks; they quickly lost track of direction and orientation. Ocker would then have the pilot repeat the experiment, this time with their head being covered by a box which contained a turn indicator and a penlight (the so-called “Ocker box”; see Figure 2). This minimal set of instruments led to a significant improvement in pilots’ performance. Ocker later added more aircraft instruments, such as a compass and an artificial horizon.

Figure 2: Pilot Testing the Ocker Box
(from “Instructions in Use Of “Ocker Box” In Teaching Instrument Flying”, 1932)

Initially, the military did not see the value in Ocker’s work and continued to dismiss instrument flying as “unnecessary, dangerous” (Wolverton, 2008). However, commercial aviation began to adopt his ideas, and military aviation would soon follow.

2.2 The 1930s –Needle, Ball and Airspeed Scan

In the 1930s, the primary instruments used by pilots were the airspeed and the turn-and-bank indicators (see Figure 3). A turn-and-bank indicator responds to airplane roll. It shows roll direction, rate, and quality. This information can be derived by visually referencing the instrument’s components and markings. Components include a roll pointer and an inclinometer (ball), which move simultaneously during a flight operation. A pilot can derive roll direction, rate, and quality by observing their movement in relation to the instrument markings (see Figure 4).

Figure 3. Airspeed (on the left) and turn-and-bank indicator (on the right)
(from https://www.aircraftspruce.com/catalog/graphics/1/10-22614.jpg)

Figure 4. Interpretation of the bank-and-turn (or bank-and-slip) indicator
(from http://learntoflyblog.com/2016/05/16/flight-instruments-the-turn-and-slip-indicator/)

Pilots were trained to employ the so-called “needle, ball and airspeed” method of flying and scanning. They were taught to adjust each control surface (rudder and aileron) separately and monitor the effects on each part of the instrument (ball and needle). Training for flying in IMC (instrument meteorological conditions) increased and improved and was greatly aided by the development of the first Link Trainer in the early 1930s. This early flight simulator allowed pilots to develop instrument flying skills in a safe ground-based environment. It accurately simulated the responses of flight instruments to a pilot’s control inputs and was a major aid in training pilots throughout World War II. By the mid-1930s, instrument flying was considered a primary pilot skill.

2.3 The 1940s–1960s – The Basic-T Configuration

During the 1940’s, the demand for trained IFR (Instrument Flight Rules) pilots grew dramatically. The main driving force was a shift in military strategy during World War II which required pilots to fly regularly in visual and instrument meteorological conditions. Training time had to be reduced to meet this quickly rising demand. To accomplish this goal, the British Royal Airforce (RAF) developed a new standard flight deck design which consisted of six instruments: an airspeed indicator, altimeter, vertical speed indicator, attitude indicator, heading indicator, and a turn coordinator (see Figure 5). These instruments are often referred to as the ‘six-pack’. The four primary instruments in this group (airspeed, attitude, altitude and heading) are arranged to form the ‘Basic-T’ (see Figure 5). Adopting this standard configuration not only allowed the military to reduce training time but also made it easier for pilots to transition between different aircraft models if necessary.

Figure 5. Six basic instruments on flight decks (top; from https://www.airpowerinc.com/six-pack-aircraft-instruments) and their Basic-T arrangement (bottom; from https://en.m.wikiversity.org/wiki/File:Basic-T_AA_1.jpg)

The Basic-T layout became the default layout for all RAF planes for two decades. The U.S. military followed suit and adopted the Basic-T in 1943. Commercial and general aviation aircraft also began using the Basic-T as the standard layout for aircraft of all sizes. This new layout led to a different training technique for IFR flight, called “full panel” or “attitude” flying. It was perceived by pilots to be a more natural method of flying and quickly replaced the needle, ball, and airspeed method. In attitude flying, pilots learn to use their instruments to determine and visualize the airplane’s attitude in relationship to the natural horizon. This includes its pitch attitude (the angle between the airplane’s longitudinal axis and the natural horizon) and the bank attitude (the angle between the airplane’s lateral axis and the natural horizon) (see Figure 6). Pitch and bank attitude are controlled by moving the elevator and ailerons, respectively. Pilots’ scan now focused primarily on the attitude indicator (the instrument highlighted in Figure 5). They regularly and briefly scanned secondary instruments, such as the airspeed indicator and altimeter, but then returned to the attitude indicator.

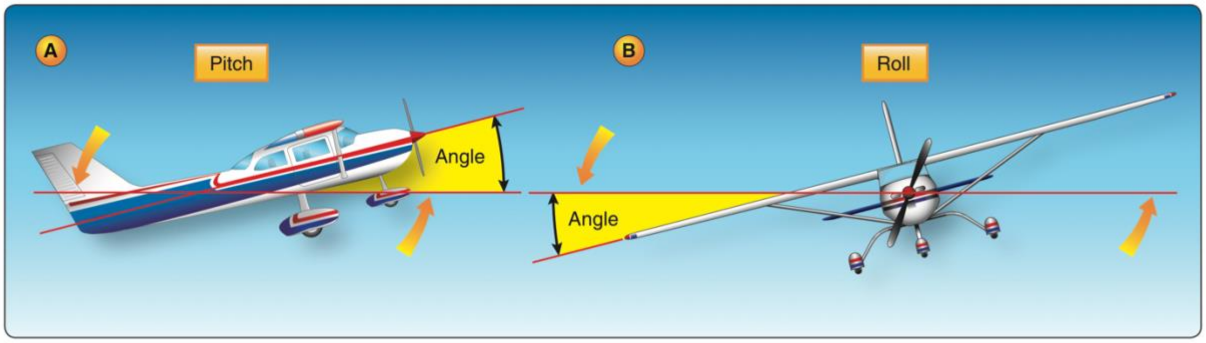


Figure 6. Illustration of pitch and bank attitude of an airplane (from https://safeblog.org/2017/02/11/effective-cfi-attitude-control-is-aircraft-control/)

To this date, the vast majority of pilots on smaller less complex aircraft are taught to scan their instruments using this hub-and-spoke, or radial, pattern where attitude serves as the hub, i.e. the attitude indicator is considered the most important instrument that should be checked after looking at any of the other indications. Some pilots have adopted an alternative approach. Their scan still focuses on the six main instruments, but they scan these instruments in a circular pattern that starts with airspeed or attitude and moves around the ‘six-pack’ in a clockwise fashion.

2.4 The 1970s To Today – The Advent of More Complex and Glass Cockpits

The next major change to flight deck layout and instrumentation did not occur for about thirty years. By the late 1960s and early 1970s, the ‘Basic-T’ was still the default instrument configuration. However, commercial flight decks were growing more complex. By the mid-1970s, the average transport aircraft had more than 100 flight deck instruments and controls, and the primary flight instruments were crowded with indicators and symbols (Wallace, 1994). For an example of this trend, Figure 7 shows the flight deck of a McDonnell Douglas DC-9.

Figure 7. Flight deck of the McDonnell Douglas DC-9 (from https://www.airliners.net)

To address this problem, work began on so-called ‘glass cockpits’. The glass cockpit relies on an electronic flight instrument system (EFIS) to combine and integrate data that were traditionally shown on separate analog dials and gauges. Early EFIS models used cathode ray tube (CRT) displays but liquid crystal displays (LCD) are now more common. The following sections describe the location and information presented on the main displays and interfaces on modern flight decks. This will help the reader interpret the findings from the eyetracking studies that are reviewed later in this document.

Note that the terms introduced in the following sections are used on Boeing aircraft. On Airbus airplanes, the Mode Control Panel (MCP) is referred to as the Flight Control Unit (FCU), the Control Display Unit (CDU) is called Multi-Function Control and Display Unit (MCDU), the name for the Engine Indicating and Crew Alerting System (EICAS) is Electronic Centralized Aircraft Monitor (ECAM), and the Flight Management Computer (FMC) is being called Flight Management and Guidance System (FMGC).

One of the most critical data-rich displays on the modern flight deck is the Primary Flight Display (PFD). The PFD contains an attitude director indicator (ADI; highlighted by yellow box in Figure 8) which shows the aircraft's pitch and roll, and the orientation of the aircraft with respect to the horizon. To the left and right of the ADI are the airspeed and altitude tape instruments. The vertical speed indicator, to the right of the altitude indicator, indicates how fast the aircraft is ascending or descending. At the bottom of the PFD is the heading display, which shows the pilot the magnetic heading of the aircraft. The arrangement of the various displays on the PFD closely, though not completely, resembles the way the traditional round-dial gauges are placed on earlier flight decks. Other information displayed on the PFD includes navigational markers, ILS glideslope indicators and, importantly, flight mode annunciations (FMAs; at the top of the PFD) which inform the pilot about the status of autoflight systems and the active or engaged modes that these systems operate in.

Figure 8. Arrangement of various instruments on the PFD (top) of a B737-800 (from https://en.m.wikipedia.org/wiki/File:Primary_Flight_Display_of_a_Boeing_737-800.png)

Next to the PFD is the Navigation Display (ND), also known as the map display. The ND provides a top-down view of the location and future path of the aircraft in relation to landmarks and waypoints. In the center, between the two pilots' NDs, are two screens presenting information on various engine parameters, and other aircraft systems, including hydraulics, electrical, and control surfaces of the aircraft. These two displays are called the 'Engine Indicator and Crew Alerting System' (EICAS). Located above the EICAS is the Mode Control Panel (MCP) which is used as a 'tactical' interface to the Flight Management System (FMS). The MCP is used to engage the autopilot and autothrottle and select the specific modes in which they operate. It also allows pilots to set target airspeed, altitude, heading and vertical speed. A more 'strategic' interface with the Flight Management Computer (FMC) is the Control Display Unit (CDU) which allows pilots to enter their entire flight plan and locate important information such as waypoints/intersections, airways, radio navigation aids, airports, runways, and Standard Instrument Departures and Arrivals (SIDs and STARs).

Figure 9. Boeing B777 cockpit (from https://wallpapercave.com/wp/wp2449834.jpg)

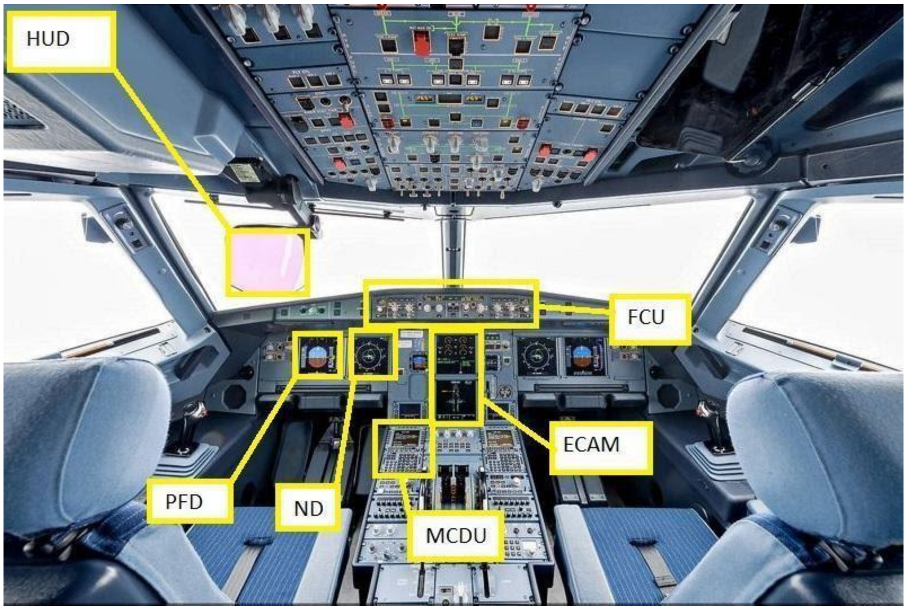


Figure 10. Airbus A320 cockpit
(from https://services.airbus.com/en/flight-operations/system-upgrades/navigation/head-up-display-hud.html)

3. Literature Review

3.1 Focus and Approach

Our review of the scientific literature on the topic of visual scanning on modern transport aircraft is based on a search of Google and Google Scholar for relevant publications between 2000 and 2023. Since these two databases do not include all pertinent journals, we also searched the archives of the International Journal of Aviation Psychology, Human Factors, Ergonomics in Design, The Journal of Cognitive Engineering and Decision Making, the Proceedings of the HFES Annual Meeting, the Review of Human Factors and Ergonomics and the Proceedings of the 1st International Workshop on Eye-Tracking in Aviation.

The search terms that were used and combined in various ways to locate relevant research included: (1) Visual/Instrument Scanning on Flight Decks, (2) Monitoring on Modern Flight Decks, (3) Pilot Scanning/Monitoring Strategies, (4) Visual Scanning and Flight Performance, (5) Eyetracking on Flight Decks, and (6) Training for Visual Scanning/Monitoring of Flight Instruments.

The search yielded a large number of publications but given the focus of our project on visual scanning on transport category aircraft, many were ultimately excluded from our review because the study focused on the use of eyetracking for other purposes (such as workload estimation), or because the research was conducted in general aviation (GA), military operations, rotorcraft, or air traffic control. The latter studies are included in earlier reviews by Ziv (2017) and Peißl et al. (2018). We also excluded studies that involved a very small number of participants and/or employed low fidelity flight simulations. Note that publications that were not included in the review for the above reasons are still listed at the end of the document as part of the list of references (see ‘other publications related to eyetracking and visual scanning’).

3.2 Methods for Studying Visual Scanning

Researchers have used a range of methods to study, describe or predict the visual scanning behavior of pilots, including interviews, surveys, modeling and eyetracking. Each of these methods involves benefits and limitations. Surveys and interviews are relatively easy to administer and a fast inexpensive way to gather information from a large number of respondents. However, introspection has been shown to be a highly inaccurate source of self-knowledge; humans may describe their assumed or desirable, rather than their actual behavior, based on widely held expectations and beliefs.

Computer models have been created to capture and predict the visual scanning behavior of pilots (e.g., Keller et al., 2004). Examples of such models are the MIDAS Model and the (N) SEEV model. MIDAS, the Air Man-Machine Integrated Design and Analysis System, was developed by NASA to assist with the design, visualization, and evaluation of complex systems. Verma and colleagues (2004), for example, used Air MIDAS to construct a model of pilots’ visual behavior and to predict the effects a new experimental display used during nominal approaches on pilots’ scanning behavior. The SEEV model (Wickens et al., 2007) predicts how scanning is driven by four components in the monitoring and control of complex workplaces like the aircraft cockpit:(1) S(alience), (2) E(ffort), (3) E(xpectancy), and (4) V(alue). The SEEV model was later expanded to include a noticing component. This expanded model is known as the N(oticing)-SEEV model. It predicts the latency and accuracy of noticing discrete events in the context of the ongoing scanning predicted by SEEV. The creation and continued improvement of these models requires the collection of reliable empirical data on actual visual search and scanning behavior. One promising technique for collecting these data is eyetracking.

3.3 Eyetracking

Eyetracking is a sensor technology that makes it possible to determine where a person is looking. Both top-down (i.e., operator-related) and bottom-up (i.e., display-related) attention control are assumed to be linked to eye movements (for a comprehensive review of these two forms of attention control see Theeuwes, 2010). Recent empirical evidence confirms the role of top-down control in that the majority of eye fixations tend to fall on task-relevant objects, and changing the task radically alters the fixation patterns. Scanpaths have also been shown to be affected by top-down factors, such as experience and training. Bottom-up factors such as the salience of a display (element) affect eye movements as well. Salience has proven to correlate with the location of fixations. Eyetracking serves as a process, rather than performance outcome measure. In other words, eyetracking makes it possible to trace changing information access strategies over time at a fine-grained level of analysis (Zelinsky & Sheinberg, 1997). Given the above advantages of eyetracking over any other method for studying visual attention allocation, our literature review focuses on studies employing this technique.

Eyetracking studies are conducted by mounting eyetracking equipment in fixed positions in a simulator, or by having participants don wearable eye trackers (see Figure 11). There are several important components of eye movements which serve as the building blocks for eyetracking metrics (see Poole and Ball (2005) for a review). Points of regard (POR) are the raw data output of eye trackers that indicate where a person is looking in the display (Munn, Stefano, & Pelz, 2008). Fixations are formed from spatially stable PORs and it is during this time that visual processing takes place (Findlay, 2004). Note that this definition of the term ‘fixation’ will be adopted throughout this report (as opposed to the use of ‘fixation’ to denote an inordinate or excessive amount of time spent on looking at and/or thinking about one specific element, potentially due to fear or confusion). The rapid eye movements in between successive fixations are called saccades, during which time visual processing is suppressed (Yarbus et al., 1967). An area of interest (AOI) is an experimenter-defined region of the display on which analysis of eyetracking data is performed. For example, the Primary Flight Display (PFD) can constitute one AOI, or it can be subdivided into multiple AOIs, such as the airspeed indicator, the artificial horizon, the vertical speed indicator, and flight mode annunciations. Alternatively, the PFD may be combined with the map display into one larger AOI. Gaze (or dwell) is the series of fixations within a particular AOI, beginning with the first fixation on that AOI and ending with the first fixation outside of that AOI (Jacob & Karn, 2003).

Common eyetracking metrics used in studies of scanning in the aviation domain include event-triggered fixations (e.g., fixations following a particular discrete event, such as a mode transition), dwell time or fixation duration, and percentage dwell time (PDT). PDT is defined as dwell time for one AOI divided by the sum of dwell times for all AOIs. Very few studies have examined the sequence in which pilots access information. These studies analyze the scanpath, i.e., the sequence of dwells and fixations, and they measure the extent to which the dwell sequence is disordered or random. This degree of randomness is referred to as entropy, an information theory measure (Shannon & Weaver, 1949). The more random the sequence in which pilots access information, the higher the degree of entropy. A small number of researchers have employed the so-called 'explore/exploit ratio' which compares the number of short-duration fixations (around 100 ms) to the number of long-duration fixations (greater than 240 ms). A relatively larger number of short fixations suggests exploring behavior whereas a dominance of longer fixations is considered an indication of exploiting (i.e., deep processing of information).

Figure 11. Eyetracking glasses in use in a simulator (from Haslbeck and Bengler 2016)

Another way in which researchers are trying to distinguish between 'looking' and 'seeing', i.e., actually processing the information that is being fixated, is by examining microsaccades. Microsaccades have been defined as "involuntary, small-magnitude saccadic eye movements that occur during processed visual fixation" (Krueger et al., 2019). They usually have an amplitude of less than two degrees of visual angle. Microsaccade rates decrease with increased mental task demands and significantly increase in conditions that require a high degree of visual attention. Also, an increase in microsaccades appears to lead to an enhanced visibility for peripheral and parafoveal visual targets (Martinez-Conde et al., 2006). Finally, some research has linked microsaccade production to cognitive processes, such as working memory (e.g., Valsecchi et al., 2007).

3.4. Empirical Studies Using Eyetracking to Examine Scanning of Flight Instruments

The following table lists 26 studies that employed eyetracking to study visual scanning in high-fidelity simulation environments, with experienced commercial pilots as participants. These studies will be described briefly, and their findings will be summarized.

Table 1. Eyetracking studies (in alphabetic order of first author's last name) included in the review

Study Author(s) and Year of Publication	Study Title
Anders (2001)	Pilot's attention allocation during approach and landing—Eye and head-tracking research in an A330 full flight simulator
BEA (2013)	Study on aeroplane state awareness during go-around
Bjorklund et al. (2006)	Mode monitoring and call-outs: An eye-tracking study of two-crew automated flight deck operations
Brams et al. (2018)	Does effective gaze behavior lead to enhanced performance in a complex error-detection cockpit task?
Diez et al. (2001)	Tracking pilot interactions with flight management systems through eye movements
Dehais et al. (2017)	Pilot flying and pilot monitoring's aircraft state awareness during go-around execution in aviation: A behavioral and eye tracking study
Diez et al. (2001)	Tracking pilot interactions with flight management systems through eye movements
Dill and Young (2015)	Analysis of eye-tracking data with regards to the complexity of flight deck information automation and management - inattentional blindness, system state awareness, and EFB usage
Faulhaber et al. (2022)	Absence of pilot monitoring affects scanning behavior of pilot flying: Implications for the design of single-pilot flight decks

Harris et al. (2023)	Assessing Expertise Using Eye Tracking in a Virtual Reality Flight Simulation
Haslbeck and Zhang (2017)	I spy with my little eye: Analysis of airline pilots' gaze patterns in a manual instrument flight scenario
Huettig et al. (1999)	Mode awareness in a modern glass cockpit attention allocation to mode information
Jarvis (2017)	Concurrent pilot instrument monitoring in the automated multi-crew airline cockpit
Lefrancois et al. (2016)	The role of pilots' monitoring strategies in flight performance
Lefrancois et al. (2018)	Pilot flying vs pilot monitoring: Study of gaze allocation during dynamic and critical flight phases
Lounis et al. (2021)	Visual scanning strategies in the cockpit are modulated by pilots' experience: A flight simulator study
Mumaw et al. (2020)	Analysis of pilots' monitoring skills and a review of training effectiveness
Reynal et al. (2016)	Pilot flying vs pilot monitoring during the approach phase: An eye-tracking study
Reynal et al. (2017)	Investigating pilots' decision making when facing an unstabilized approach: An eye-tracking study
Sarter et al. (2007)	Pilots' monitoring strategies and performance on automated flight decks: an empirical study combining behavioral and eye-tracking data

Spady, A. (1978)	Airline pilot scan patterns during simulated ILS approaches
van de Merwe et al. (2012)	Eye movements as an indicator of situation awareness in a flight simulator experiment
van Dijk et al. (2011)	A coherent impression of the pilots' situation awareness: Studying relevant human factors tools
Vine et al. (2015)	Individual reactions to stress predict performance during a critical aviation incident
Zaal et al. (2021)	Eye-tracking analysis from a flight-director-use and pilot-monitoring study
Zuo et al. (2023)	Eye movement of pilot flying in simulated flight: an eyetracking study

The following sections briefly describe each of the 20 eyetracking-based studies listed in Table 1. The studies are organized around the following themes, with some studies falling into more than one category:

(1) Scanning As A Function of Pilot Role and Experience
(2) Scanning During Specific Maneuvers/Flight Phases
(3) Monitoring Flight Deck Automation
(4) Monitoring For Malfunctions and Failures
(5) Fixation Sequences and Scan Patterns

For each theme, the brief descriptions of studies are followed by a summary of the most important findings.

3.4.1 Scanning As A Function of Pilot Role and Experience

Visual attention allocation is affected by both bottom-up factors (such as the salience of an indication) and top-down factors, such as a pilot's mental model of a system and resulting expectations of system status and behavior. In the context of threat and error management, these two modes of attention allocation have been termed reactive and predictive monitoring, respectively (IATA 2016):

Figure 12. Two complementary forms of monitoring (adopted from IATA, 2016, page 21)

Given the role of top-down factors in visual scanning, it can be expected that monitoring behavior and performance differ as a function of pilots' experience level and the pilot's role - Pilot Flying (PF) or Pilot Monitoring (PM). The PF is responsible for flying the aircraft and for monitoring the flight path. The PM also monitors the aircraft's flight path, as well as communications and the activities of the PF (IATA, 2016). These different responsibilities should translate into distinct and complementary monitoring strategies, as described in some of the studies below.

