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The Journal of Instrumentation, Automation and Systems

The Effect of Automation on Human Factors in Aviation

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Abstract—This paper looks to examine the effect of modern day automation on the human machine by reviewing literature spanning over three decades. Using the human factors model SCHELL, we will review a significant aviation accident to determine the human factors components that contributed to the fatal crash. Conditions such as automation bias and complacency continue to surface as contributing factors in aviation incidents and accidents. A novel application to combat these human errors for operational pilots during low workload phases of flight is suggested. The importance of visualisation in the maintenance of manual flying skills is discussed with support from a neuroplasticity experiment that highlights the significance of this repetitive action.

Keywords—Automation, human factors, complacency, automation bias, cognitive load theory.

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doi: 10.21535/jias.v3i2.916

I. INTRODUCTION

THE rapid introduction of highly advanced automated systems into military service from significantly older platforms highlights the large gap and leap in automated technologies for current pilots. Whilst the bridge in capability of the platform dichotomies has been widened, human factors considerations in relation to increased automation use are critical to ensure that capability is maximised, effective, and sustainable.

Academic literature and accident investigations reveal advanced automation can have a negative impact on human factors, psychologically and psychosocially. Given complacency has been identified as a contributing factor in numerous aviation accidents and is proving synonymous with automation in related literature, it may be likely a causal relationship exists between complacency and human error in advanced automation. The intent of automation is to minimise pilot workload and increase safety, however, evidence indicates that when automation does not function as it should, the pilot(s) can become overloaded and overwhelmed, experiencing a complete loss of situational awareness. Information processing is significantly affected and cognitive resources are strained.

The use of the SCHELL model, Hawkins [25], can greatly assist in determining the contributing human factors of an aviation accident. Referencing the fatal Air France flight 447 accident from 2009 in a brief case study, the paper will attempt to explore the human factor elements in an effort to understand the complexities of human interactions more intimately. Decades of research in neuroscience support theories of neuroplasticity in relation to knowledge retrieval and neurogenesis. The effect of visualisation in mitigating the impact of automation failure and its impact on manual flying skills may be trialled using an anecdotal technique called chair flying. This paper will discuss the latent dangers associated with operating highly automated systems, the importance extraneous cognitive load plays in determining the amount of working memory resources of the pilot, and suggest a novel solution to combat complacency in the cockpit.

II. AUTOMATION

The aim of automation is to replace certain tasks, once completed by the human operator with an automatic system; namely by devices and computers including autopilots, flight management systems, flight directors, warning and alerting systems, and auto-throttles [22]. The common unchanged element in the exponential growth of the automation systems has been the human operator. Cognitively, the human machine continues to function the same and due to his information processing versatility, is unfortunately difficult to describe quantitatively [38]. This provides researchers the opportunity to look at management of the human element in the automation process in terms of cognition, ergonomics, and psychosocial frameworks.

Bibby and colleagues [7] highlight that humans will always play a role in the automation process. The question for today with advanced automation systems is, "what is that role and what effect is it having on human factors?". Bainbridge [7] identifies the irony in the concept of automation that the greater the complexity of the system, the greater the role of the human operator, especially in terms of the criticality to safety. Design engineers that look to fully automate a role or task performed by a human operator still leave an arbitrary collection of tasks for the human to conduct due to an inability of the designer to eliminate the operator completely [7]. Wiener and Curry [66] state that the priority today is not if a task can be automated but, due to human factor considerations, if it should be. Evidently, some tasks have been automated resulting in imperfect

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This paper was submitted on June 