Visual scanning is also likely affected by pilots' experience level. A more experienced pilot will have a more developed scan pattern, process information more quickly and efficiently and notice discrepancies between desired and actual aircraft and system state and behavior more quickly and reliably. The effects of experience and pilot role on scanning were described quite extensively in recent reviews of the literature by Ziv (2017) and Peißl et al. (2018). However, many of the studies included in those reviews involved GA pilots with very low flying time. In contrast, the following seven of the total of twenty studies included in this literature review examined these factors with airline pilots as participants. Note that the majority of studies define pilots' experience level in terms of total flight hours or total time in type (rather than in terms of recency or currency).

BEA (2013)
Study on Aeroplane State Awareness during Go-Around

In this study, 11 flight crews (12 B777 pilots and 10 A330 pilots) completed a 2hr15min scenario in a B777 or A330 simulator. During approach to runway 18R at Lyon, ATC announced a change of runway and asked the crew to perform an ILS approach to runway 36L. When passing through 200ft, a go-around is ordered by air traffic control (ATC) due to traffic on the runway. The published go-around requires the crew to climb on a magnetic heading of 350° to an altitude of 5,000 feet. However, in this scenario, ATC instructs the crew to turn left on a heading of 340° and to climb to an altitude of 2,500 feet. Following this first go-around, the crew diverts to Marseille where they perform a standard ILS approach to runway 31R. The simulated wind gradually swings around to become a tailwind of 15-20 kts, requiring a second go-around. On completion of the second go-around, the role of PF switched to the other pilot and the crew then performed a LOC DME approach to runway 13L. Visibility falls to zero, forcing the crew to perform a third and final go-around.

During the debriefing, almost all PMs reported that they encountered difficulties with managing the first go-around due to task overload. They struggled with absorbing and reading back the ATC instructions and with prioritizing actions. During this go-around, the PF's scanning differed from that of the PM. While the PF and the PM both spent the same amount of time viewing the same AOIs, they did not fixate them in the same way, or in the same sequence. The PF mostly looked at the ADI, the airspeed and the altitude to control the flight path. In contrast, the PM's visual attention was spread more broadly, consistent with this pilot's responsibilities. The PM most often looked at areas that are related to configuration management (landing gear, flaps, radio panel, overhead panel and reference speeds). The management of the flight path via the MCP/FCU led to that interface being the second most frequently viewed AOI for the PM.

During the third go-around which was performed as published and with the autopilot engaged, after the pilots had swapped roles between Pilot Flying (PF; now the first officer) and Pilot Not Flying/Pilot Monitoring (PNF/PM; now the Captain), the scanning behavior of the pilots differed from the previous two go-arounds, especially with respect to the PF's visual attention. The PF experienced less workload during this standard go-around, and thus the percentage of time looking at the ADI dropped and was replaced by fixations on airspeed, FMAs and the navigation display. Surprisingly, the time spent by the PM on the FCU was rather high, given that the pilot is not supposed to operate the interface when the autopilot is engaged.

Dehais et al. (2017)
Pilot Flying and Pilot Monitoring's Aircraft State Awareness During Go-Around Execution in Aviation: A Behavioral and Eye Tracking Study.

Expanding on the BEA study above, Dehais and colleagues presented 24 commercial airline pilots (12 flight crews) with a scenario that involved a night-time manual ILS approach, with the runway becoming clearly visible only once the aircraft descended below 1,000 ft. The study was conducted on a Boeing 777 (seven crews) and an Airbus A330 (5 crews) full flight simulator. When passing through 200 ft, ATC informed the crew of the presence of traffic on the runway and instructed them to perform an immediate go-around. Unlike the published go-around, which requires the crew to climb to 5,000 ft on a magnetic heading of 354, ATC cleared the crew to turn left on a heading of 340° and to climb and level off at an altitude of 2,500 ft. While all flight crews managed to stabilize the aircraft in accordance with the ATC clearance, the debriefing indicated that this maneuver was perceived to be particularly demanding. With one exception, the PMs reported that they felt overwhelmed by the PF's callouts, ATC instructions, and the numerous actions to be performed during a short period of time. Also, only 3 out of the 12 flight crews were able to correctly read back the complete ATC instructions which requires working memory abilities that are known to be negatively affected by pilot workload.

In terms of eyetracking data, the authors found that, during the go-around, both pilots paid less attention to outside view (less than 5% of the time, compared to 40% during final approach; see Figure 13). Both pilots increased their monitoring of airspeed and the ND. The PF looked mainly at three AOIs located in the primary flight display (PFD; airspeed, attitude, and altitude indicators: 70%) and paid a lot more attention to the ADI (showing the flight director guidance) than the PM. The visual attention of the latter was spread more broadly over different AOIs, with briefer dwells to check that parameters were within range. The PF significantly increased their allocation of attention to the FCU to set target and modes for the go-around. The following table (Table 2) provides a more detailed breakdown of mean dwell times for six areas of interest during the final approach and go-around.

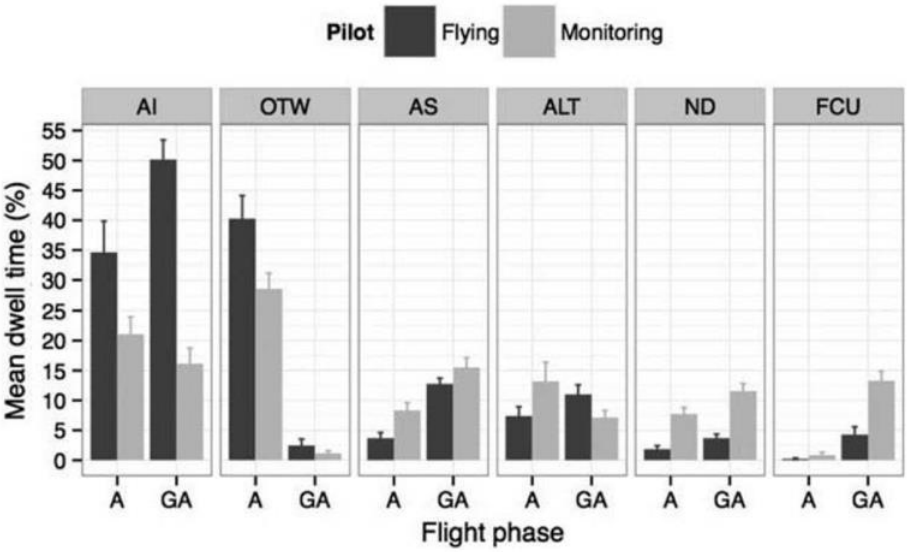


Figure 13. Distribution of PF’s and PM’s mean dwell time during the final approach and go-around for AI (attitude indicator), OTW (out-the-window), AS (airspeed), ALT (altitude), ND (navigation display) and FCU (flight control unit) (from Dehais et al., 2017, page 20)

Dill and Young (2015)
Analysis of Eye-Tracking Data with Regards to the Complexity of Flight Deck Information Automation and Management - Inattentional Blindness, System State Awareness, and EFB Usage.

In this study, 10 participating airline flight crews executed a mix of 40 different approach scenarios using the Research Flight Deck (RFD) within NASA’s Cockpit Motion Facility (CMF) at Langley Research Center. The scenarios involved different types and levels of information, operational complexity, and uncertainty. The study also included off-nominal conditions and events, such as unexpected weather events, traffic deviations, equipment failures, poor data quality, communication errors, and unexpected clearances (for a list of all independent variables, see Table 3 below).

Table 2. Independent Variables (from Young et al., 2013)

Independent Variable	Values
Weather conditions	(0) Cloud ceiling: 1000 ft, Visibility: 3 nmi, Dusk, Storm (None) (1) Cloud ceiling: 0500 ft, Visibility: 2400 ft, Night, Storm (Feb 25, 2011) (2) Cloud ceiling: 0200 ft, Visibility: 1800 ft, Night, Storm (Apr 27, 2011)
Airport configuration	(0) North flow (Runways 36L/C/R) (1) South flow (Runways 18L/C/R)
Traffic	(0) None (1) 3 nmi in-trail spacing, 1.5 nmi stagger, no departures (2) 5 nmi in-trail spacing, 2.5 nmi stagger, with departures on the outer runway
RNAV-based arrival and approach path	(FSD-18R, FSD-36L) Arriving from Northwest (EWR-18C, EWR-36C) Arriving from Northeast (MCO-18C, MCO-36C) Arriving from Southeast (IAH-18R, IAH-36L) Arriving from Southwest
Off-nominal condition	See Appendix
Crew	10 two-pilot crews

The study showed that, as PF, the participating pilots spent the majority of their time looking out the window, followed by fixating the PFD. As PM, pilots also prioritized the out-the-window (OTW) view and the PFD but they distributed their attention more widely, between a larger number of interfaces (see Figure 14). This allocation of attention is in line with the different responsibilities of the two pilots.

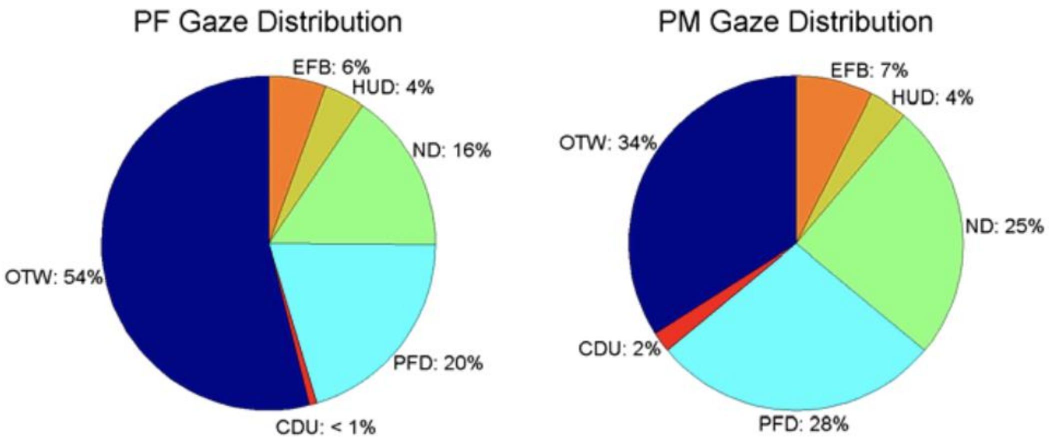


Figure 14. Average distribution of time each pilot spent looking at the specified AOIs (from Dill and Young, 2015)

Faulhaber et al. (2022)
Absence of Pilot Monitoring Affects Scanning Behavior of Pilot Flying: Implications for the Design of Single-Pilot Cockpits.

Ten pilots (seven of them with an A320 type rating) were asked to manually fly various ILS approach and landing scenarios (baseline, turbulence, and abnormal (engine fire triggered at an altitude of 1,800 ft)) at Frankfurt Airport, either with (Two-Person Crew Operations) or without (Single Pilot Operations (SPO)) a pilot monitoring present. The study was conducted in a fixed-base A320 simulator. The results showed that pilots' scanning patterns were, in general, more dispersed and included more time on secondary instruments (such as the radio management panel and the gear and flap levers) in the SPO crew configuration. Moreover, participants spent more time on the ECAM during SPO, particularly in the abnormal scenario. They compensated for these additional attentional demands by looking less at primary instruments. Participants also transitioned more frequently between the cockpit instruments, and dwells on the external view were significantly shorter in the SPO condition.

Harris et al. (2023)
Assessing Expertise Using Eye Tracking in a Virtual Reality Flight Simulation

The overall goal of this work was to examine the fidelity and validity of a VR flight training tool. Eighteen airline pilots, with varying levels of flight experience and familiarity with the Airbus A320, completed seven flight scenarios. A range of dependent measures was collected, including pilots' sense of presence, performance and eyetracking data. The findings from this study show that more experienced pilots used a similar visual search strategy, characterized by lower entropy (i.e., the level of randomness or variability in eye movements), fewer antipersistent saccades (in contrast to persistent saccades which continue moving in a similar direction, anti-persistent saccades return in the (approximately) opposite direction), plus fewer fixations and a reduced search rate. These results suggest that more experienced pilots performed a more efficient search of the flight deck, driven by their greater domain-specific knowledge.

Jarvis (2017)
Concurrent pilot instrument monitoring in the automated multi-crew airline cockpit.

This study involved 17 B737 flight crews who were asked to fly a series of approaches in instrument meteorological conditions (IMC), half of them manually, the other half coupled. When flying manually, the PF spent more than 50% of the dwell time on the ADI. During coupled approaches, the dwell time on the ADI decreased significantly while it more than doubled for the horizontal situation indicator (HSI). The same pattern was observed for the PM.

Lefrancois et al. (2018)
Pilot flying vs pilot monitoring: Study of gaze allocation during dynamic and critical flight phases.

Twenty pilots (ten crews) who were qualified on the Airbus A320 completed two flights in a full flight simulator, from take-off to landing, one approach as Pilot Flying and one as Pilot

Monitoring, in random order. These flights involved fully manual approaches (without flight directors and without auto-thrust engaged) in standard visibility conditions. Six out of the ten crews performed an additional automatic landing, with flight directors and auto-throttle engaged and in in low visibility conditions (runway visual range between 75 and 400 meters). The study showed that, during takeoffs, the PF spent most of the time looking out the window, while the PMs spread their attention more widely between the outside view, the airspeed indicator and the ECAM.

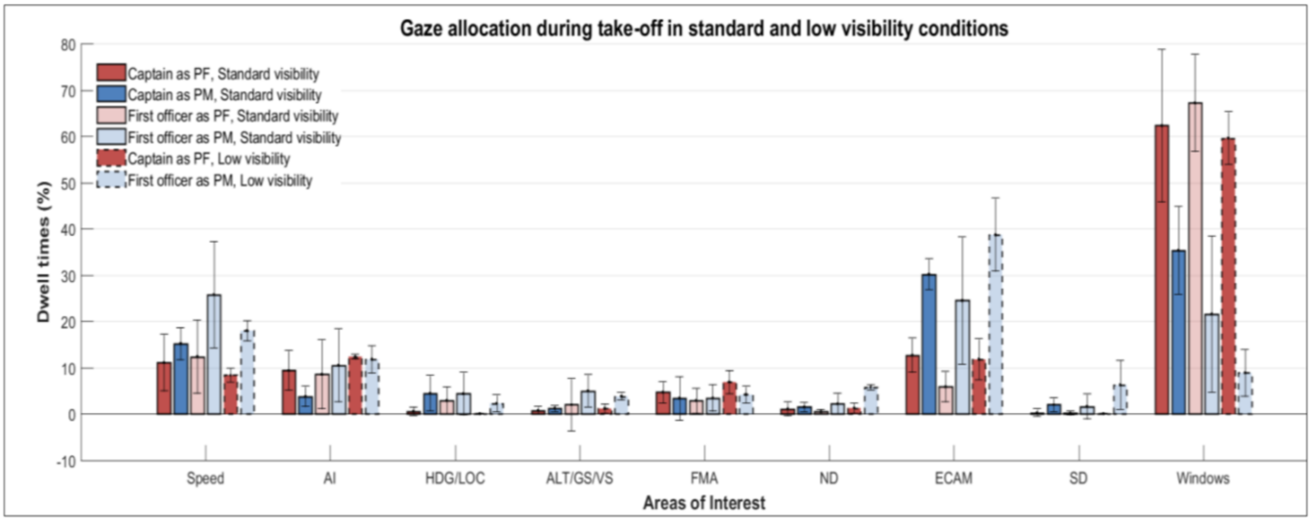


Figure 15. Mean percentage dwell time for various AOIs during takeoff (from Lefrancois et al., 2018)

Five of the flight crews performed a go-around. During that maneuver, the PF primarily monitored the attitude indicator (AI), while the PM distributed their attention primarily between the airspeed, attitude indicator, vertical speed, navigation display and flight mode annunciations. Thus, the two pilots complemented one another with respect to their monitoring behavior.

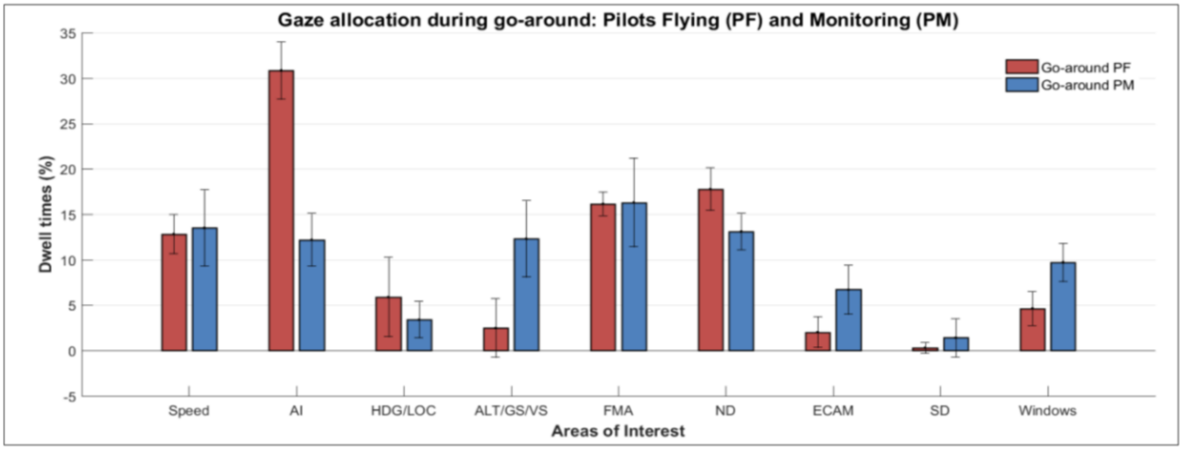


Figure 16. Mean percentage dwell times for PF and PM for various AOIs during go-around (from Lefrancois et al., 2018)

Lounis et al. (2021)
Visual scanning strategies in the cockpit are modulated by pilots' experience: A flight simulator study

This study compared visual information acquisition, gaze dispersion, and gaze patterns between novices and pilots. Sixteen certified professional pilots and a group of sixteen novices performed manual landing scenarios in an A320 flight simulator. Their task was only to control the trajectory and the speed of the aircraft (to enable the novices to perform their task). The two groups landed the airplane manually three times at different levels of difficulty. The baseline was a nominal landing without any secondary task. The "easy dual task scenario" and the "difficult dual task scenario" were similar to the "control scenario", except that participants were asked to perform an additional monitoring task. They had to regularly check the map display. In the "easy dual task scenario", they were asked to say aloud the distance between the aircraft and the runway threshold every 0.5 nm. In the "difficult dual task scenario", they were asked to say aloud this distance every 0.2 nm.

Eyetracking data were collected at 60Hz with a SmartEye remote eye tracker. The data show that, compared to novices, professional pilots had shorter average dwell times and a higher number of dwells. This is being interpreted as a sign of faster extraction of information which, in turn, allows for more frequent sampling of flight instruments. Experts included more flight instruments in their visual scan and thus showed a greater spatial distribution of their visual attention. The addition of the monitoring task resulted, for both groups, in an increased use of peripheral vision. In the hard dual-task scenario, this combined ambient-focal monitoring strategy remained unchanged for expert pilots only.

Reynal et al. (2016)
Pilot flying vs pilot monitoring during the approach phase: An eye-tracking study.

Reynal et al. (2016) asked 8 flight crews to fly 4 coupled approaches in a B777 and an Airbus A330 (4 crews each) simulator: the first three leading to a go-around during short final, and the last one ending with a landing. In the first two scenarios, the Captain served as PF and the First Officer was PM. In the last two scenarios, the Captain was PM and the First Officer was PF. The findings from this study show that both pilots monitored primary flight parameters more than secondary ones (see Figure 17). The only significant difference between their monitoring behavior was that the PF spent significantly more time looking at the ADI, compared to the PM. During the three approaches, the PM increasingly redistributed their attention to the outside view (35% below 500ft) instead of monitoring critical flight parameters.

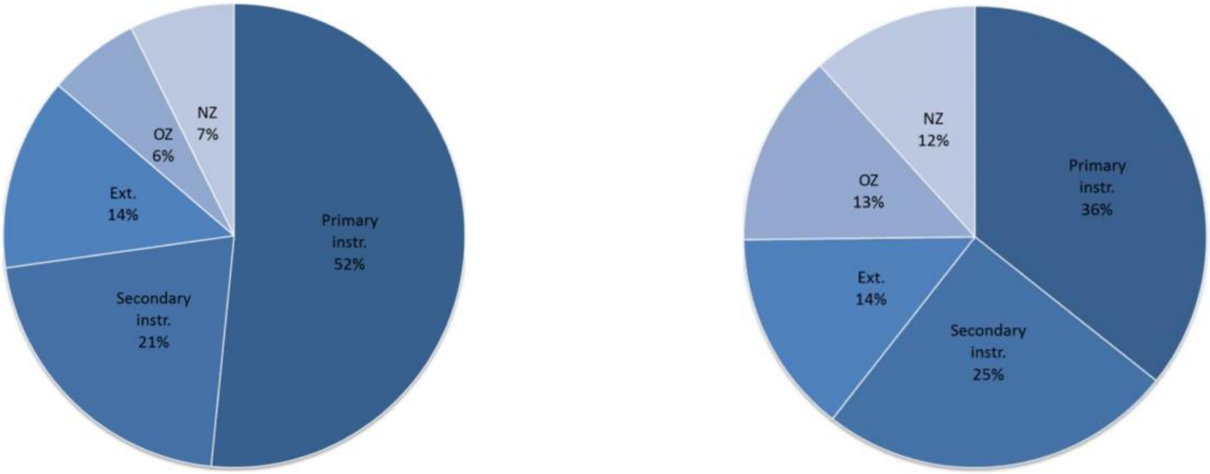


Figure 17. Average percentage dwell times for the PF (on the left) and the PM (on the right) (from Reynal et al. (2016)

Zaal et al. (2021).
Eye-tracking analysis from a flight-director-use and pilot-monitoring study.

In this study, nineteen first officers (FOs) with a major US airline who were active and current on the Boeing 737NG completed four simulated scenarios that presented challenges related to meeting flight path targets. During half of the scenarios, the flight director was turned on. Participants assumed the role of pilot monitoring (PM) in the right seat, from top-of-descent to landing. The PF was always the Captain and a confederate of the study team. Eyetracking data were collected using Seeing Machines equipment for 8 AOIs: primary flight display (PFD), navigation display (ND), out-the-window visual (OTW), mode control panel (MCP), electronic flight instrument system (EFIS) settings panel, flight management system (FMS), and upper and lower engine-indicating and crew-alerting system (EICAS) displays. Proportion dwell time and AoI neglect latency were computed. Proportion dwell time is defined as the dwell time percentage of the total duration of a scenario challenge for a specific pilot. AoI neglect latency is the time between moving fixation away from an area of interest and again fixating that area as determined by the intersection of the gaze vector with an AoI.

The first finding from this study is that during final approach, the PM tended to focus their visual attention less on the PFD when the flight director (FD) was on (as compared to when it was turned off). This finding is the opposite of what the study team had expected. The second finding relates to the main focus of the experiment, namely pilots' ability to cope with four monitoring challenges: two waypoint restrictions and two cases where pilots had to extend flaps at the appropriate time. Pilots focused more on the PFD and ND compared to other AoIs for all challenges. Those pilots who successfully completed the challenges focused more on the AoI that contained the most relevant information to successfully complete the challenge while unsuccessful pilots did not seem to have a clear shift in focus on particular AoIs between different challenges.

Summary

Taken together, the above studies suggest that:

- On takeoff:
    - PF and PM complement one another in terms of their scanning behavior.
    - in VFR conditions, the PF spends more time looking out the window, while the PM allocates more attention to the airspeed indicator and the ECAM.
- On approach:
    - PF and PM show similar, rather than complementary scanning strategies.
    - Both the PF and the PM spend the majority of their time looking out the window, followed by fixating the PFD. However, the PM distributes their attention more widely, between a larger number of interfaces.
    - During final approach, the PM focuses their attention less on the PFD when the flight director is turned on.
    - During coupled approaches (i.e., instrument approaches performed by the autopilot, and/or visually depicted on the flight director, which is receiving position information and/or steering commands from onboard navigational equipment; from https://www.faa.gov/air_traffic/publications/) the dwell time on the ADI decreases while it increases significantly for the HSI/ND.
    - At very low altitudes, the PM’s attention may inappropriately focus on the outside view, rather than critical flight parameters.
    - When excluding the out-the-window view from the analysis, both the PF and the PM spend more than 50% of the dwell time on the ADI during manual approaches.
- During go-arounds:
    - PF and PM assist each other by paying attention to different instruments
    - The PF primarily monitors the PFD (in particular, the attitude indicator), while the PM’s attention is spread more broadly on interfaces related to configuration management, MCP/FCU, airspeed, altitude, FMAs and vertical speed.
    - In case of a non-standard more challenging go-around, the PF focuses on airspeed, attitude, and altitude 70% of time, while the PM engages with the MCDU.
- During single-pilot operations (no PM):
    - Scanning patterns become more dispersed as the single pilot needs to spend more time on secondary instruments. Pilots compensate by monitoring primary instruments less and, during approaches, they transition more often between cockpit instruments and the outside view, with significantly shorter dwell times on the outside.
- Pilot Experience:
    - Monitoring is more efficient in experienced pilots, likely driven by their greater domain-specific knowledge. They extract information more quickly and distribute their visual attention more widely. They do so in a consistent manner, across scenarios of varying difficulty.

3.4.2 Scanning During Specific Maneuvers/Flight Phases

Pilots can be expected to employ different scanning techniques and focus on different types of information during various maneuvers and phases of flight, such as takeoff, approach/landing and go-around. The following section first highlights relevant findings from a literature review conducted by Mumaw et al. (2020). This is followed by a summary of pertinent results from four individual experiments.

Mumaw et al. (2020)
Analysis of pilot monitoring skills and a review of training effectiveness

Findings from eyetracking studies on pilots' instrument scanning behavior during specific maneuvers and phases of flight were summarized in a recent report by Mumaw et al. (2020). The following sections reproduce the tables included in their report for the takeoff, approach, and go-around. Additional information for these studies as well as additional studies on specific flight phases and maneuvers will be described.

Takeoff

The following two tables, adopted from the Mumaw et al. (2020) report, show the % dwell time for various experimenter-defined AOIs during takeoff observed in studies by Mumaw et al. (2000) in a B747-400 simulator and by Lefrancois et al. (2018) in an Airbus A320 simulator.

Tables 3 and 4. Percentage dwell time for various experimenter-defined AOIs during takeoff (adapted from Mumaw et al. (2000))

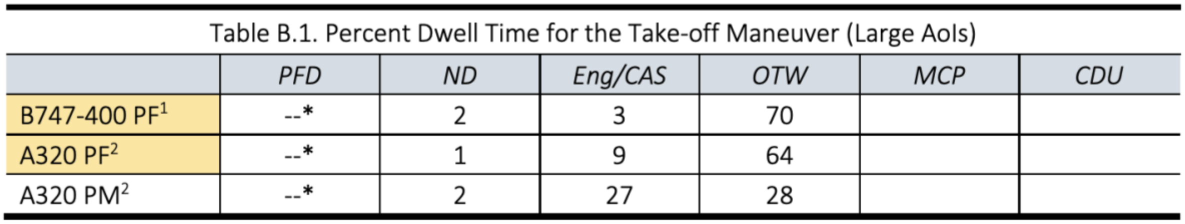


Table B.1. Percent Dwell Time for the Take-off Maneuver (Large AoIs)

	PFD	*ND*	*Eng/CAS*	*OTW*	*MCP*	*CDU*
B747-400 PF[1]	--*	2	3	70		
A320 PF[2]	--*	1	9	64		
A320 PM[2]	--*	2	27	28		

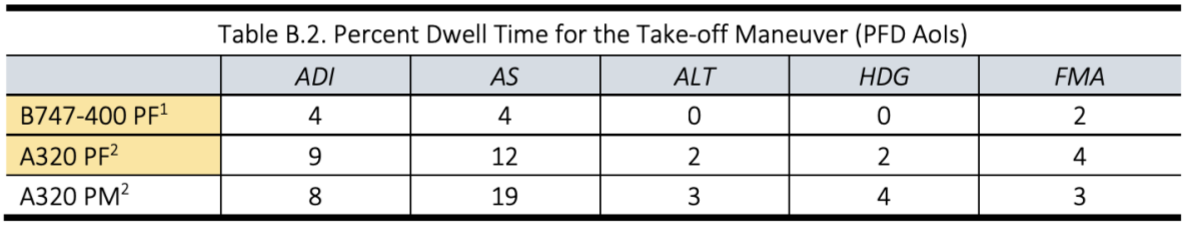


Table B.2. Percent Dwell Time for the Take-off Maneuver (PFD AoIs)

	ADI	*AS*	*ALT*	*HDG*	*FMA*
B747-400 PF[1]	4	4	0	0	2
A320 PF[2]	9	12	2	2	4
A320 PM[2]	8	19	3	4	3

** %DT for the PFD is partitioned into sub-elements, presented in the 2nd Table*
A blank cell means that this study did not use this AoI.
[1] Mumaw et al., 2000 (data from 17 PFs).
[2] Lefrancois et al., 2018 (data from 10 PFs and 10 PMs).

Approach

The following two tables (adopted from Mumaw et al., 2020) provide an overview of findings from nine studies examining instrument scanning during manual or autoflight approaches on the B777, Airbus A330, Airbus A340 and the Airbus A320:

Tables 5 and 6. Percentage dwell time for manual and autoflight approaches (adopted from Mumaw et al. (2000))

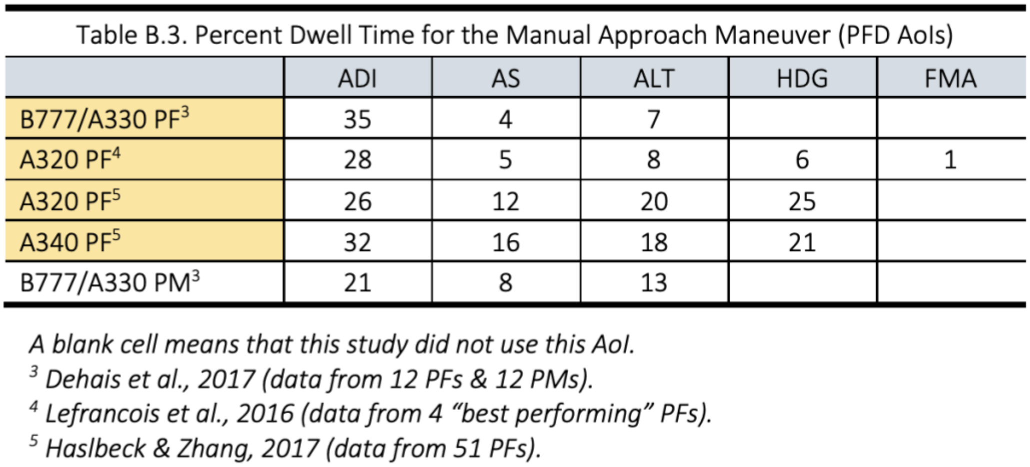


Table B.3. Percent Dwell Time for the Manual Approach Maneuver (PFD AoIs)

	ADI	AS	ALT	HDG	FMA
B777/A330 PF[3]	35	4	7		
A320 PF[4]	28	5	8	6	1
A320 PF[5]	26	12	20	25	
A340 PF[5]	32	16	18	21	
B777/A330 PM[3]	21	8	13		

A blank cell means that this study did not use this AoI.

[3] Dehais et al., 2017 (data from 12 PFs & 12 PMs).

[4] Lefrancois et al., 2016 (data from 4 "best performing" PFs).

[5] Haslbeck & Zhang, 2017 (data from 51 PFs).

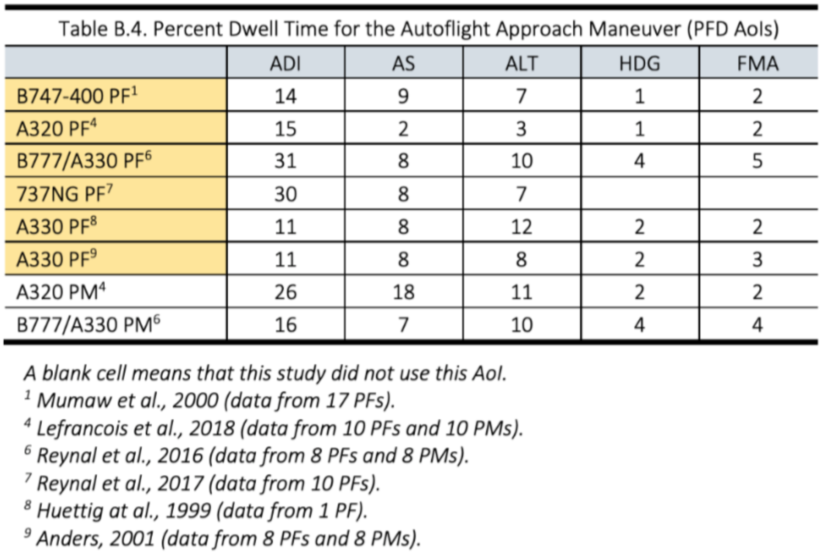


Table B.4. Percent Dwell Time for the Autoflight Approach Maneuver (PFD AoIs)

	ADI	AS	ALT	HDG	FMA
B747-400 PF[1]	14	9	7	1	2
A320 PF[4]	15	2	3	1	2
B777/A330 PF[6]	31	8	10	4	5
737NG PF[7]	30	8	7		
A330 PF[8]	11	8	12	2	2
A330 PF[9]	11	8	8	2	3
A320 PM[4]	26	18	11	2	2
B777/A330 PM[6]	16	7	10	4	4

A blank cell means that this study did not use this AoI.

[1] Mumaw et al., 2000 (data from 17 PFs).

[4] Lefrancois et al., 2018 (data from 10 PFs and 10 PMs).

[6] Reynal et al., 2016 (data from 8 PFs and 8 PMs).

[7] Reynal et al., 2017 (data from 10 PFs).

[8] Huettig at al., 1999 (data from 1 PF).

[9] Anders, 2001 (data from 8 PFs and 8 PMs).

Go-Around

The final two tables (adopted from Mumaw et al., 2020) summarize findings from two studies (Dehais et al., 2017 and Lefrancois et al., 2018) examining pilots' instrument scanning during a go-around:

Tables 7 and 8. Percentage dwell time for various experimenter-defined AOIs during go-around (adopted from Mumaw et al. (2000))

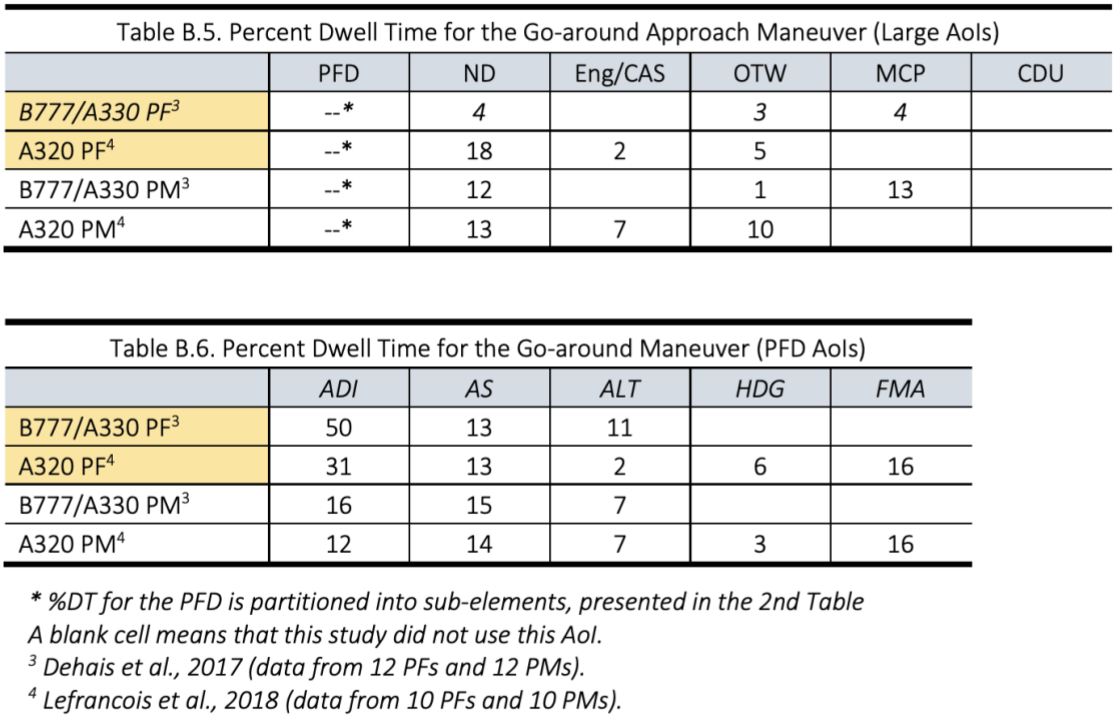


Table B.5. Percent Dwell Time for the Go-around Approach Maneuver (Large AoIs)

	PFD	ND	Eng/CAS	OTW	MCP	CDU
B777/A330 PF[3]	--*	*4*		*3*	*4*	
A320 PF[4]	--*	18	2	5		
B777/A330 PM[3]	--*	12		1	13	
A320 PM[4]	--*	13	7	10		

Table B.6. Percent Dwell Time for the Go-around Maneuver (PFD AoIs)

	ADI	*AS*	*ALT*	*HDG*	*FMA*
B777/A330 PF[3]	50	13	11		
A320 PF[4]	31	13	2	6	16
B777/A330 PM[3]	16	15	7		
A320 PM[4]	12	14	7	3	16

** %DT for the PFD is partitioned into sub-elements, presented in the 2nd Table*
A blank cell means that this study did not use this AoI.
[3] Dehais et al., 2017 (data from 12 PFs and 12 PMs).
[4] Lefrancois et al., 2018 (data from 10 PFs and 10 PMs).

Additional findings from some of the above studies, as well as results from other studies examining scanning behavior as a function of flight phase or maneuver are summarized below:

Haslbeck and Zhang (2017)
I spy with my little eye: Analysis of airline pilots' gaze patterns in a manual instrument flight scenario

The study by Haslbeck and Zhang (2017) aimed to analyze pilots' visual scanning when performing a manual approach (raw data) and landing task. Specifically, the authors' goals were to (1) examine the influence of practice on visual scanning, (2) identify frequently occurring gaze patterns, and (3) evaluate the effectiveness of several different gaze patterns. Two groups of 51 pilots total –flying either long-haul (n=25; A340) or short-haul (n=26; A320) routes – completed a 10-minute manual flight and landing scenario approaching Munich Airport in an Airbus simulator. Shortly after the scenario started, a (simulated) malfunction of the autopilot (AP) and the flight director (FD) necessitated a manual approach. The attitude indicator showed the highest fixation rates, especially in long-haul pilots. The latter focused on the ADI (32%) while short-haul pilots showed a more balanced allocation of visual attention with scanning the ADI and HDG for about one fourth of the time each (26% and 25%, respectively). For both groups, fixations on the heading indicator were significantly longer than for the other three AOIs.

Lefrancois et al. (2018)
Pilot flying vs pilot monitoring: Study of gaze allocation during dynamic and critical flight phases.

Lefrancois et al. (2018) examined pilots' instrument scanning and its relationship to performance during manual approaches. Twenty pilots who were qualified on the Airbus A320 flew an ILS approach to Toulouse airport, in a full flight simulator, without the use of automation (i.e., neither flight director nor auto throttle were engaged). Pilots were randomly assigned the role of pilot flying or pilot monitoring. The four best-performing pilots (based on their deviation from the glide slope and localizer and their touchdown accuracy) spent most of their time looking outside, followed by the attitude indicator, the glideslope, and the localizer indications. Five pilots decided to go around at approximately 750 ft MSL because their approach was not stabilized. Fixations for those pilots were more widely dispersed. Specifically, the standard deviations for the % gaze time in each of the three areas of interest (attitude, glideslope, localizer) were at least twice as large for pilots who decided to go around, compared to those flying a stabilized approach.

Reynal et al. (2017)
Investigating pilot's decision making when facing an unstabilized approach: An eye-tracking study.

Reynal et al. (2017) conducted an experiment with 10 type-rated, commercial pilots who flew a forced unstabilized approach to the Hamburg airport in a B737 full-flight simulator. Half of the pilots decided not to go around. These pilots (note that data were collected for the PF only) showed longer dwell times on the attitude indicator/flight director whereas the group of pilots who performed the go-around exhibited more fixations on the navigation display prior to their decision to abort the landing. The two groups of pilots did not differ in their scanning earlier, during the initial approach segment, suggesting that their overall visual scanning behavior and performance was appropriate. However, the pilots who did not go around appear to have missed the cues indicating that their approach was unstable and thus focused on the attitude indicator/flight director which provides guidance for landing.

Sarter et al. (2007)
Pilots' monitoring strategies and performance on automated flight decks: an empirical study combining behavioral and eye-tracking data.

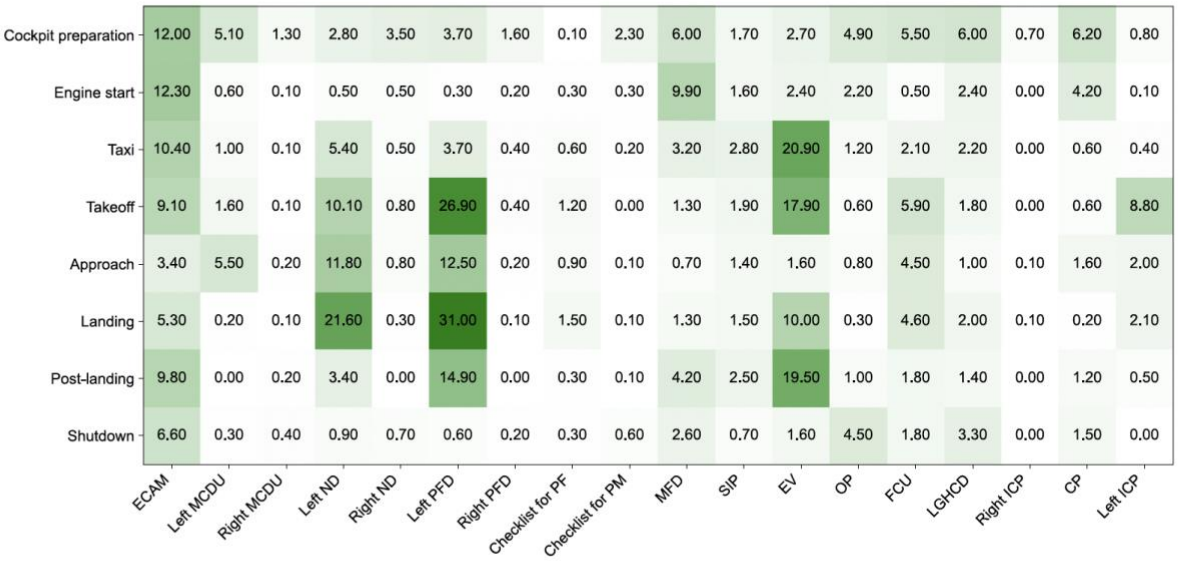
Twenty experienced B747-400 airline pilots flew a 1-hr scenario on a full-mission 747-400 simulator. The analysis of the data revealed an expected dominance of PFD scanning (attended 31% of the time, averaged over flight phases), compared with the next most dominant area of interest, the navigation display (25% of the time). Fixations within the PFD were mostly on the airspeed tape, the ADI, the altimeter, and vertical speed. The outside world was monitored only 3% of the time until the final approach phase, when this percentage jumped to 12%. Differences were observed between various phases of flight. The percentage of fixation duration on parts of the display that present information regarding the vertical axis of flight (e.g., altitude, vertical speed) was higher during the climb (~35%) and the descent (~25%) phases compared to the cruise phase (< 20%). In contrast, fixations to the airspeed were lowest during the climb phase

(~15%), followed by the cruise phase (~20%), and highest during the descent phase (~27%). Mean dwell duration (the time spent per glance at an instrument) was also examined.

Zuo et al. (2023).
Eye movement of pilot flying in simulated flight: an eyetracking study.

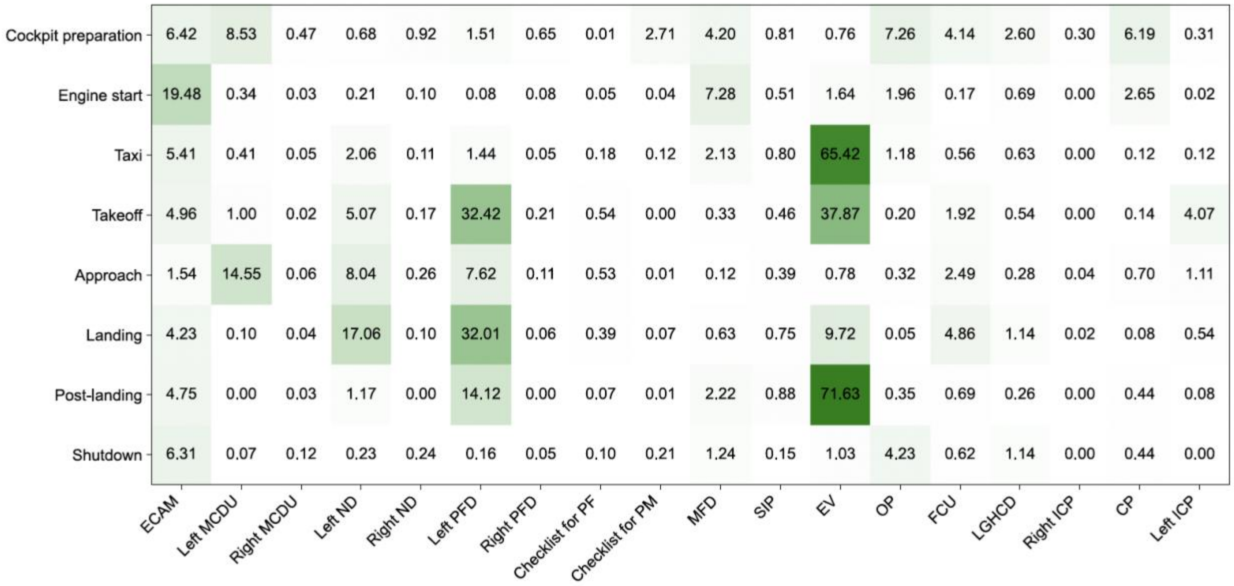
The objective of this study was to analyze the eye movements of the pilot flying (PF) during as many flight phases as possible, with the goal to improve the design of flight deck interfaces as well as pilot training. The study was conducted in an A320 simulator with ten professional pilots who had over 3,000 hours of flight experience. Participants completed two scenarios, one as PF and the other as PM. Eyetracking data were collected for the PF using Tobii Pro Glasses 2. The data were analyzed to determine the number of visits (signifying the importance of the AOI) and the total duration of fixation (indicating cognitive load) for 18 AOIs.

The following tables summarize the findings from this study. Darker colors indicate a higher visit frequency and a longer fixation duration. The AOIs shown in these tables are: (1) Overhead Panel (OP), (2) External View (EV), (3) Flight Control Unit (FCU), (4) Left Instrument Control Panel (ICP), (5) Left PFD, (6) Left ND, (7) Standby Instruments Panel (SIP), (8) Electronic Centralized Aircraft Monitor (ECAM), (9) Multifunction Display (MFD), (10) Landing Gear Handle Control and Display (LGHCD), (11) Right ND, (12) Right PFD, (13) Right ICP, (14) Checklist for PF, (15) Left Multipurpose Control and Display Unit (MCDU), (16) Center Pedestal (CP), (17) Right MCDU, (18) Checklist for PM.



	ECAM	Left MCDU	Right MCDU	Left ND	Right ND	Left PFD	Right PFD	Checklist for PF	Checklist for PM	MFD	SIP	EV	OP	FCU	LGHCD	Right ICP	CP	Left ICP
Cockpit preparation	12.00	5.10	1.30	2.80	3.50	3.70	1.60	0.10	2.30	6.00	1.70	2.70	4.90	5.50	6.00	0.70	6.20	0.80
Engine start	12.30	0.60	0.10	0.50	0.50	0.30	0.20	0.30	0.30	9.90	1.60	2.40	2.20	0.50	2.40	0.00	4.20	0.10
Taxi	10.40	1.00	0.10	5.40	0.50	3.70	0.40	0.60	0.20	3.20	2.80	20.90	1.20	2.10	2.20	0.00	0.60	0.40
Takeoff	9.10	1.60	0.10	10.10	0.80	26.90	0.40	1.20	0.00	1.30	1.90	17.90	0.60	5.90	1.80	0.00	0.60	8.80
Approach	3.40	5.50	0.20	11.80	0.80	12.50	0.20	0.90	0.10	0.70	1.40	1.60	0.80	4.50	1.00	0.10	1.60	2.00
Landing	5.30	0.20	0.10	21.60	0.30	31.00	0.10	1.50	0.10	1.30	1.50	10.00	0.30	4.60	2.00	0.10	0.20	2.10
Post-landing	9.80	0.00	0.20	3.40	0.00	14.90	0.00	0.30	0.10	4.20	2.50	19.50	1.00	1.80	1.40	0.00	1.20	0.50
Shutdown	6.60	0.30	0.40	0.90	0.70	0.60	0.20	0.30	0.60	2.60	0.70	1.60	4.50	1.80	3.30	0.00	1.50	0.00

Figure 18. Number of visits for each AOI (from Zuo et al., 2023)



	ECAM	Left MCDU	Right MCDU	Left ND	Right ND	Left PFD	Right PFD	Checklist for PF	Checklist for PM	MFD	SIP	EV	OP	FCU	LGHCD	Right ICP	CP	Left ICP
Cockpit preparation	6.42	8.53	0.47	0.68	0.92	1.51	0.65	0.01	2.71	4.20	0.81	0.76	7.26	4.14	2.60	0.30	6.19	0.31
Engine start	19.48	0.34	0.03	0.21	0.10	0.08	0.08	0.05	0.04	7.28	0.51	1.64	1.96	0.17	0.69	0.00	2.65	0.02
Taxi	5.41	0.41	0.05	2.06	0.11	1.44	0.05	0.18	0.12	2.13	0.80	65.42	1.18	0.56	0.63	0.00	0.12	0.12
Takeoff	4.96	1.00	0.02	5.07	0.17	32.42	0.21	0.54	0.00	0.33	0.46	37.87	0.20	1.92	0.54	0.00	0.14	4.07
Approach	1.54	14.55	0.06	8.04	0.26	7.62	0.11	0.53	0.01	0.12	0.39	0.78	0.32	2.49	0.28	0.04	0.70	1.11
Landing	4.23	0.10	0.04	17.06	0.10	32.01	0.06	0.39	0.07	0.63	0.75	9.72	0.05	4.86	1.14	0.02	0.08	0.54
Post-landing	4.75	0.00	0.03	1.17	0.00	14.12	0.00	0.07	0.01	2.22	0.88	71.63	0.35	0.69	0.26	0.00	0.44	0.08
Shutdown	6.31	0.07	0.12	0.23	0.24	0.16	0.05	0.10	0.21	1.24	0.15	1.03	4.23	0.62	1.14	0.00	0.44	0.00

Figure 19. Heatmap of total fixation duration for each AOI. (from Zuo et al., 2023)

Summary

- During takeoff, for the PF, the percentage dwell time for the out-the-window view is significantly longer than for any other AOI/instrument (64-70%). For the PM, a more balanced distribution of attention between outside view and the engine instruments is observed.
- During manual approaches, the percentage dwell time for the outside view is again the highest, followed by the ADI. The emphasis on monitoring the ADI was observed especially for long-haul pilots who have less practice flying and for pilots flying glass cockpit aircraft. There is considerable variability for monitoring the airspeed, altitude and heading indications, with the latter receiving a lot of attention from the PF.
- During autoflight approaches, the ADI receives the most attention. Altitude and heading get fewer fixations than during manual approaches. Instead, the flight mode annunciations are fixated more often since they are an important indicator of the autoflight system's behavior.
- Finally, during a go-around, the percentage dwell time for the PF is highest for the ADI, followed by airspeed and the ND. For the PM, their attention is more widely distributed between the ADI, ND, airspeed, and FMAs. Also, the PM spends considerable time looking at the MCP where s/he is expected to enter target values and activate modes.

3.4.3 Monitoring Flight Deck Automation

Effective monitoring of indications associated with flight deck automation is one important prerequisite for the safety of flight. It supports mode awareness which refers to the pilots' knowledge and understanding of the current and future status and behavior of the system. Errors of commission and omission that result from a reduction in, or loss of, mode awareness can lead to so-called "automation surprises (e.g., Sarter and Woods, 1995) and have been implicated in a number of aviation incidents and accidents. Five of the twenty studies included in this review collected data specific to monitoring flight deck automation. The main findings from these studies are described and summarized below.

Björklund et al. (2006)
Mode Monitoring and Call-Outs: An Eye-Tracking Study of Two-Crew Automated Flight Deck Operations.

Twelve professional pilots completed a 1-hr scenario (a flight from Amsterdam to London) in a high-fidelity, motion-based flight simulator with Boeing 737NG displays. At the end of the scenario, a glide slope capture failure was introduced to force a go-around. There were a total of 418 automation-related mode transitions across the twelve flights. These consisted of 247 pilot-induced and 171 automation-induced transitions. About 40% of mode transitions were never visually verified. Within 10 seconds of the transition, 47% of them were visually verified. And 13% of the transitions were fixated 10-20 seconds after the mode change. There was no significant difference in visual verification between manually induced or automation-induced mode transitions. The PF visually verified mode transitions in 56% of the cases, compared with 65% for the PNF.

Diez et al. (2001)
Tracking pilot interactions with flight management systems through eye movements.

Five B-777 pilots were asked to fly two scenarios (50 and 30 minutes in duration, respectively) on a B-747-400 desktop simulator. Eye-tracking data were collected, and pilots were interrupted six times throughout the scenario and asked to recall as many details as possible about the flying situation and values from specific instruments. Participants were quite accurate at remembering basic flight parameters, such as altitude, airspeed, engine power, and aircraft position. In contrast, they performed significantly worse with respect to recalling automation-related indications – in particular, the throttle and pitch FMAs. They were able to report whether or not some mode was engaged but failed to remember the specific mode annunciations. This was true especially for the submodes of vertical navigation (VNAV), the most complex of the automation systems for the three axes of flight. A trend toward longer fixation times (on the order of an additional 200–300 ms) was observed for those indications that pilots were able to recall correctly.

Dill and Young (2015)
Analysis of Eye-Tracking Data with Regards to the Complexity of Flight Deck Information Automation and Management - Inattentional Blindness, System State Awareness, and EFB Usage.

As described earlier, 10 airline flight crews participated in this study and executed a mix of 40 different approach scenarios using the Research Flight Deck (RFD) within NASA's Cockpit Motion Facility (CMF) at Langley Research Center. The scenarios involved different types and levels of information, operational complexity, and uncertainty. The study also included off-nominal conditions and events, such as unexpected weather events, traffic deviations, equipment failures, poor data quality, communication errors, and unexpected clearances. The study showed that the FMAs were typically fixated by at least one of the pilots for approximately 12% of the flight. On average, the PM looked at the FMAs more than the PF. PFs typically fixated the FMAs once every 9.5 seconds while the PMs glanced at them significantly more often, at an average of one engagement every 4.1 seconds. For both pilots, the average interaction with the FMA lasted for less than 2 seconds and a majority of gazes lasted for less than 3 seconds. FMA fixations lasting longer than 8 seconds were rare and happened when pilots appeared to be uncertain about the meaning of the indication.

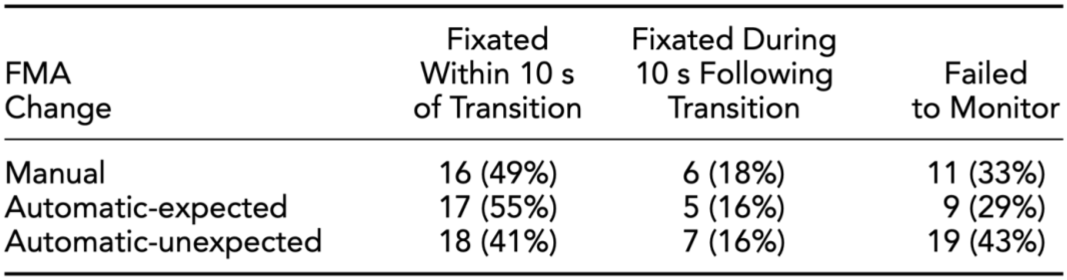
Huettig et al. (1999)
Mode awareness in a modern glass cockpit: Attention allocation to mode information.

Two experiments were conducted. In the first study, three flight crews were asked to fly a line-oriented scenario between two European airports while, in the second experiment, one commercial flight crew flew six simulated instrument landing system (ILS) approaches (four under normal conditions; two involving non-normal events). Both experiments were conducted in a full-flight Airbus A-340 simulator. In both studies, eyetracking data were collected only for the pilot flying. Gaze behavior did not differ significantly between the two studies. Pilots attended mostly to the PFD (~40% of the total fixation time), followed by the navigation display (~20% of the total fixation time), and the outside world (~10% of the total fixation time). Within the PFD, the most fixated areas were the artificial horizon (~25%), the altimeter (~30%), and the airspeed tape (~20%). Importantly, pilots tended to monitor raw data, i.e., indications of actual aircraft behavior (such as airspeed, altitude, and attitude), rather than flight mode annunciations (FMAs), which indicate automation states and modes on the three axes of flight (lateral, vertical, speed). FMAs were fixated on average only 4.7% of the time.

Sarter et al. (2007)
Pilots' monitoring strategies and performance on automated flight decks: an empirical study combining behavioral and eye-tracking data.

As described earlier, twenty experienced B-747-400 airline pilots flew a 1-hr scenario on a full-mission 747-400 simulator. The scenario included challenging autoflight-related events that required a thorough understanding of the FMS to be able to manage and monitor the system effectively: (1) experimenter-induced mode transitions (once during climb, once when established on the de- scent path, and once later during the descent). These transitions led to the display of a pitch or autothrottle mode that would not normally appear in the given flight context but they did not lead to any changes in airplane behavior; (2) a revision of the cruise altitude. When the pilot entered this change via the CDU, the automation transitioned to the VNAV altitude (VNAV ALT) pitch mode. In this mode, the airplane will not automatically start its descent at the top-of-descent point unless the pilot takes an extra step, and (3) loss of glide slope diamond and glide slope during the ILS approach. Regarding automation monitoring, most notable is the finding of a pronounced preference for looking at raw data over the FMAs, with the latter being scanned only 2.5% of the time on average. Glances at the FMA were considerably shorter (mean = 0.40 s) than they were to the other instruments within the PFD (mean = 0.60 s). When comparing fixations for changes on FMAs that were triggered by a pilot action versus those that were initiated by the automation and either likely expected or unexpected by the pilot, fixation percentages were as follows:

Table 9. FMA fixations for three types of mode transitions. (from Sarter et al., 2007)



FMA Change	Fixated Within 10 s of Transition	Fixated During 10 s Following Transition	Failed to Monitor
Manual	16 (49%)	6 (18%)	11 (33%)
Automatic-expected	17 (55%)	5 (16%)	9 (29%)
Automatic-unexpected	18 (41%)	7 (16%)	19 (43%)

Finally, with respect to the experimenter-induced inappropriate mode transitions, a considerable number of pilots (between 10 and 12 pilots in each case) fixated the FMAs; however, with the exception of 1 pilot during the early descent phase, they failed to notice the inappropriateness of the mode annunciations.

Summary

- Pilots show a tendency to monitor raw data, i.e., indications of actual aircraft behavior (such as airspeed, altitude, and attitude), rather than flight mode annunciations (FMAs), which indicate automation states and modes on the three axes of flight (lateral, vertical, speed). As a result, they are quite accurate at remembering basic flight parameters, when prompted, such as altitude, airspeed, engine power, and aircraft position.
- FMAs are fixated rarely (in one study, only 4.7% of the time) and a large percentage of mode transitions (40% in one study) are never visually verified. Pilots consequently perform poorly at recalling automation-related indications. This is true especially for the submodes of vertical navigation (VNAV).
- Most mode transitions are visually verified within 10 seconds of their occurrence. If they are not fixated within 20 seconds, they tend to be missed.
- Glances at the FMA tend to be considerably shorter (in one study, mean = 0.40 s) than to the other indications within the PFD (in the same study, mean = 0.60 s). This may be the case because FMAs are easily interpreted, as suggested by the observation that gazes lasting longer than 8 seconds were observed only when pilots were uncertain about the meaning of an FMA. It may also be explained by the above observation that pilots tend to rely more on raw data to assess the behavior of the automation and its impact on aircraft status and behavior.
- Across all phases of flight, the PM fixates FMAs more often than the PF.

3.4.4 Monitoring For Malfunctions and Failures

Effective monitoring for failures and malfunctions that are not associated with highly salient attention-capturing alarms or alerts likely involves different information gathering behaviors and strategies, compared to monitoring during routine operations. The detection of such failures may, in turn, lead to a change in scanning behavior (e.g., monitoring may become more random and fragmented). Only four of the 20 studies included in this review examined pilots' eye movements when they had to detect malfunctions that were either introduced without their knowledge or that were announced but not specified.

Brams et al. (2018)
Does effective gaze behavior lead to enhanced performance in a complex error-detection cockpit task?

Brams and colleagues (2018) compared the gaze behavior of 30 airline pilots (mean age 26.4 ± 8.22 years) with at least 200 hours of flight experience on an Airbus A330-200 and 28 novices with no flight experience (mean age 23.86 ± 2.85 years). Participants had to detect malfunctions in a cockpit instrument panel. They found that pilots exhibited shorter dwell times, which is likely due to the fact that it takes them less time to process the information; pilots transitioned more often between instruments, and they visited task-relevant areas more often. When comparing high- and low-performing pilots, the authors found that low performing participants used a more exhaustive search as indicated by a larger number of dwells. They also transitioned more often between instruments that were further apart.

van Dijk et al. (2011)
A coherent impression of the pilots' situation awareness: Studying relevant human factors tools.

The primary goal of this flight simulator experiment was to evaluate human factors tools for assessing pilots' situation awareness. The participants in this study were six crews of two A320 airline pilots each. The apparatus was the Generic Research Aircraft Cockpit Environment (GRACE) which was set up to mimic the Airbus A320. The 25-minute scenario for this study involved a malfunction, namely a discrepancy between the indicated air speed (IAS) shown on the Captain's and on the First Officer's PFDs. The malfunction was introduced unbeknownst to the pilots during flight and slowly got worse over time while researchers monitored if and how pilots detected the IAS discrepancy and figured out the correct airspeed. Eyetracking data were collected, and two different SA rating scales (the Instantaneous Self-Assessment (ISA) rating scale and the Crew Awareness Rating Scale (CARS)) were used. A significant negative correlation was found between the time it took pilots to discover the malfunction and the amount of time spent cross-checking the other pilot's PFD. Entropy increased after the malfunction.

van de Merwe et al. (2012)
Eye movements as an indicator of situation awareness in a flight simulator experiment.

In this study, a system malfunction, specifically a fuel leak that resulted in a fuel imbalance, was introduced directly after a pause in the 25-minute scenario. During the break, the pilots were informed that once they continued their flight, a system malfunction would occur. Their task was to detect and investigate this malfunction. Twelve A320 airline pilots participated in the experiment. Differences in attentional focus and scanning entropy were observed when the crews searched for the malfunction. Specifically, before the break, the largest number of fixations were on the navigation display (ND) and the PFD. Once the crew was informed that a malfunction had occurred, the ECAM display became the primary focus of attention at the cost of the number of fixations on the NAV and PFD. Also, during the diagnostic search time, the randomness of the viewing pattern increased. Crews displaying a structured and more distributed scan patterns were able to diagnose and correct the malfunction faster and more accurately.

Vine et al. (2015)
Individual reactions to stress predict performance during a critical aviation incident.

The aim of this study was to investigate the reaction of experienced pilots to a simulated stressful incident (engine failure) and to further probe the influence of these responses (challenge vs. threat) on attentional control and manual flying performance. Challenge refers to a situation where an individual determines that resources are sufficient to meet the demands of the situation; in contrast, a situation is perceived as a threat if resources are judged to be insufficient. Sixteen pilots from a regional commercial airline performed an "engine failure on take-off" scenario in a high-fidelity Bombardier Dash-8 Q400 flight simulator. Their reactions to the event were assessed via self-report; performance was assessed subjectively (flight instructor assessment) and objectively (simulator metrics); gaze behavior data were captured using a mobile eye tracker, and measures of attentional control were subsequently calculated (search rate, stimulus driven attention, and entropy). The engine failure (left engine) was triggered immediately after takeoff. Eyetracking data were collected for 12 of the 16 pilots tested. The results of this study show that pilots who perceived the scenario as being more of a threat displayed higher search rates, increased randomness in scanning behavior (entropy), and a reduced ability to suppress irrelevant stimuli. This disrupted gaze control was associated with poorer manual control of the aircraft and lower flight instructor ratings.

Summary:

- Failures that are not known to the flight crew take longer to discover with less time spent cross-checking instruments.

- Searching for a known (but unidentified) malfunction leads to a shift in scanning. Attention moves away from primary displays, such as the PFD and map display, to the ECAM display.

- A failure that is being perceived as highly threatening can lead to increased randomness in scanning behavior (entropy) and a reduced ability to suppress irrelevant stimuli which, in turn, leads to poor flying performance.

- Both training and operational experience benefit scanning and performance in a top-down fashion such that pilots (as opposed to non-pilots) show shorter dwell times, transition more often between instruments and visit task-relevant areas more often.

- There is a negative correlation between detection performance and the number of dwells and transitions between widely separated displays.

3.4.5 Fixation Sequences and Scan Patterns

Most eyetracking studies employ traditional metrics such as the number and duration of fixations or percentage dwell time for various AOIs. These metrics involve aggregating and averaging data over time; they provide no information regarding the sequence in which pilots access information. Fixation sequence is thought to be associated with pilot expertise and/or experience and is one of the critical issues under investigation in the present project. Only two of the studies identified as part of this literature review provide insight into this topic.

Haslbeck and Zhang (2017)
I spy with my little eye: Analysis of airline pilots' gaze patterns in a manual instrument flight scenario

In the study by Haslbeck and Zhang (2017) with a total of 51 short- and long-haul pilots from one major European airline completing a manual approach and landing task, four main scanpaths or saccade groupings were identified:

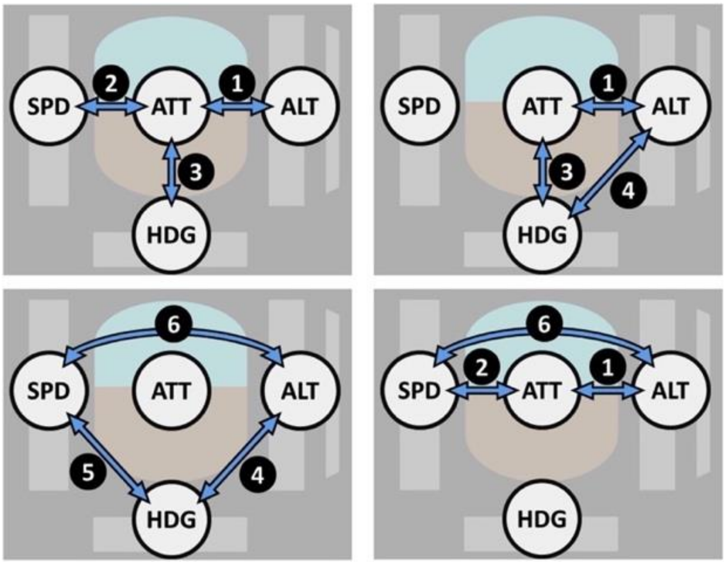


Figure 20. Four main scanpaths: top left: 123 “spokes-of-a-wheel” pattern (12 pilots); top right: 134 “small-right-triangle” pattern (8 pilots); bottom left: 456 “big-triangle” (5 pilots; and bottom right: 126 “long-and-short-horizontal” (6 pilots) (from Haslbeck and Zhang, 2017)

These groupings were found by calculating the transition matrices for the six possible saccades between defined AOIs and identifying the most frequent saccade grouping sets (SGs; see Figure 21):

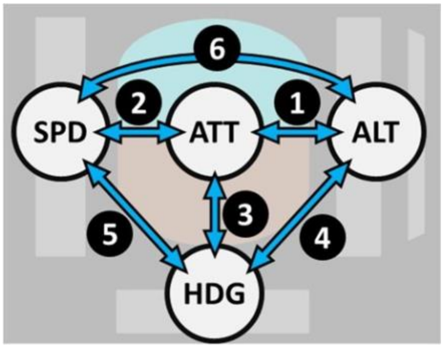


Figure 21. Six possible saccades between AOIs (1 ATT-ALT, 2 ATT-SPD, 3 ATT-HDG, 4 ALT- HDG, 5 SPD-HDG, 6 SPD-ALT) (from Haslbeck and Zhang, 2017)

Short- versus long-haul pilots did not differ with respect to parameters such as proportional dwell times but the two groups differed significantly in terms of the gaze pattern they adopted, as shown below:

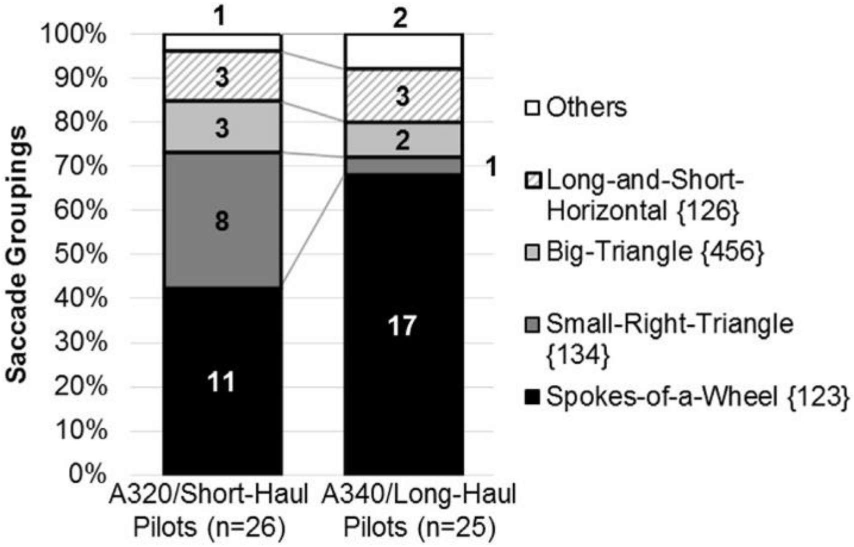


Figure 22. Gaze patterns adopted by short- versus long-haul pilots. (from Haslbeck and Zhang, 2017)

The spokes-of-a-wheel gaze pattern was by far the most often employed pattern for long-haul pilots. In contrast, short-haul pilots used both spokes-of-a-wheel and triangular patterns to nearly the same extent. Short-haul pilots using the spokes-type strategy showed significant larger deviations from the localizer (but not glideslope), compared to pilots using triangular types. Too few long-haul pilots employed a triangular pattern to compare deviations from localizer and glideslope for the two gaze patterns in this group.

Spady, A. (1978)
Airline pilot scan patterns during simulated ILS approaches

Spady (1978) asked seven airline pilots to fly a series of manual and coupled ILS approaches in a Boeing 737 simulator, with a traditional non-EFIS instrument arrangement (see Figure 23). For the most part, pilots in this study employed a radial scan pattern (see Figure 24). Their monitoring differed between the two types of approaches. Specifically, pilots looked less often at the flight director during the coupled approach **(**52 percent for the coupled condition, compared to 73 percent for the manual condition). Also, the mean dwell time on the flight director was shorter during coupled approaches **(**0.8 sec for coupled, compared to 1.6 sec for manual approaches).

Figure 23. Boeing 737-300 non-EFIS flight instruments (from http://www.b737.org.uk/flightinsts.htm)

Figure 24. Radial scan pattern where the pilot spends most of the time looking at the attitude indicator, with quick glances at other instruments before returning to the attitude indicator (adapted from https://nashvillecfi.com/instrument/ils.cgi)

Summary

- Pilots differ considerably in terms of the overall scan pattern they adopt.
- While long- and short-haul pilots do not differ with respect to aggregate metrics such as percentage dwell time, they do employ different gaze patterns. Long-haul pilots are more likely to employ a ‘spokes-of-a-wheel’ radial pattern while short-haul pilots embrace triangular patterns. It is not clear whether the difference in scan patterns accounts for poorer manual flying performance as long-haul pilots also have less practice than their short-haul colleagues.
- With a more traditional instrument arrangement, pilots tend to employ a radial scan pattern.

3.5 Research Gaps and Needs

Our review of the literature highlights the sparsity of empirical eyetracking-based studies of pilots’ visual scanning techniques on modern transport aircraft. In addition, it is difficult to summarize and integrate findings across these studies because they differ with respect to research question, aircraft type, flight phase, participants, and eyetracking metrics/AOIs. Still, the above summary sections highlight important findings on five themes: (1) Scanning As A Function of Pilot Role and Experience; (2) Scanning During Specific Maneuvers/Flight Phases; (3) Monitoring Flight Deck Automation; (4) Monitoring For Malfunctions and Failures; and (5) Fixation Sequences and Scanning Patterns. The review also helped identify problems with current scanning behavior as well as research gaps that need to be addressed to accomplish the goal of the present effort, namely “to understand flight crew visual scanning techniques to inform design and training interventions that better support pilots in tracking automation status and behavior and to determine the acceptability of design assumptions and mitigations for new flight deck layouts, specifically for Transport Category Aircraft (Part 25)”. The main research gaps and limitations relate to:

3.5.1 Single Pilot Versus Flight Crew Scanning

Most of the studies summarized in this report record eyetracking data and examine the scanning behavior of a single pilot when, in commercial transport operations, flight crews consist of two pilots who alternate between the role of pilot flying versus pilot monitoring. These roles are associated with different responsibilities and thus, the two pilots should adopt different attention allocation strategies and complement each other to improve overall flight crew awareness. The few studies that did assess and compare the PF’s and PM’s visual attention allocation suggest that during takeoff and go-arounds, for example, they monitor different instruments but during approaches, their monitoring strategies are nearly identical. This highlights the need for developing recommendations and training not only for individual pilots but for flight crews as well (for a good example of how to analyze the gaze behavior of a flight crew, see Weibel et al., 2012).

3.5.2 Aggregate Metrics Versus Fixation Sequences

The majority of studies in this literature review used raw eyetracking data to calculate aggregate metrics, such as percentage dwell time on various AOIs. This is important information about prioritization of different types of instruments/data but it does not provide insight into the temporal distribution and sequence in which information is being accessed (as in the radial scan patterns discussed early in this document). The latter may be critical, however, to determine the appropriateness of scanning and to suggest promising approaches to training. For example, the same percentage dwell time may be observed for a set of AOIs when pilots properly and equally distribute their attention over time and when they, for some period of time, exhibit a lack of inhibition of return or attentional narrowing for some of the instruments. Inhibition of return refers to suppressing orienting toward recently inspected locations and objects in the interest of orienting toward novelty (Posner & Cohen, 1984).

3.5.3 Fixating Versus Processing

Eyetracking data are important as they tell us what a pilot is looking at. But these data need to be interpreted with care. While Just and Carpenter (1980) proposed that what a person looks at is what they are processing and thinking about, others have questioned that this ‘mind-eye hypothesis’ holds true in all cases. A person may look at something without registering the corresponding object. For example, studies of mind-wandering (Casner and Schooler, 2015) have shown that pilots’ mind may be focused on internal thoughts while their eyes fixate an object or location in their environment. Conversely, (covert) attention may be paid to something in peripheral vision, and objects may be recalled that were never fixated on (Holmqvist et al., 2011).

A related issue is the distinction between scanning and monitoring, as pointed out by Mumaw et al. (2020). These authors point out that “monitoring, essentially, is “sense making”. It is systematic observation and interpretation of the current state of the airplane and its operational environment; it requires integration of current inputs with operational knowledge, which includes mental models, and the generation of expected values of flight path targets.” In other words, looking is not necessarily seeing and comprehending. For example, Sarter et al. (2007) have shown in a simulator study that, when they introduced artificial ‘non-sensical’ or ‘context-inappropriate’ flight mode annunciations to a simulated Primary Flight Display in a simulator, a number of pilots would fixate those FMAs but not express surprise, confusion or intervene in any way.

One way in which researchers are trying to distinguish between ‘looking’ and ‘seeing’, i.e., actually processing the information that is being fixated, is by examining microsaccades. Microsaccades have been defined as “involuntary, small-magnitude saccadic eye movements that occur during processed visual fixation” (Krueger et al., 2019). They usually have an amplitude of less than two degrees of visual angle. Microsaccade rates appear to decrease with increased mental task demands and significantly increase in conditions that require a high degree of visual attention. Also, an increase in microsaccades appears to lead to an enhanced visibility for peripheral and parafoveal visual targets (Martinez-Conde et al., 2006). Finally, some studies have linked microsaccade production to cognitive processes, such as working memory (e.g., Valsecchi et al., 2007). More research is needed to validate this approach which requires eyetracking equipment with very high sampling rates (on the order of 1200 Hz).

The above limitations suggest that eyetracking data should be considered one of several complementary markers of pilots' attention, awareness and understanding. They need to be augmented by and combined with concurrent measures of pilot actions and verbal behavior.

3.5.4 Real-Time Processing of Eyetracking Data To Support Adaptive Feedback Design

Training plays an important role in developing an instrument scan. Not only can a standardized scan pattern be taught explicitly but the development of a mental model of aircraft systems helps develop top-down expectations and thus guides monitoring. At the same time, properly designed feedback can complement training by attracting and guiding attention in a bottom-up fashion. For example, salient cues can capture attention in an involuntary fashion to help pilots notice unexpected changes and events (such as mode changes). Recently, adaptations of feedback based on real-time processing of eyetracking data have been proposed (e.g., Peysakhovich et al., 2018). Here, eyetracking data would be used to detect when pilots spend too little or too much time attending to relevant indications, and information presentation could be changed (salience changes, temporary removal of information, etc.) (see Figure 25).

While real-time processing of a limited set of eyetracking data is, in principle, possible, the main challenge for adaptive feedback design remains the question whether a certain scanning behavior is appropriate given flight context and pilot role and to avoid that changes in feedback design lead to confusion. Still, this approach could be useful to overcome attentional failures, such as attentional tunneling which was identified as a problem in the BEA (2013) study: During one go-around, the PF focused for 22 s on the vertical flight path to capture the target altitude, to the detriment of monitoring the horizontal flight path. This led to a flight path deviation. The PM neither detected nor notified the PF of the deviation from the lateral flight path as this pilot's attention was taken up entirely by configuring the flaps (as indicated by exclusive switching between the flaps and the airspeed indicator). During another go-around, the PF took responsibility for setting the altitude and heading values on the FCU. He focused on this interface and did not notice, on his PFD, that the aircraft was significantly overshooting the target altitude of 2,500 feet, despite his co-pilot calling out this deviation ("*We're climbing through 3,000 [feet]*").

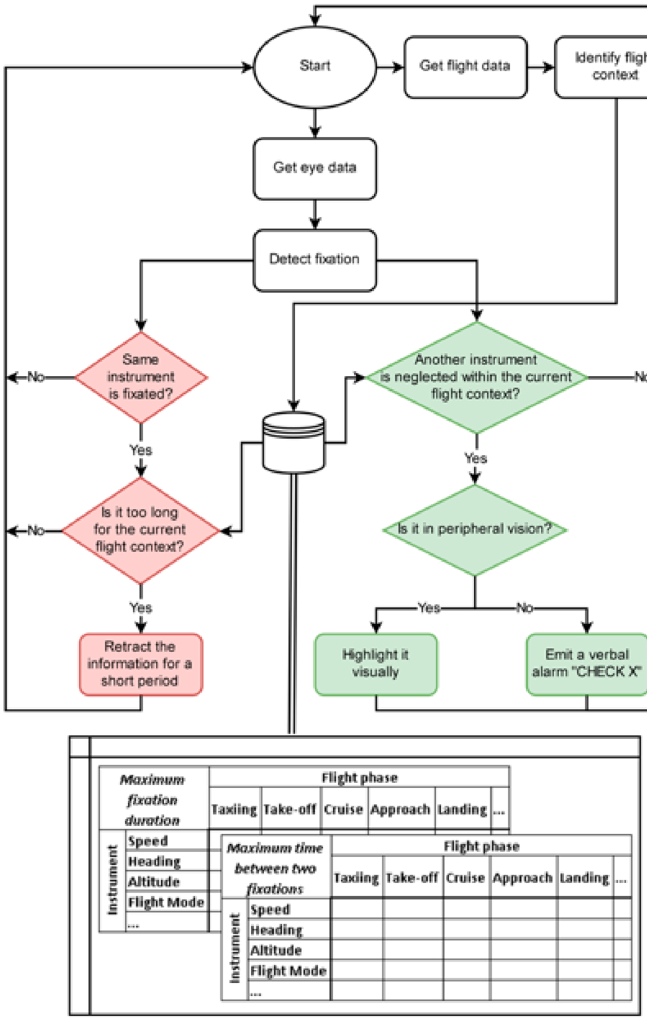


Figure 25. Gaze-based flight deck adaptation (from Peysakhovich et al., 2018)

3.6 Advisory Circulars, Reports/Papers and Guides/Handbooks on Monitoring

The following FAA advisory circulars, reports/papers and guides/handbooks were searched for guidance on how to monitor flight instruments and the surroundings of the aircraft. Keywords used for this search included visual scanning, instrument scan, pilot monitoring, cross-checking and gaze, and visual alerts. Note that information on how to design instruments and displays to support monitoring is not included in the list below.

Advisory Circulars

- AC 20-167A: Airworthiness Approval of Enhanced Vision System, Synthetic Vision System, Combined Vision System, and Enhanced Flight Vision System Equipment
- AC 23-1523: Minimum Flight Crew
- AC 25.1302-1: Installed Systems and Equipment for Use by the Flightcrew

- AC 25-11B: Electronic Flight Displays
- AC 90- 48D: Pilots' Role in Collision Avoidance (note that the audience for this AC is smaller general aviation operations which may not be comparable with visual scanning in a modern transport aircraft)
- AC 120-71 B: Standard Operating Procedures and Pilot Monitoring Duties for Flight Deck Crewmembers
- AC 120-74B: Parts 91, 121, 125, and 135 Flightcrew Procedures During Taxi Operations
- AC120-123: Flight Path Management

Reports/Papers

- FAA Human Factors Team Report titled "The Interfaces Between Flightcrews and Modern Flight Deck Systems"
- Final Report of the Performance-based operations Aviation Rulemaking Committee/Commercial Aviation Safety Team Flight Deck Automation Working Group, titled "Operational Use of Flight Path Management System"
- Human Factors Considerations in the Design and Evaluation of Flight Deck Displays and Controls - Version 2.0
- A Practical Guide for Improving Flight Path Monitoring - Flight Safety Foundation
- Monitoring Matters Guidance on the Development of Pilot Monitoring Skills – CAA (Civil Aviation Authority)

Guides/Handbooks

- FAA-H-8083-15B: Instrument Flying Handbook
- Guidance Material for Improving Flight Crew Monitoring – IATA (International Air Transport Association)

The available guidance is presented under four headings below:

(1) Cross-Check and Scan Patterns
(2) Contributors to Monitoring Deficiencies
(3) Scanning for Traffic
(4) Glass Cockpits and FMAs

Cross-Check and Scan Patterns	
1. At any point in time during the flight, one pilot is the PF and one pilot is the PM.[2] 2. The PF is responsible for managing, and the PF and PM are responsible for monitoring, the current and projected flightpath and energy of the aircraft at all times. 3. The PF is always engaged in flying the aircraft (even when the aircraft is under AP control) and avoids tasks or activities that distract from that engagement. If the PF needs to engage in activities that would distract from aircraft control, the PF should transfer aircraft control to the other pilot, and then assume the PM role. 4. Transfer of PF and PM roles should be done positively with verbal assignment and verbal acceptance to include a short brief of aircraft state. 5. The PM supports the PF at all times, staying abreast of aircraft state and ATC instructions and clearances.	AC 120-123
Training should also include recognition of and signs of diminished crewmember performance on the part of the PF or PM (e.g., lack of communication, channelized attention, failure to make required callouts, etc.). Training should include monitoring-related CRM, TEM, and human performance vulnerabilities related to monitoring, the importance of monitoring, and the operator-approved practices that achieve effective monitoring of the flightpath.	AC 120-123
To effectively monitor, the pilot should know what information to attend to and when. The pilot should apply strategies to perceive flight deck indications and interpret their meaning for the current context and assimilate them into a mental model of airplane state relative to the flightpath. The pilot actively compares their mental model of what is expected (or normal for the context) to the indications in the environment (e.g., flight instrument, mode annunciations) that are available. Therefore, the pilot needs to have sufficient knowledge to form an accurate mental model of the aircraft systems and performance, to know what information to acquire, and how to process it to formulate an accurate understanding of the current state of the aircraft flightpath. Differences between what is expected/desired and what is observed should trigger corrective action.	AC 120-123
• The PM is responsible for monitoring the current and projected flight path and energy of the aircraft at all times. • The PM supports the PF at all times, staying abreast of aircraft state and ATC instructions and clearances.	AC 120-71 B

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[2] Note that, regardless of their role, both pilots will scan the outside scene, flight deck displays, etc. to visually acquire information. However, what is scanned, and why, might be the same or different depending on context or task.

• The PM monitors aircraft state and system status, calls out any perceived or potential deviations from the intended flight path, and intervenes if necessary.	
The first fundamental skill is cross-checking (also called “scanning” or “instrument coverage”). Cross-checking is the continuous and logical observation of instruments for attitude and performance information. In attitude instrument flying, the pilot maintains an attitude by reference to instruments, producing the desired result in performance. Observing and interpreting two or more instruments to determine attitude and performance of an aircraft is called cross-checking. Although no specific method of cross-checking is recommended, those instruments that give the best information for controlling the aircraft in any given maneuver should be used. The important instruments are the ones that give the most pertinent information for any particular phase of the maneuver. These are usually the instruments that should be held at a constant indication. The remaining instruments should help maintain the important instruments at the desired indications, which is also true in using the emergency panel.	FAA-H-8083-15B: Instrument Flying Handbook
<u>Selected Radial Cross-Check</u> When the selected radial cross-check is used, a pilot spends 80 to 90 percent of flight time looking at the attitude indicator, taking only quick glances at the other flight instruments (for this discussion, the five instruments surrounding the attitude indicator are called the flight instruments). With this method, the pilot’s eyes never travel directly between the flight instruments but move by way of the attitude indicator. The maneuver being performed determines which instruments to look at in the pattern. The radial scan pattern works well for scanning the PFD. The close proximity of the instrument tape displays necessitates very little eye movement in order to focus in on the desired instrument. While the eyes move in any direction, the extended artificial horizon line allows the pilot to keep the pitch attitude in his or her peripheral vision. This extended horizon line greatly reduces the tendency to fixate on one instrument and completely ignore all others. Because of the size of the attitude display, some portion of the attitude indicator is always visible while viewing another instrument display on the PFD.	FAA-H-8083-15B: Instrument Flying Handbook
<u>Inverted-V Cross-Check</u> In the inverted-V cross-check, the pilot scans from the attitude indicator down to the turn coordinator, up to the attitude indicator, down to the VSI (Vertical Speed Indicator) , and back up to the attitude indicator.	FAA-H-8083-15B: Instrument Flying Handbook
<u>Rectangular Cross-Check</u> In the rectangular cross-check, the pilot scans across the top three instruments (airspeed indicator, attitude indicator, and altimeter), and then drops down to scan the bottom three instruments (VSI, heading indicator, and turn instrument). This scan follows a rectangular path (clockwise or counterclockwise rotation is a personal choice). This cross-checking method gives equal weight to the information from each instrument, regardless of its importance to the maneuver being	FAA-H-8083-15B: Instrument Flying Handbook

performed. However, this method lengthens the time it takes to return to an instrument critical to the successful completion of the maneuver.	
Good monitoring relies upon effective task management and 'making time for monitoring'… Flight path monitoring/ selective radial instrument scan must be a priority task that is not compromised by other priority tasks. Task scheduling (e.g., carrying out normal checklist), sharing (e.g., balancing the monitoring workload and being aware when the PM has very limited capacity) and shedding (e.g., prioritizing tasks) must be considered as strategies to achieve a good monitoring practice.	CAA: Monitoring Matters

These are a few strategies that could be employed to enhance good monitoring behavior:
• Stay in the loop by mentally flying the aircraft even when the autopilot or other pilot is flying the aircraft.
• When you have been distracted ensure that you always check the FMAs and your flight instruments to get back in the loop as soon as possible.
• Monitor the flight instruments just as you would when you are manually flying the aircraft.
• Be diligent in monitoring all flight path changes – pilot ACTIONS, system MODES, aircraft RESPONSES.
  o Always make monitoring of the PF a priority task when flight path changes are being made.
  o Always check the FMA after a change has been selected on the autopilot mode control panel.
• During briefings include 'monitor me' type comments to encourage intervention – 'remind me if I haven't asked for the after-take-off checks'.
• Provide the occasional monitoring reminders e.g. – 'make sure that the tail wind doesn't exceed 10 kt'.
• Manage the workload:
  o when the workload gets too high, prioritise which parameters to monitor – don't multi-task for too long;
  o when dealing with emergency situations ensure adequate time and space to enable the continuation of the monitoring tasks; and
  o avoid programming the FMS at critical phases of flight.
• Mentally rehearse during low periods of workload, monitoring tasks that will occur in the next phase of flight.
• Make cross checking achievement of the autopilot targets a force of habit.
• At the end of the flight discuss how well the monitoring was carried out – did you both share the same plan.
• When the aircraft is carrying defects that are acceptable in the MELs (Minimum Equipment Lists) consider the impact on the monitoring task – make a note (mental or otherwise) of the affected flight parameters, modes or systems that will require more
	CAA: Monitoring Matters

attentive monitoring (discuss this during briefing).	
As monitoring is vital to maintain safety of flight, it is of upmost importance that operators define in their operation manual an overarching policy providing guidance on the monitoring process, monitoring tasks, assigned flight crew monitoring duties, crew communications, and SOPs related to monitoring. Additionally, the operator’s flight crew training or flight crew techniques manual should describe in detail effective monitoring training, including observable behaviors, briefings/debriefings, and expected performance.	Guidance Material for Improving Flight Crew Monitoring
Recommendation 1 Institute practices that support effective flight path monitoring. Recommendation 2 Clearly define the monitoring role of each pilot Recommendation 3 Establish among pilots the concept that there are certain, predictable areas during each flight where the risk of a flight path deviation increases, heightening the importance of proper task/workload management. Recommendation 4 Practice interventions to maintain effective monitoring or to resume effective monitoring if degraded Recommendation 5 Implement policies and practices that protect flight path management from distractions and interruptions Recommendation 6 Practice interventions to resume effective monitoring after distractions and interruptions Recommendation 7 Promote policies, procedures and practices to improve monitoring of altitude changes. Recommendation 8 Emphasize the effects that emergency and non-normal situations have on monitoring. Recommendation 9 Review current operating procedures for conflicts with operating policy. Recommendation 10 Review the specific monitoring-related procedures that standards pilots are not willing or able to enforce. Recommendation 11 Analyze corporate messages — whether explicit or implicit — that conflict with emphasizing good monitoring. Recommendation 12 Institute policies/procedures/practices to ensure common understanding among crewmembers of ATC clearances. Recommendation 13 Explicitly address monitoring as part of a comprehensive flight path management policy that includes guidance on use of automated systems. Recommendation 14 Develop and enhance training to improve the monitoring of automated systems as incorporated into the flight path management policy. Recommendation 15 Train pilots about why they are vulnerable to errors and monitoring lapses Recommendation 16 Reinforce the responsibility of monitoring pilots to challenge deviations.	A Practical Guide for Improving Flight Path Monitoring (note that this document discusses each of the recommendations in a lot more detail)

Recommendation 17 Develop and publish clearly defined monitoring tasks, training objectives and proficiency standards. Ensure instructors and evaluators are proficient at training and evaluating these standards. Recommendation 18 Implement a comprehensive approach to training and evaluating autoflight and flight path monitoring. Recommendation 19 Incorporate monitoring training into simulator or other device training Recommendation 20 Place greater emphasis on monitoring in operator flight standards programs.	
Contributors to Monitoring Deficiencies	
In the interviews and other communications, the WG heard significant concerns about the development and retention of manual handling skills. This was described as a concern for several operational situations, such as visual approaches and crosswind landings. Associated issues also mentioned included the definition of specific knowledge and skills that comprise "manual flying skills;" e.g., instrument pattern scan, knowledge and "stick and rudder." While almost every interview group mentioned a possible decrease in manual handling skills, few were able to provide direct evidence because specific data on manual handling skills usually are not collected.	PARC
A number of human behaviors that are typically associated with high workload are listed below. The test conductor/observer should be especially cognizant of these behaviors during the conduct of the test and pay particular attention as to when and under what conditions any of these behaviors are observed. If any of these behaviors are observed during the course of the evaluations, more detailed examinations of workload may be necessary… Observed cockpit operational behavior a. Repeatedly refers to manuals or handbooks b. Makes repeated unsuccessful attempts to enter or alter data c. Exhibits excessive head-down time (1) Break-down of normal scan (2) Fixation on single display or interface (3) Insufficient monitoring of surrounding airspace in VMC (Visual Meteorological Conditions) d. Insufficient monitoring of cockpit displays	AC 23.1523
Effective flightpath monitoring also requires effective management of attention. If pilots become distracted or workload is high, attention may be insufficient. The management of attention is an important cognitive skill that requires effort. Because the modern flight deck has many visual displays and sources of information, pilot attention may be captured by interpreting aircraft system behavior or compelling, information-rich displays. Therefore, it is important that pilots are skilled at managing attention, information, and distractions to ensure flightpath remains the primary focus of the flightcrew.	AC 120-123

Pilots should be trained and evaluated on recognizing barriers to effective flightpath monitoring and indications of inadequate flightpath monitoring. Conditions that may lead to inadequate flightpath monitoring may include high task loading, insufficient attention management, or distractions. For example, during times of high task loading, pilots may focus on individual tasks or channelize their attention, which may lead to diminished communication between the crewmembers. Training should include strategies to respond to these risks and identify the resources to be used during high workload on the flight deck.	AC 120-123
Pilots should be trained on common errors in monitoring the flightpath, and potential mitigations for those errors. This includes training on appropriate methods of recognizing precursors to, and signs of, degraded monitoring and on resolving monitoring errors and/or lapses.	AC 120-123
In addition, human performance limitations should be acknowledged as potential challenges for effective monitoring. The human brain has difficulty with sustained vigilance and has quite limited ability to multitask. Pilots are vulnerable to interruptions and distractions and to cognitive limitations that affect what they notice and do not notice.	AC 120-71 B
It can be difficult for humans to monitor for errors and deviations on a continuous basis when errors and deviations rarely occur. This is true for the range of workload conditions experienced by the flightcrew members. Monitoring during high-workload periods is important since these periods present situations in rapid flux and because high workload increases vulnerability to error. However, studies show that poor monitoring performance can be present during low-workload periods as well. Lapses in monitoring performance during lower-workload periods are often associated with boredom, complacency, or both.	AC 120-71 B
A beginner might cross-check rapidly, looking at the instruments without knowing exactly what to look for. With increasing experience in basic instrument maneuvers and familiarity with the instrument indications associated with them, a pilot learns what to look for, when to look for it, and what response to make. As proficiency increases, a pilot cross-checks primarily from habit, suiting scanning rate and sequence to the demands of the flight situation. Failure to maintain basic instrument proficiency through practice can result in many of the following common scanning errors, both during training and at any subsequent time.	Instrument Flying Handbook
Fixation, or staring at a single instrument, usually occurs for a reason, but has poor results. For example, a pilot may stare at the altimeter reading 200 feet below the assigned altitude and wonder how the needle got there. While fixated on the instrument, increasing tension may be unconsciously exerted on the controls, which leads to an unnoticed heading change that leads to more errors. Another common fixation is likely when initiating an attitude change. For example, a shallow bank is established for a 90° turn and, instead of maintaining a cross-check of other pertinent instruments, the pilot stares at the heading indicator throughout the turn. Since the aircraft is turning, there is no need to recheck the heading indicator for	Instrument Flying Handbook

approximately 25 seconds after turn entry. The problem here may not be entirely due to cross-check error. It may be related to difficulties with instrument interpretation. Uncertainty about reading the heading indicator (interpretation) or uncertainty because of inconsistency in rolling out of turns (control) may cause the fixation.	
Omission of an instrument from a cross-check is another likely fault. It may be caused by failure to anticipate significant instrument indications following attitude changes. For example, in a roll-out from a 180° steep turn, straight-and-level flight is established with reference only to the attitude indicator, and the pilot neglects to check the heading indicator for constant heading information. Because of precession error, the attitude indicator temporarily shows a slight error, correctable by quick reference to the other flight instruments.	Instrument Flying Handbook
Emphasis on a single instrument, instead of on the combination of instruments necessary for attitude information, is an understandable fault during the initial stages of training. It is a natural tendency to rely on the instrument that is most readily understood, even when it provides erroneous or inadequate information. Reliance on a single instrument is poor technique. For example, a pilot can maintain reasonably close altitude control with the attitude indicator but cannot hold altitude with precision without including the altimeter in the cross-check.	Instrument Flying Handbook
When moderate to severe turbulence is encountered, aircraft control is difficult, and a great deal of concentration is required to maintain an instrument scan. Pilots should immediately reduce power and slow the aircraft to the recommended turbulence penetration speed as described in the Pilot's Operating Handbook/Airplane Flight Manual (POH/AFM).	Instrument Flying Handbook
Pilots should also realize that their eyes may require several seconds to refocus when switching views between items in the cockpit and distant objects. Proper scanning requires the constant sharing of attention with other piloting tasks; thus, it is easily degraded by psychophysiological conditions, such as fatigue, boredom, illness, anxiety, or preoccupation.	AC 90-48D
There are certain human states which can be transitory in nature whereby the pilot becomes 62raumatized and unable to function normally. They are insidious conditions because the pilot may appear to be functioning normally but only have a partially functioning brain. Mental incapacitations will always affect the monitoring task and may manifest itself in either a complete freeze or tunnel vision.	CAA: Monitoring Matters
Scanning for Traffic	
The probability of spotting a potential collision threat increases with the time spent looking outside, but certain techniques may be used to increase the effectiveness of the scan time. The human eyes tend to focus somewhere, even in a featureless sky. If there is nothing specific on which to focus, your eyes revert to a relaxed intermediate focal distance (10 to 30 feet). This means that you are looking without actually seeing anything, which is dangerous. In order to be most effective, the pilot should shift glances and refocus at intervals. Most pilots do this in the	AC 90-48D Pilot Vision Brochure

process of scanning the instrument panel, but it is also important to focus outside to set up the visual system for effective target acquisition.	
Effective scanning [for traffic; added by UM team] is accomplished with a series of short, regularly spaced eye movements that bring successive areas of the sky into the central visual field. Each movement should not exceed 10 degrees, and each area should be observed for at least 1 second to enable detection. Although most pilots seem to prefer horizontal back-and-forth eye movements, each pilot should develop a scanning pattern that is most comfortable and then adhere to it to assure optimum scanning.	AC 90-48D
Peripheral vision can be most useful in spotting collision threats from other aircraft. Each time a scan is stopped and the eyes are refocused, the peripheral vision takes on more importance because it is through this element that movement is detected. Apparent movement is almost always the first perception of a collision threat, and probably the most important, because it is the discovery of a threat that triggers the events leading to proper evasive action. It is essential to remember, however, that if another aircraft appears to have no relative motion, it is likely to be on a collision course with you. If the other aircraft shows no lateral or vertical motion, but is increasing in size, take immediate evasive action.	AC 90-48D
Glass Cockpits and FMAs	
Autoflight mode awareness is of particular importance because effective monitoring of autoflight modes is necessary for successful FPM. Below are some recommended strategies for effective monitoring of the autoflight modes that could be included in operator policies and procedures. The pilot should: 1. Stay in the loop by mentally flying the aircraft even when the AP or other pilot is flying the aircraft. 2. Monitor the flight instruments just as when the pilot is manually flying the aircraft. 3. Be diligent in monitoring all flightpath changes including pilot actions, system modes, and aircraft responses. 4. Always make monitoring of the flightpath a priority task when changes are being made. 5. Always check the FMA after a change has been selected on the autoflight mode control panel. 6. Check the FMAs and flight instruments after being distracted to regain full awareness of the flightpath state. 7. Maintain an awareness of the autoflight systems and modes selected by the crew or automatically initiated by the FMS (mode awareness) to effectively monitor the flightpath. 8. Maintain an awareness of the capabilities available in engaged autoflight modes to avoid mode confusion. 9. Effectively monitor systems and selected modes to ensure that the aircraft is on the desired flightpath.	AC 120-123
Training should ensure that pilots have a thorough understanding of the knowledge and skills to apply the combinations of flight guidance and	AC 120-123

flight control automation (e.g., given a certain set of circumstances, what will happen next?). Training should also ensure pilots are proficient and can transition seamlessly between combinations/levels of flight guidance/flight control automated systems (including manual flight) during line operations. Training should be enhanced to teach pilots to interpret the FMA and other FPM systems relative to aircraft state and to know what to expect based on programming, configuration, and aircraft state. Training should explicitly address the management of deviations or off-path operations and include strategies for managing “automation surprises” and unknown situations.	
Methods for monitoring mode information. Standard instrument scan patterns used with older analog instruments may not apply to glass cockpit displays. The HF Team notes that nothing comparable to the standard instrument scan pattern has arisen for these new displays, especially in terms of continuously monitoring mode information. Instead, there are conflicting ideas on how best to maintain awareness of the active mode. For example, some manufacturers and operators recommend that flightcrews call out all mode changes. Other manufacturers and operators find this philosophy too burdensome and consider it to be unnecessary and potentially distracting, especially for mode changes that are associated with normal system behavior.	Human Factors Team Report

4. Focus Groups on Training, Monitoring Breakdowns and the Role of Design

Building on the findings from our literature review, we next conducted three focus groups on visual scanning with aviation professionals to gain a better understanding of current practices in the commercial aviation sector. Participants in the focus groups included active commercial airline pilots, flight instructors and check airmen for major airlines, aviation safety and flight deck human factors experts, and flight deck designers. The main goal of these focus groups was to learn (1) what current training needs and approaches are, (2) what factors lead to breakdowns in monitoring, and (3) how flight deck design affects visual scanning. This report documents the key findings from the three focus groups.

4.1 Methods

In April and May 2021, three focus groups were conducted virtually, on Zoom, each lasting three hours. One researcher (the PI) was present for each focus group to facilitate and record the conversations. Table 10 below shows the number and background of participants.

Table 10. Participants in three focus groups on visual scanning

Focus Group I	Focus Group II	Focus Group III
Airline Pilot/Flight Instructor	Regional Airline Pilot and Training Expert	Airline Pilot
Flight Deck Designer/Researcher	Airline Pilot and Flight Safety Expert	Airline Pilot
Airline Pilot/Flight Instructor and Human Factors Expert	Flight Deck Designer/Researcher	Airline Pilot and Training Expert
Airline Pilot and Human Factors Expert	Airline Pilot and Flight Safety Expert	
Regional Airline Pilot, Check Airman and Human Factors Expert		

Participants were informed in advance of the zoom call about the overall goals and objectives, as well as IRB-related aspects (e.g., confidentiality, compensation) of the research activity (see Appendix A). On the day of the meeting, the following agenda was followed:

- Introductions
- Brief overview of the project by the PI
- Discussion Theme 1: Training needs, approaches to training and associated challenges
- 10-minute break
- Discussion Theme 2: Monitoring breakdowns
- 10-minute break
- Discussion Theme 3: The impact of design on scanning/monitoring
- Wrap-Up

Sample questions that were raised by the experimenter to guide the discussion included:

- At your airline, (how) are pilots trained for scanning flight deck instruments and the outside world?
- In your experience, how do pilots actually monitor flight deck instruments and the outside world?
- Under what circumstances and for what reasons does visual scanning tend to break down?
- How is pilots' scanning behavior affected by transitions between aircraft, especially those on aircraft designed by different manufacturers?
- Are there design features of modern flight deck displays that help or hinder visual scanning?

The discussions among participants were recorded using the zoom recording function and later transcribed. References to specific people, companies, and organizations were removed. The transcripts (210 pages total) were then analyzed separately by the graduate student working on the project and by the PI. The following sections will present key takeaways from the discussion of the three main topics. Throughout, quotes are included, in italics, and connections to findings from the literature review are mentioned. Note that, even though we included participants with a range of different backgrounds, the perceptions they shared represent qualitative data that do not necessarily represent all pilots and operations.

4.2 Findings

Given the composition of the focus groups, the following sections present findings from the perspective of a 14 CFR Part 121[3] Advanced Qualification Program (AQP)[4] air carrier, unless otherwise noted.

Also, as indicated in the Introduction to this report, we [the research team] adopt the definition of monitoring by the Civil Aviation Authority (CAA) Loss of Control Action Group (2013): "The observation and interpretation of the flight path data, configuration status, automation modes and on-board systems appropriate to the phase of flight. It involves a cognitive comparison against the expected values, modes and procedures. It also includes observation of the other crew member and timely intervention in the event of deviation." Visual instrument scanning is considered one element of monitoring. It cannot be determined in every instance whether focus group participants based their comments on the same definition.

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[3] Part 121, 135, and 91 are examples of Federal Aviation Administration (FAA) approved frameworks for how air carriers will conduct their aviation business. Part 121 covers aviation businesses—like commercial operators—that publish flight schedules and offer flight and cargo services in exchange for a fee. Unlike part 121, part 135 covers only on-demand service, such as airplane sightseeing, air taxi, and helicopter transportation. Part 121 operations require a two-pilot crew whereas the other parts allow for single-pilot operations.

[4] AQP is a voluntary, alternative method for qualifying, training, and certifying pilots. It is a process (or performance-based rule) that allows for customized training to the certificate holder's unique demographic and flight operation (https://www.faa.gov/training_testing/training/aqp). The training programs are developed by operators and evaluated, approved, and overseen by the FAA.

4.2.1 Lack of/Inadequate Training

Participants in the three focus groups pointed out that visual scanning is currently not a standard element of most pilot training programs. Even if monitoring is addressed in training, there is no standard approach or procedure, even within one airline. According to some of the focus group participants, this can be explained, in part, by the fact that most airlines operate a wide array of different aircraft which requires them to tailor policies and procedures to the various fleets.

- *"…they [the airlines] went through the flight manuals and tried to harmonize as many of the call-outs, checklists, procedures as they possibly could. Which, led to a lot of disagreements and angst for Airbus folks flying like Boeing and Boeing, folks flying like Airbus on some of the equipment. Some of the policies, your procedures don't make sense because that's not equipment was designed to be operated, but it does complicate the situation enough to where it causes a safety concern."*

Participants felt that the little scan training that is provided tends to be inadequate. It often consists of telling pilots to focus on the flight director (FD) which leads to problems when flight guidance becomes unavailable:

- *"…then you take the flight director away and maybe they don't actually know what pitch target and power target gives them a certain performance because all they've been taught to do is follow the flight director."*
- *"…it becomes a stare and not a scan."*

Also, there is a strong emphasis on monitoring trend vectors (specifically, airspeed and altitude).

- *"… they struggle with a predictive scan, meaning they're behind the airplane, they're chasing the flight director and those trend vectors; those tend to be kind of a crutch rather than branching out, using all the information that's in front of them."*

The focus groups highlighted that training focuses almost exclusively on the pilot flying (PF) and that more effort needs to go into training the pilot monitoring (PM) and the joint flight crew. This sentiment was expressed also by airline representatives who participated in earlier discussions conducted by Mumaw et al. (2019). Also, airlines need to better support pilots transitioning from analog round-dial gauges to a 'glass cockpit' with electronic (digital) flight instruments, or vice versa. Switching between aircraft built by different manufacturers was considered by many to be less challenging.

- *"….when pilots first fly a glass cockpit* aircraft [this refers to airline pilots who transition from an aircraft equipped with traditional analog gauges to an aircraft that features electronic (digital) flight instrument displays], *I don't think we really tell them to do anything, unfortunately."*
- *"And so what I did as a new instructor was I just sat down with the guys after the third or fourth week when we got them in the course is just to sit down and have them read the instruments, show them what the scan is, what everything means, how it relates to the old*

aircraft and they had never done that, they should have done this on day one because they'd been lost for the last three weeks I think, all this new stuff that they didn't understand."

Explanations for the lack or inadequacy of training included (1) attempts by airlines to keep training costs and time (current initial training lasting anywhere between … and recurrent training….) to a minimum:

- "*…but to go back with what the other major carrier said, you go fleet to fleet and you only have so much time in that first week where you're creating the habits of a good monitor, and that gets pushed to the side because there's not that day…"*

and also (2) assumptions made by the airlines about pilots' proficiency level.

4.2.2 Assumptions About Transferability of Scanning Techniques Across Aircraft and Operations

Participants explained that by the time a pilot starts flying for an airline, it is – often incorrectly – assumed that they are highly proficient and employ an appropriate visual scan. Only when deficiencies in monitoring become apparent during training would instructors work with that pilot and try to go back to basics:

- *"….it's not something that the airlines focus on or train in terms of a scan. If somebody's displaying a trouble in training, that's going to be evident. And they're going to focus on that and try to address it and fix it. But as far as something that is intentionally trained absence of problem, it's not."*
- *"So put them in the simulator, at 10,000ft, turn everything off and have them do climbs, turns, etc. – all that sort of stuff like you do with a new instrument student for about 20 minutes."*

Assumptions about pilots' scanning proficiency are sometimes incorrect due to the fact that, in recent years, less experienced pilots are being hired by airlines.

- *"…for airplanes like the 737, we're still seeing crews coming into those airplanes with really, really minimal hours of flight time and just general flight experience. And I think we, as a company have been struggling with what to do about that…"*

One regional carrier representative pointed out that they cannot make the same assumptions as major airlines since they often hire pilots for whom it is their first experience flying a jet.

4.2.3 Mental Models and Debriefs

Participants highlighted the importance of pilots developing accurate and complete mental models (i.e., cognitive representations of the physical and conceptual aspects) of the aircraft and aircraft systems to guide visual attention allocation which is affected by both bottom-up factors (such as the salience of an indication) and top-down factors (such as a pilot's mental model). In the context of threat and error management, these two modes of attention allocation have been termed reactive and predictive monitoring, respectively (IATA, 2016):

Figure 26. Two complementary forms of monitoring (image adopted from International Air Transport Association (IATA), 2016, page 21)

The importance of training that supports predictive monitoring was emphasized by several participants.

- *"it's really hard to talk about the monitoring part without the mental model part. And if there is this policy of encouraging maximum use of automation, then it doesn't necessarily seem like they're also encouraging maximum knowledge or maximum mental model of automation in order to support that monitoring."*
- *"...we're just taught a sequence of button pushes and not necessarily the underlying... And I know I talked about this earlier, but the underlying functionality, and in order to be a really good monitor, you have to know a lot more than just the sequence of buttons or lights that you're expected to see. .... What's going to happen next, so you know where to look next, so you can be predictive."*

It was noted that both visual scanning training and training dedicated to mental model development are missing from, or inadequate in current airline training programs.

- *"I could take some of the captains I flew with, they were the best 747 pilots* I'd *ever flown with and they couldn't fly the -400 because the glass threw off their mental models, they didn't know how to associate that information."*

Participants mentioned facilitated debriefs - i.e., an in-depth discussion of what happened during a training session, why it happened, and how it should be responded to - as one of the most effective ways to inspect, evaluate and improve pilots' mental models during training. These debriefs should explicitly address visual monitoring skills and techniques:

- *"... it's amazing how much a pilot will talk and learn through their own self-reflection on, "Okay. That's why I was making this mistake because I was busy or I didn't use my time well, or I was focused on the wrong task or didn't ask for help"" .... until you ask all those, why, why, why questions, you don't know exactly why it didn't come out."*

4.2.4 Proceduralization

Participants expressed concerns about too much reliance on procedures for supporting monitoring. This finding echoes results from interviews with airline representatives conducted by Mumaw et al. (2019) who describe "struggles to balance SOPs with effective monitoring". Participants in our discussions acknowledged that standard procedures are critical, for example, for safely handling events leading to a startle response (the startle response is "an unlearned, rapid, reflex-like response to sudden, unexpected, and intense stimuli (e.g. loud noises, flashing lights)"; this contrasts with surprises which are experienced when a violation of an expectation or the detection of novelty in the environment are experienced (American Psychological Society, 2022). Procedures can help a pilot focus on critical information. Two pilots explained that, when used to a limited extent, standard procedures help them ensure system awareness.

- *"... so I was trained by some instructors ... to look at everything in threes. So, once you select it, you verify that the change it happens, and then you obviously you have to also hit the button. So, if I haven't done my three, I know I'm missing something. So to me, that's how I learned it. And that was kind of proceduralizing ..."*
- "*... verbalize, verify, and monitor. So when we make changes, we're supposed to call out the things we're seeing on the FMA. That we're seeing the expected change. What we expect to have happened, actually happens."*

However, most participants felt that there has been an overreliance on proceduralization for monitoring and aircraft/flight path awareness which has resulted in pilots not actually completing required checks and callouts.

- *"....what they* [airlines] *found was that in a number of areas, they over-proceduralized too much, and that led to intentional non-compliance... For example, we were so regimented on how you've had to call that you were within 1,000 feet of an approaching altitude, the only SOP* [standard operating procedure] *compliant manner of acknowledging of that was to say the altitude you were at and the altitude that you were going to in terms of flight level 300 for 310. You couldn't say, "30 for"31," you couldn't say, "one to go," you couldn't say, "coming up on"31," you couldn't say any of that. You had to say, "Flight level 300 for flight level 310," or, "7,000 for 8,000." And we do the LOSA* [Line Operations Safety Assessments] *and we see that essentially nobody's doing that."*

In response to observing the discrepancies between prescribed and actual pilot behavior, some airlines now rely less on procedures and have reduced the number of required callouts:

- *"So in terms of proceduralizing the pilot monitoring duties' we've tried to avoid that, except in specific circumstances where the criticality of it is so high that you don't have time. So for example, FMA call-outs below 2,500 feet, you're actively on an approach by that point, probably approaching the final approach fix, you're on the final vectors,…"*

The overuse of verbal callouts was criticized also because it leads to 'automatic behavior' where pilots 'tune out' and fail to engage in interpreting information. In other words, excessive verbal callouts lead to desensitization and inhibit sensemaking (Weick, 1995), the process that is being initiated when a discrepancy is being noticed between what is observed and what is expected. Sensemaking requires a conceptual framework, or a mental model, that allows a pilot to infer meaning from observed data.

- *"It was too much talking, too much verbalizing. You started to tune it out."*
- *"I don't think it was correct to do it [verbal callouts] on the line as a routine because it does desensitize the pilots when they do it day in, day out, hours and hours on end. However, I think that for training purposes, that was an excellent way to train verbalizing the FMA changes and talking about what they mean, and I would say that should continue…"*

4.2.5 "You Get What You Regulate"

The observed lack or inadequacy of scan training was explained, in part, by the fact that airlines tend to limit their training to what is being prescribed by regulations. For example, one participant stated that:

- *"Because what we find is that airlines, especially those with less financial resources to dump into a training department will simply teach what they're told to teach. That's regulated, what they have to do, and not necessarily what the best research is pointing us towards."*

Therefore, focus group members highlighted the need for new government standards as the only way to force more training in the commercial aviation sector.

".... But the FAA has to mandate more training. Period. And they have to do that so that' it's competitive for all the operators because if one operator chooses to extend their training by say five days, that's a cost to them that 'they're competing with other operators. So the playing field needs to be level."

One difficulty with developing and imposing new standards and regulations is the lack of systematic empirical research on the effectiveness of different visual scanning techniques:

- *"…we all have these silos throughout the industry, whether' it's this fleet or this airline, or this type of airline operation. We have kind of a rotating group of instructors and fleet management and whoever it is, and everybody's kind of trying to solve the problem. We have to have some sort of standard that is based on research. And instead of just every fleet manager, throwing a dart at it saying, 'let's see if this fixes it, and ASAP (Aviation Safety Action Program) rates go down."*

It is important to note that the FAA issued advisory circular (AC) 120-123 ‘Flight Path Management’ in 2022 (after the focus groups were conducted). This AC provides guidance and recommended practices for operators to implement operational procedures and training for the planning, execution, and assurance of the guidance and control of aircraft trajectory and energy, including pilot monitoring.

In 2013, § 121.544 stated already that “each pilot who is seated at the pilot controls of the aircraft, while not flying the aircraft, must accomplish pilot monitoring duties as appropriate in accordance with the certificate holder's procedures contained in the manual required by § 121.133. Chapter 5 of AC 120-123 expands on this rather general requirement by describing effective monitoring, including during autoflight operations, how to define and train PM duties, and how to integrate the task of monitoring into SOPs.

Specifically, the AC requires operators to have clear and explicit definitions and assignment of the roles of PF and PM. It recommends that pilots are trained to develop proper mental models of systems and integrate observed data with those models to notice and address any observed discrepancies. Attention and distraction management are mentioned as additional important components of training to ensure that pilot properly divide and allocate their attentional resources and are not unnecessarily or inappropriately distracted by irrelevant information. Standard operating procedures (SOPs) are mentioned as one way of assuring that monitoring by individual pilots and the flight crew are effective and coordinated. Autoflight mode awareness is highlighted as one particularly important aspect of monitoring which requires careful checking of flight mode annunciations and instruments, especially around the time when changes are made to the flight path. Monitoring training should address the above topics, as well as barriers to, and common errors in monitoring. One important topic in this context is the anticipation of situation where monitoring is vulnerable due to high workload. The management of deviations or off-path operations should be addressed explicitly and strategies for managing “automation surprises” and unknown situations should be discussed. Training should also prepare pilots for intervening and potentially taking over the PF role if it is determined that the PF is not correcting an observed flightpath issue in a timely manner.

4.2.6 Contributors to Breakdowns in Monitoring Tasks/Activities

The discussion of breakdowns in monitoring tasks/activities focused on a range of contributors and countermeasures to the problem. The main risk factors mentioned by participants included:

- Complacency
    - In this context, complacency refers to the failure to continuously monitor the aircraft and its on-board technology to ensure it is doing what it is expected to do
    - Complacency was assumed to be related to factors such as overreliance on automation and uneven division of work between crew members
- Fatigue
    - Fatigue can be mental and/or physical in nature. Comments made by focus group participants suggest that they are mostly concerned about mental fatigue and sleepiness. Sleepiness is mainly caused by circadian rhythm disruptions, sleep loss and time awake, whereas mental fatigue is mainly caused by time-on-task and cognitive

workload (Balkin and Wesensten, 2011).The main reason for fatigue and sleepiness cited by participants were indeed extended hours of flight, especially for long-haul pilots, and associated time zone changes.

- High-tempo operations
    - Participants in our focus groups voiced concerns about high-tempo operations which can lead to pilots feeling rushed. Operational tempo has been defined as "the speed and intensity of our actions relative to the speed and intensity of unfolding events in the operational environment" (https://www.nwcg.gov/committee/6mfs/operational-tempo). Examples of high-tempo operations and reasons for feeling rushed include trying to push back from the gate on time and certain phases of flight.
        - *"But where we see the biggest incident of issues is the approach phase and the go-around phase, that's where most of our monitoring lapses are and automation issues and scan issues, especially in intermediate go-arounds, pilots become very confused by the modes. They don't get a lot of repetition with that. I mean, they do it maybe once every nine months."*
        - *"So where we see the biggest challenge is on the descent ... trying to scan the FMA, understanding what the FMA gives you, so you can then scan your instruments to make sure that you've got the right power set or your speed, is this an ideal descent or what are we doing?"*
        - *"…the go rounds are another place where about half the significant mistakes we make at Company 2 are on go rounds. Because it's a startle event where you are probably not on autopilot, so now you're having to do a dynamic maneuver and not only are you having to look at this stuff, it's something you're not used to and you're trying to redo your instrument scan very quickly."*
- Being either new to the airplane/airline or being extremely experienced (e.g., line check airmen (LCA))
- Recency/lack of practice
    - Recency was mentioned as a problem resulting from having had a lot of time off from flying (for example, during the COVID pandemic)
    - One example of lack of practice was:
        - *"it's bad enough when you're only flying one trip a month in the first place, but then if you're not even landing on that trip, all you're doing is babysitting the autopilot at altitude."*
- Attentional narrowing
    - Attentional narrowing has been defined as the "involuntary allocation of attention to a particular channel of information, diagnostic hypothesis, or task goal, for a duration that is longer than optimal, given the expected cost of neglecting events on other channels, failing to consider other hypotheses, or failing to perform other tasks" (Wickens, 2005)
    - Attentional narrowing has been documented in a number of eyetracking studies that examined visual scanning on flight decks (Lefrancois et al. 2018; Reynal et al. 2016)
- Pilot monitoring
    - Some focus group participants mentioned that the pilot monitoring is sometimes "lost" in a secondary task that is not critical to flying the aircraft
        - *"I can say without a doubt every single one of our undesired aircraft state significant events, but one, all but one have all been attributed to a lack of*

> *communication or attentiveness, the pilot monitor in each case where the pilot flying is task saturated, the pilot monitor is multitasking, is doing some extraneous secondary duty in a high-risk phase of flight. Every single one."*

Participants felt that pilots need to experience the above known contributors to breakdowns in monitoring during training to learn how to detect and counteract their detrimental effects.

4.2.7 Countermeasures to Breakdowns in Monitoring Tasks/Activities

Three countermeasures to monitoring breakdowns were discussed: (1) redundancy gain, (2) accurate mental models, and (3) verbal callouts.

In this context, **redundancy gain** refers to both pilots monitoring the same information with the goal to reduce the likelihood that it will be missed completely.

Earlier research covered in our literature review has shown that pilot flying (PF) and pilot monitoring (PM) at times monitor the same information (albeit possibly for different purposes or in support of different crewmember-specific tasks); at other times, they complement each other by scanning different instruments or areas of interest. For example, on takeoff, in VFR conditions, the PF spends more time looking out the window, while the PM allocates more attention to the airspeed indicator and the ECAM (Electronic Centralized Aircraft Monitoring). On approach, both the PF and the PM spend the majority of their time looking out the window, followed by fixating the PFD. However, the PM distributes their attention more widely, between a larger number of interfaces. And during go-arounds, the PF primarily monitors the PFD (in particular, the attitude indicator), while the PM's attention is spread more broadly on interfaces related to configuration management, MCP/FCU, airspeed, altitude, FMAs and vertical speed.

Participants in the three focus groups felt that either situation – pilots monitoring the same or different pieces of information - may be desirable, depending on context. We found that while a number of airlines believe the PM should not be monitoring as though flying the airplane, they have not fully articulated the appropriate role of the PM. Others cautioned against relying too much on complementarity between pilots and pointed out that having two pilots look at the same information – redundancy – can reduce the risk of critical information being missed:

- *"And the fact that both people are looking at that is redundancy, that's what you want. If one person is slow to get to that, the other person is right there. So I, just again, offer that as respectfully as a cautionary note here that while certainly sometimes you don't want everybody to look at it at the same thing, but sometimes you have that need everybody to be looking at the same thing."*
- *"I do not believe that it's necessarily bad that both pilots were looking at the same thing, it depends. It depends on the context what's going on right now. For example, if you are at extremely low altitude, let's say just for fun, let's just call it a CAT 2 approach 50 feet and you have to initiate a go around, what can you control right now that's going to keep you from smashing into the dirt? It's pitching power and so when someone goes, go around, I expect everybody to confirm that the pitch attitude raises to the appropriate climb attitude and the*

> *power goes to TO/GA. And if everybody's verifying that, that's happening, I believe that to be correct, because that's exactly what has to happen.”*

Similar perspectives were highlighted in earlier work by Mumaw et al. (2019). The authors interviewed 15 airline representatives and asked them about the role of PF and PM in flight path management and monitoring. Some participants in that research felt that the PM should monitor the flight instruments like a PF with no control inputs. The alternative point of view was that the PF and PM should focus on different aspects of flight path management; the PF should focus mostly on short-term flight path objectives and following the flight director while the PM should be more strategic.

As mentioned earlier, complete and **accurate mental models** were highlighted as an important means of guiding pilots’ visual attention and thus reducing the risk of monitoring breakdowns. Accurate mental models allow pilots to perform predictive scanning and spend less time monitoring equipment/information that is not helpful for a given situation. Focus group participants stated that the need to construct and maintain increasingly complicated mental models is one negative arising from increased automation on the flight deck and that current training does not support the formation of those models. One participant highlighted that managing the automation is being taught as “a sequence of button pushes” rather than conveying a deeper understanding of how the automation works and what system behavior pilots should expect and monitor for.

Finally, while concerns were raised by participants about an overreliance on **verbal callouts**, there was agreement that they can serve as a countermeasure to monitoring breakdowns, provided the appropriate level and frequency of verbal callouts is determined and implemented.

4.2.8 The Impact of Design on Visual Scanning

Two major differences in flight deck design and their implications for scanning/monitoring were discussed: (1) the use of analog round-dial gauges on older aircraft versus electronic (digital) flight instruments on ‘glass’ cockpit airplanes and (2) differences in flight deck design between two main manufacturers, Boeing and Airbus.

On older aircraft, raw data tend to be spread out across multiple separate round-dial gauges, forcing pilots to more widely distribute their visual attention and integrate the information in their mind. In contrast, on modern ‘glass’ cockpit aircraft, information has been moved/duplicated, combined, and integrated on a small number of displays (for example, flaps and thrust lever settings are included on the Primary Flight Display (PFD) of the Airbus A 350 – see Figure 27), allowing for a narrower scan which, in some cases, is heavily focused on the flight director.

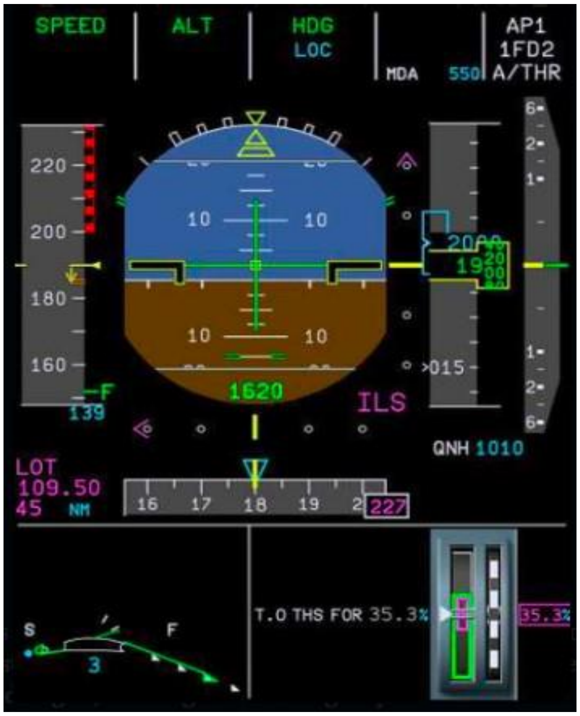

Figure 27. Airbus A350 Primary Flight Display (PFD) with flap and thrust lever settings (bottom left and bottom right of the PFD, respectively; from https://karlenepetitt.blogspot.com/2020/10/power-of-a350.html)

One participant described riding the jumpseat on a DC-9 and seeing that pilots were:

- *"constantly active and engaged … throughout the whole flight. I mean, whether it was looking at the instruments, pulling out paper and checking the route, it was just a constant flow and stream of activity where, at any given moment, I just knew that they were on top of everything."*

In contrast, when riding the jumpseat on the A320, this person observed:

- *"nothing was happening… the crews, the pilots weren't talking to each other at all, folks were looking out different side of the window."*
- *"It's all just right there… it becomes a stare and not a scan."*

Participants expressed the view that not enough time is spent in training to help pilots develop a different, appropriate scan when switching to 'glass' cockpit aircraft.

- *"…because our brains have gotten away from that basic scan technique of focusing on the hub, which is the PFD, or the airplane symbol dot above or below the horizon and how far above or below the horizon it's riding and that being your focal point, and then going out and getting some other information from an altimeter, and then back to that focal point, that hub and spoke scan that we learned early on, we really have trouble, I think, just because we don't use it anymore. We have trouble switching to it in the heat of battle on short final and you click it off."*

To counteract this problem, some airlines now train pilots to redevelop a hub-and-spoke approach to monitoring:

- *"…flight director and airplane symbol are the hub, we train people to scan out to the airspeed, scan out to the localizer, glide slope, VSI, so on and so forth, and just kind of keep coming back to the middle of the screen as the hub…"*

Differences between Boeing and Airbus designs and their implications for monitoring were discussed also. Participants pointed out that pilots trained on Airbus airplanes are expected to make more verbal callouts, specifically related to the Flight Mode Annunciations (FMAs).

- *"… I think Airbuses tend to be... They're meant to be flying in automated mode. And so I think that's one of the reasons they spend a lot more time making sure that you're looking at what mode the airplane's in."*
- *"Guys who grow through Airbus training spend more time on FMAs. … Airbuses are meant to be flown in automated mode. And so, I think that's one of the reasons they spend a lot more time making sure that you're looking at what mode the airplane's in… Whereas Boeing tends to think of it more as the autopilot is another mode to fly the airplane in, and their planes are kind of set up that way too."*

Some participants reported that pilots struggle more with transitioning from Boeing to Airbus models (as opposed to the other way around) and therefore try to plan their career accordingly:

- *"Almost every pilot that I have worked with, they go to the 330 or the 320 to learn the Airbus because they want to do it when they're younger. Because they say it's harder to learn as you get older. And it is a large transition, it's a large mindset shift, when you go from Boeing to Airbus. Once you get it, you get it. But it takes a lot of brain cells, especially if you're going to a 350. So, people plan their careers, based on the carrier that they are at … They want to learn that philosophy at a younger age to make that easier."*

Specific design features were highlighted that contribute to difficulties with monitoring. They include the spatial separation of where control inputs are made to the automation (on the flight control unit (FCU) of Airbus aircraft or the mode control panel (MCP) in the same location on Boeing aircraft; see Figures 28 and 29 below) and where associated automation feedback is provided (on the primary flight display (PFD)). Participants discussed that pilots tend to focus their visual attention on the MCP or FCU as they enter targets, rather than looking at the PFD to verify that their input was received and is displayed as the upcoming automation target. This can be problematic because, as one participant described:

- *"…what's on the FCU or MCP does not necessarily match what may be on the PFD"*

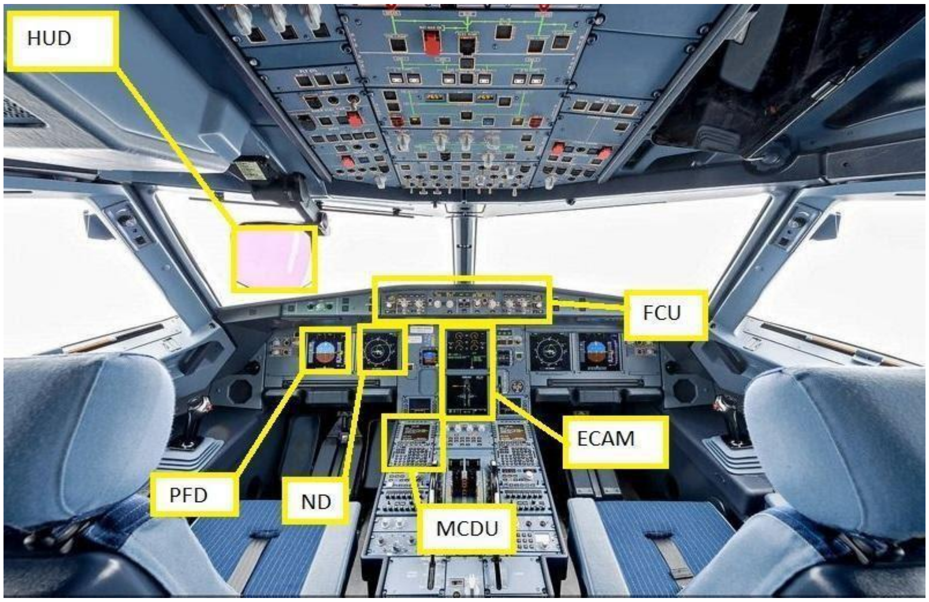

Figure 28: Airbus A320 flight deck (from https://services.airbus.com/en/flight-operations/system-upgrades/navigation/head-up-display-hud.html)

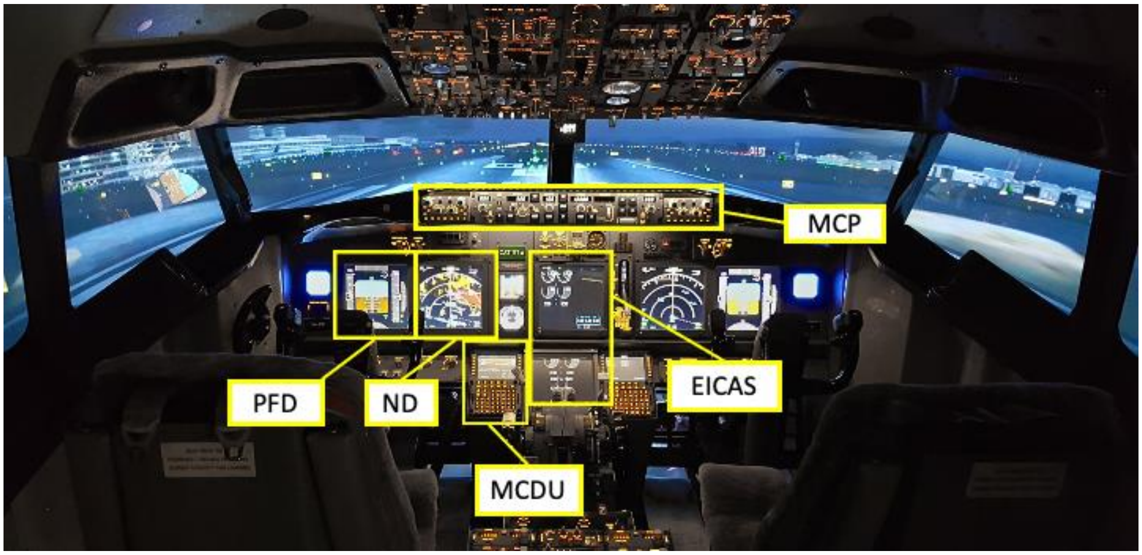

Figure 29: Boeing 737 NG flight deck (from https://flightdecksolutions.com/image-gallery#b737ng)

Participants proposed that design (and not just training) could better support pilots in anticipating future states/modes and actions of the automation to aid in predictive monitoring. One example of how design can accomplish this goal is the vertical situation display (VSD; see Figure 30) which is present on the flight deck of most advanced airliners. It provides a real-time side view of the vertical flight path from approach to landing.

- *“There's definitely areas of improvement where the design can make those kinds of errors more obvious to the flight crew in terms of predicting what the automation is going to do. I think the other obvious one that came to mind for me is the vertical situation display. So, having to integrate all these different sources of speed and altitude targets, a lot of them are going to be heads down and in the FMS, and just being able to convert that into a visualization instead of a memory task and putting that up in the primary visual field”*

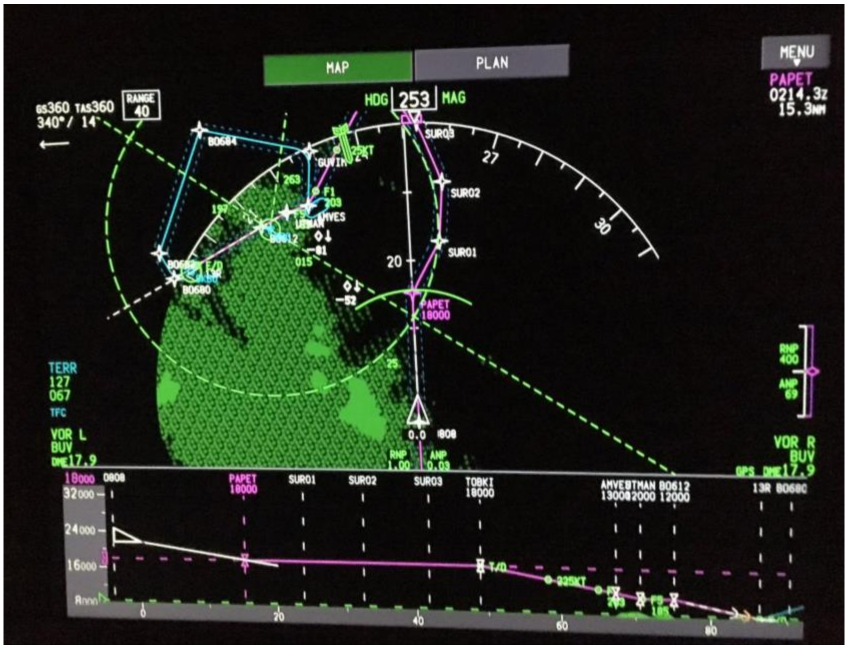

Figure 30: Sample view of the B 787 VSD (shown at the bottom of the PFD)
(from https://twitter.com/peytour13/status/1054951808840425473/photo/1)

Participants also described how the head-up display (HUD) on some aircraft has led to changes in scanning:

- *“Just speaking from experience on the 787, below 18,000, we're in the HUD. Most of the time you get very spoiled with the HUD. You're required to have the HUD down below 18,000 feet. And then the scan is also different on the HUD than it is on the glass, because you have normal, then you have to declutter mode and depending on what you're doing and what you're comfortable with in terms of shooting the approach…*

Finally, the design of autothrottles was mentioned as an example of how modern technology affects monitoring in both the visual and haptic channel:

- *“Like I said, Boeing likes to keep the throttles moving, even if you have the auto throttles engaged, the throttles move. That sounds like a little thing, but actually, when I'm flying in approach, I get a lot of feedback from the throttles. Even with auto-throttles on, I'll have my hands sitting there and I'll actually notice vertical deviations on the throttles almost before I* *will on any of the other instruments. Because as soon as the nose goes down, the power starts coming back. So I'll know, ooh, I need to pull the throttle and I need to pull the yolk back, which I wish I would be pulling the stick back.“*

- *“…the biggest elephant in the room is autothrust. When you talk about automation, because if you're in a 200* [B 737-300], *you're monitoring, your eyes are scanning over to the engine instruments….. But at Company 3, every airplane has autothrust and we become very lazy at looking at power settings.”*

4.3 Summary and Conclusions

Three 3-hour long focus groups were conducted with a total of 12 aviation stakeholders (regional and domestic airline/instructor pilots, check airmen, human factors/flight safety/training experts, flight deck designers/researchers) to gain insight into the current state of visual scanning on commercial aircraft flight decks. Three main themes were discussed by participants: (1) training, (2) breakdowns in monitoring, and (3) the impact of design in visual scanning.

The discussions revealed that training and standards for visual scanning are lacking. Training is either not provided at all or only in response to observed shortcomings in a pilot’s monitoring performance. Deficiencies in training, which vary somewhat between airlines, are partly the result of efforts to minimize training time and costs as much as possible while still complying with requirements imposed by regulators and also stem from the challenge of developing standards across the wide range of aircraft types and models that are operated by many carriers. It can be explained also by often incorrect assumptions about pilots’ scanning proficiency and how their skills transfer when they transition to modern ‘glass’ cockpit aircraft. If training is provided, it often encourages a narrow scan that focuses on the flight director and trend vectors on the PFD. The importance of, but lack of training for developing accurate and complete mental models of the aircraft and aircraft systems in support of predictive monitoring was highlighted. Instead, there appears to be a strong reliance on proceduralization which was considered inappropriate by most participants. Finally, participants expressed that there is a need for more research to identify the most effective scanning techniques and for the regulatory agency to require that visual scanning be included in airline training programs.

Several contributors to monitoring breakdowns were identified: (1) complacency, (2) fatigue, (3) high-tempo operations/being rushed, (4) being either inexperienced or extremely experienced, (5) recency/lack of practice, (6) attentional narrowing, (7) pilot monitoring being “lost” in a secondary task. Three promising countermeasures were mentioned by participants: (1) redundancy gain (both pilots monitoring the same information), (2) support for the development of accurate mental models (in part through facilitated debriefs), and (3) verbal callouts.

Finally, aspects of design that either help or hinder visual scanning were discussed. These include: (1) the difference in design between older aircraft with analog round-dial gauges and more advanced ‘glass cockpit’ flight decks, (2) differences in design between manufacturers, (3) spatial separation between control inputs and associated feedback, (4) support for predictive monitoring by interfaces like the VSD, and (5) lack of feedback from non-moving throttles on some flight decks.

The following mind map captures the main discussion points from the three focus groups. A mind map is a tool that visually organizes information by showing relationships between a central concept (in this case, visual scanning) and various other related concepts and ideas (https://en.wikipedia.org/wiki/Mind_map):

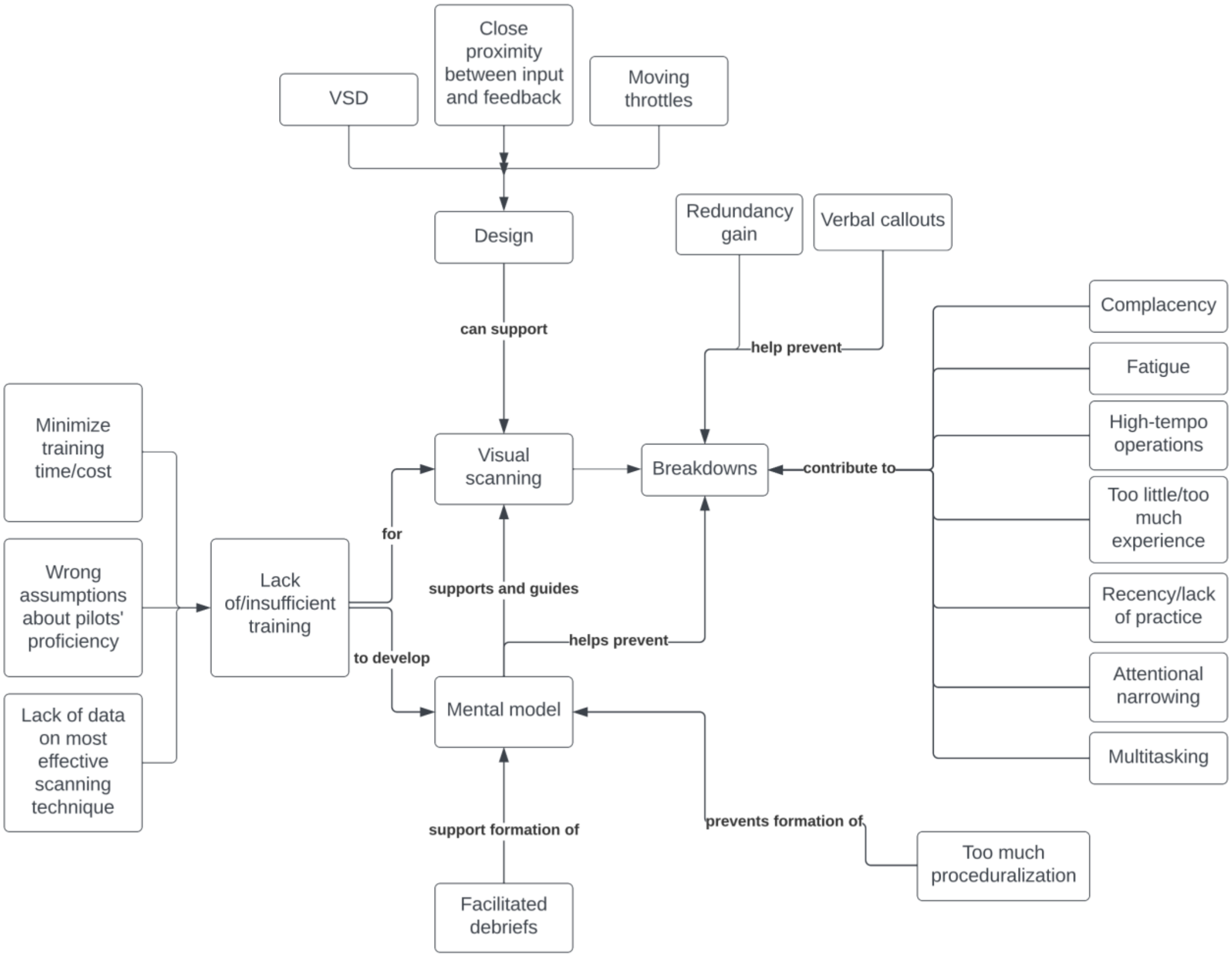

Figure 31. Mind map of main discussion points and their relationships

5. Eyetracking as a Training Tool

Participants in the focus groups highlighted the need for new government standards as an important way to force more scan training in the commercial aviation sector (“you get what you regulate”).

In fact, major aviation organizations including the FAA, IATA (International Air Transport Association), and the BEA (Bureau Enquêtes-Accidents; the French accident investigation agency) have already issued recommendations that airlines should incorporate monitoring as an explicit element of pilot training. Introducing more/better training for visual scanning involves challenges, however, such as the lack of agreement on recommended scanning practices and also the need for instructors to be able to “monitor the monitoring”. Currently, instructors cannot know where pilots are looking at any given point in time. They sit behind the trainees and need to control the simulator setup and events using a visual interface. They also play the role of air traffic control and other agents (such as flight attendants) that the flight crew may interact with (Niehorster et al., 2020). This means that they have neither the time nor access to information that would allow them to monitor pilots’ attention allocation in real time. Instead, instructors either have to ask pilots to describe their scan pattern and, more generally, their monitoring behavior – something that is difficult to do and not very reliable – or they have to infer trainees’ attentional focus from actions and performance.

One way to address the above challenges is to introduce eyetracking to the training environment. As described in section 2.3 of this report, eyetracking is a sensor technology that makes it possible to determine where a person is looking. Recent advances in eyetracking technology allow us to do so in a rather unintrusive way. For example, a company called ‘Seeing Machines’ has developed a precision eye-tracking system for integration in full flight simulators. The camera-based eyetracker does not require the user to wear any form of hardware or sensors, nor does it require calibration. It provides, in real-time, measures and metrics such as gaze tracking and pupil diameter (see Figure 32).

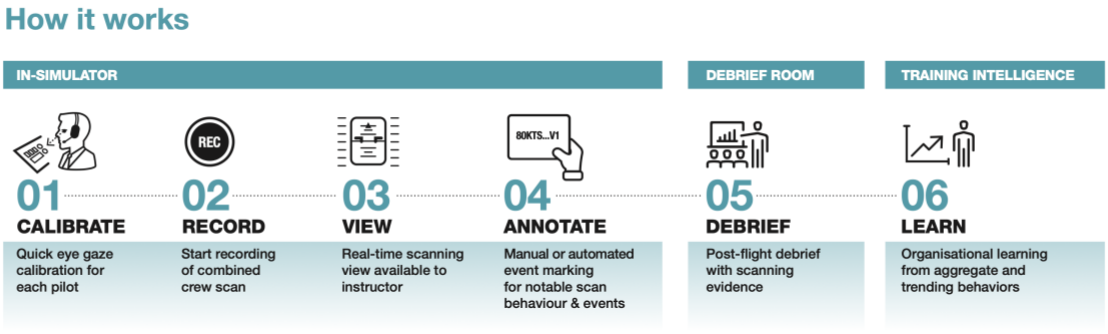

Figure 32. How Seeing Machines’ eyetracker works (from https://seeingmachines.com/wp-content/uploads/2023/08/SeeingMachines-Crew-Training-Sell-Sheet-2023.pdf)

Australia’s Qantas Airways was the first airlines to introduce the Seeing Machines eyetracker into its 787-9 Full Flight Simulator (FFS) making it the first purpose-built eye tracker/simulator combination (Gray, 2021). Two eye-tracking cameras, one for each pilot, were installed in the coaming of the glare shield to determine the pilots' visual focus, particularly when monitoring a HUD and for pilots returning for recurrent training. Other airlines, including Air France, Emirates Airlines, and Singapore Airlines, are also developing eyetracking technology and procedures to support pilot training but, to our knowledge, none of these efforts have reached the level of maturity required for eyetracking to be deployed as a regular element of training. In May 2023, Seeing Machines established an exclusive intellectual property licensing agreement with Collins Aerospace with the goal to develop the equipment required to install the Seeing Machines technology on a range of (simulated and actual) flight decks.

A systematic review of the literature on the use of eyetracking in pilot training was conducted by Ayiei (2020). 15 journal articles were included and further divided into studies reporting the use of eyetracking as a training tool and studies reporting the use of eyetracking as an assessment tool. The literature review concluded that eyetracking can, in principle, be a valid and effective tool that can provide quantitative data for flight performance and safety assessments. In 2021, Lefrancois and colleagues provided additional empirical evidence that feedback on their visual scanning behavior and exposure to eye movement samples from highly accurate pilots helped a group of seven airline pilots improve their own monitoring and flight performance during a manual approach, compared to a control group of seven pilots who did not receive specific instruction and visualizations.

Eyetracking data can be used in two ways to support visual scan training: during training in a flight simulator and during debriefs following the simulator session. In principle, using an eyetracker in the simulator has the advantage of allowing instructors to monitor, in real time, where pilots are looking and to intervene, discuss and correct their scanning behavior immediately, if necessary. However, one major challenge is how to present the eyetracking data to instructors without overwhelming them. They are bound to struggle with keeping up with the high rate of change in pilots' gaze and with tallying fixations over time to determine how much total time a pilot spends looking at a particular instrument (Niehorster et al., 2020). One way to address the above challenges is to introduce 'smart' eyetracking to the training environment where 'smart' refers to technology that aggregates and visualizes gaze information for instructors (see Mumaw et al., 2019). The following sections will describe some recent and ongoing efforts in this direction, based on publicly available documents and information gained from online interviews we conducted with airline representatives.

Vlasbom and van Rooij (2020) describe the development of a prototype augmented reality-based support tool called 'Augmented Eye' (see Figure 33). This augmented reality (AR)-based tool enables instructors to monitor students' scan behavior in real-time, without requiring trainees to wear any special equipment and thus without risking interfering with or changing their natural monitoring behavior. 'Augmented Eye' has a modular set-up, including a fusion of simulator data, eyetracking data and their real-time analyses.

Figure 33. Pilot instructor wearing the ‘Augmented Eye’ headset during simulation training (from https://www.linkedin.com/pulse/putting-innovation-work-real-training-needs-making-visible-vlasblom/)

Figure 34. Trainee’s point of gaze as seen by the instructor (from https://www.nlr.org/wp-content/uploads/2019/06/Blog-Vlasblom_NLR-1030x580.jpg)

Another approach to making the use of eyetracking in a simulator feasible is a concept called ‘CandyBar’ (Knabl-Schmitz et al., 2023). Gaze information is collected from pilots, processed (to calculate fixations and gaze duration), and graphically represented along a vertical bar (see Figure 35). On the bar, each area of interest on the flight deck is color-coded. Fixation duration is indicated by the width of the box on a moving time axis. The usefulness and feasibility of the concept was evaluated in a fixed-base Airbus A330 simulator, with eight pairs of pilots and two instructors. Each crew completed a take-off, an instrument approach and go-around, an instrument approach with autoland and a missed approach, an instrument approach and go-around with air traffic control interference, and a take-off with a technical fault. Both instructors and pilots felt that the tool enhanced training and allowed for real time observation and feedback on scanning behavior.

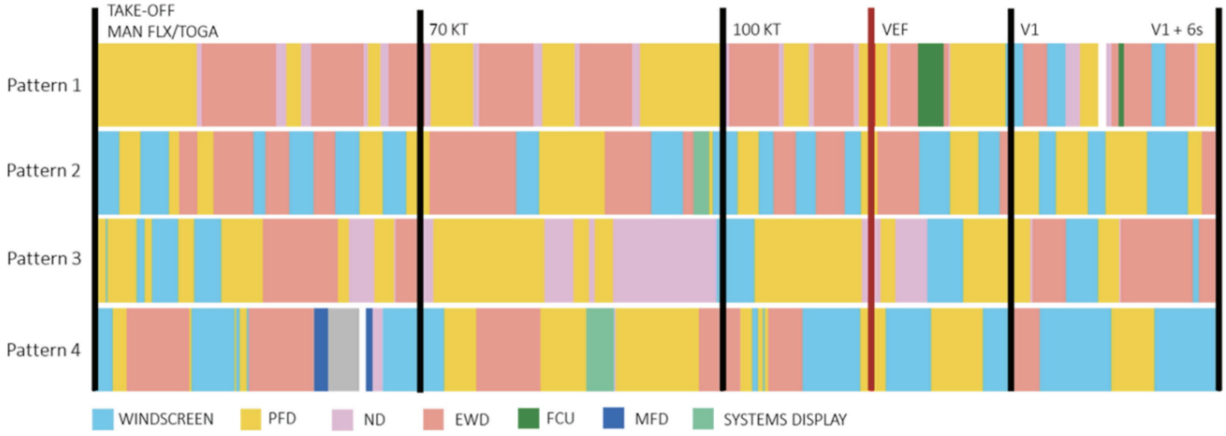

Figure 3. CandyBar pilot monitoring (PM) pattern examples of four PMs. Each bar represents a PM scan over the scenario from take-off to V1 + 6 s. Colors represent fixations on different areas of interest, whereas the color width represents their duration. PFD = primary flight display, EWD = engine warning display, ND = navigation display, FCU = flight control unit, MFD = multifunction display.

Figure 35. The ‘Candy Bar’ (from Knabl-Schmitz et al., 2023)

In addition to, or in place of using an eyetracker in the simulator, eyetracking data can be helpful during debriefs when instructors are not as task-saturated. For example, Li et al. (2020) examined, from an instructor's perspective, whether eyetracking technology, integrated with De-Briefing Facilities (DBF), could help identify trainee pilots' errors. Nineteen experienced instructor pilots participated in their research. Most of them felt that the eye tracker provided sufficient and specific information to assist them with debriefs. Moreover, some of instructors acknowledged that by utilizing eyetracking information, they spotted more inappropriate operational behaviors than they otherwise would. Still, the authors acknowledge that even during debriefs, eyetracking information significantly increases the volume of data for instructors to interpret.

For the same purpose, the above described ‘Candy Bar’ was integrated with views of other flight deck components/displays on an instructor interface called ‘Session Player’ (see Figure 36). The interface provides visualizations of scanning behavior that can be reviewed as part of replays of scenario events. It was evaluated by 15 highly experienced Airbus A380 type rating examiners. Subjective feedback from instructors following the study showed that 73% held a very positive opinion of the use of eyetracking, and the remaining 27% (N = 4) held a positive opinion. They identified contexts and scenario events where eye-tracking would be particularly helpful. These included engine failure after take-off, rejected take-off, approaches and landings, go-arounds, low-visibility operations, upset prevention and recovery, loss of instrumentation, windshear, and startle events.

Name	Time (s)
Scenario 3	0.00
Callout (Man Flex/TOGA)	40.87
Speed (70 Knots)	50.81
Speed (100 Knots)	58.40
Speed (VEF)	63.69
Speed (V1)	67.23
Callout (Stop Declared)	66.13
V1+6s (6 seconds after V1)	73.23
V1+10s (10 seconds after V1)	77.23

Figure 5. Prototype of the instructor interface (Session Player) components. (1) Cockpit view. (2) Face view. (3) Primary flight display (PFD) and navigation display (ND) overlaid with precise gaze vector and gaze trail presenting the real-time eye movements. (4) CandyBar. (5) Cumulative dwell time: A time plot illustrating dwell time over elapsed scenario/event time. (6) Start/stop bar and elapsed time axis. (7) Selectable event markers.

Figure 36. The ‘Session Player’ Interface (from Knabl-Schmitz et al., 2023)

To our knowledge, no U.S. airline currently uses eyetracking as part of their pilot training but, as indicated above, some foreign carriers are exploring and developing the hardware and interfaces required to make this concept feasible. In November 2023, we interviewed representatives from 2 major airlines outside the U.S. to learn about the status of their efforts and their experiences with employing eyetracking. Airline A reported that they are currently using eyetracking primarily as a research tool and to answer specific questions related to flight safety. For example, they try to identify monitoring-related reasons why pilots continue an unstabilized approach, and they are interested in how much time pilots spend monitoring the PFD in the presence or absence of a head-up display (HUD). The airline also uses the tool in collaboration with flight instructors to record training videos, and, in some cases, they work with individual pilots who seek assurance that their scan pattern is appropriate (for example, after an extended period of not flying the line). Reasons that were cited for not yet using eyetracking on a regular basis in pilot training include its price tag, difficulties with integrating the equipment into simulators and the problem of generating too much data for instructors to monitor and interpret.

Airline B first used the Seeing Machines eyetracker in 2015 to show how the equipment might be used in a procedure trainer. However, like airline A, they have not reached the point where eyetracking can be deployed as a standard training tool, in part due to limitations of the equipment. For example, it is challenging to trace pilots’ visual attention when they are using a

HUD since the eyetracker works only when the HUD is set to the medium level of brightness. Also, eyetracking does not provide insight into 3D attention allocation, and therefore it is impossible to tell whether the pilot attends to data on the HUD or to information in the outside world. Another limitation is that the eyetracker provides the most accurate information for the forward field of view but is less effective when pilots look at information to the far left or right on the flight deck. The airline is integrating their eyetracking equipment in one of their B777 simulators and plans to conduct a large-scale evaluation of the tool in early 2024. They hope to collect enough data to see a reliable correlation between pilot performance and visual scan patterns which would suggest desirable monitoring strategies, such as ‘look at the airspeed 4-7 times during final approach’. The plan is to combine eyetracking data with telemetry and biometrics data, review these data offline (outside of the simulator) for specific events and contexts, and to link the data to competencies and observable pilot behavior as part of evidence-based training.

6. Conclusion

Aviation incidents and accidents have often been linked to inadequate monitoring of flight deck information. Still, to date, limited data and guidance exist on how pilots should, and how they actually do allocate their attention to various flight deck displays. This project aimed to help fill this gap with the goal to inform design and training interventions that better support flight crews in monitoring their flight path, automation status, and associated behaviors.

First, we conducted a review of the scientific literature (with a special focus on eyetracking-based empirical studies), regulatory documents, and general guidance on visual scanning on modern transport category aircraft. Next, we held three focus groups with 12 aviation stakeholders to gain a better understanding of current visual scanning practices in the commercial aviation sector. Specifically, we explored (1) current training needs and approaches, (2) factors that lead to breakdowns in monitoring, and (3) the effects of flight deck design on visual scanning. Finally, publicly available documents were reviewed, and zoom meetings were held with airline representatives to learn about plans and ongoing efforts to make eyetracking an integral part of pilot training, both for assessing and for shaping pilots' visual scanning behavior.

In combination, the above research activities highlight that, despite widespread agreement on the need for improving pilots' monitoring strategies and performance in the interest of aviation safety, significant gaps still exist in our understanding of what effective scanning behavior, training and procedures look like for individual pilots, in their role as PF or PM, for entire flight crews, and across flight phases and events. Existing guidance and recommendations tend to be rather broad and focus on desired outcomes rather than describing the specific means of achieving those goals.

Eyetracking has emerged as a promising tool to fill the above gaps. It was used in the empirical studies reviewed in this report where it yielded descriptive data on pilots' actual scanning behavior (albeit almost exclusively in simulated flight operations). More work is needed to replicate these findings in actual flight operations and to establish the connection between monitoring and pilot performance and thus develop prescriptive monitoring standards. Eyetracking has also been proposed as a training tool to assess and correct pilots' attention allocation, both in the simulator and during debriefs. A small number of foreign airlines are engaged in efforts to develop the hardware, processes and interfaces needed to deploy the tool for those purposes but their efforts face obstacles and resistance as they require considerable investment of time and financial resources.

7. References

Note that three separate lists of references are provided. The first list includes the eyetracking studies that were discussed as part of the literature review. The second list contains publications that are related to pilot visual scanning behavior but are not included in the review for one or more of the following three reasons: (1) the research was conducted on GA, military operations, helicopter flying, and ground operations, (2) the study involved very few participants, participants with no or very little piloting experience, or very low fidelity simulation environments, (3) the research relied entirely on subjective data or focused on modeling visual attention allocation. The second list also includes references to eyetracking methods and the use of eyetracking in pilot training. The third list comprises regulatory and guidance documents related to visual scanning.

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Appendix A.

INFORMATION SHEET AND CONSENT FORM
VISUAL SCANNING ON COMMERCIAL TRANSPORT FLIGHT DECKS

Principal Investigator: Nadine Sarter, Richard W. Pew Collegiate Professor in Industrial and Operations Engineering and Director, Center for Ergonomics, University of Michigan

Invitation to participate in a research study

You are invited to participate in a research study for an FAA-funded project on 'Visual Scanning on Commercial Transport Flight Decks'. As part of this study, we are conducting two focus group discussions with subject matter experts in various fields relevant to commercial air transport operations, with the goal to learn about training for, approaches to and difficulties with monitoring flight instruments on advanced highly automated aircraft.

Description of your involvement

If you agree to be part of the research study, you will be asked to participate in an online zoom-based focus group session. You will join 4 to 5 other people to discuss, as a group, your experiences with and approaches to visual instrument scanning on modern transport aircraft. The group will discuss (1) how pilots are trained for scanning instruments versus how they actually perform this task, (2) observed problems with current approaches to monitoring: when/ why does it break down (distractions/failures/fatigue/high tempo/transitions between aircraft)? and (3) the role/interplay of training and design.

The focus groups will run for 3 hours and will be audio-recorded.

Benefits

The proposed research aims to document current training approaches, pilot techniques and known challenges associated with monitoring a wide range of flight instruments on modern aircraft, both during routine and off-nominal conditions. A better understanding of visual scanning on transport aircraft will help develop improved training methods and procedures and highlight the possible need for design changes.

Compensation

There is no monetary compensation for participating in this study.

Confidentiality

The discussion will be audio-recorded (no video recording) for later transcription and analysis. The recording will be deleted after the transcription is complete. Participants' comments will not be associated with their names to ensure the confidentiality of their contributions to the discussion. Participants' names will not be included in the report describing our findings to the sponsor nor in any publications resulting from this activity.

Voluntary nature of the study

Participating in this study is completely voluntary. Even if you decide to participate now, you may change your mind and stop at any time. You may choose not to answer any question or continue with the discussion for any reason.

Contact information

If you have questions about this research study, please contact Nadine Sarter, University of Michigan, Department of Industrial and Operations Engineering, 1891 IOE Building 1205, Beal Ave, Ann Arbor, MI 48109, (734) 763-5773, sarter@umich.edu.

I agree to participate in the study. As part of my consent, I agree to be audiotaped.

____ _______________

Signature Date

As part of their review, the University of Michigan Institutional Review Board Health Sciences and Behavioral Sciences has determined that this study is no more than minimal risk and exempt from on-going IRB oversight.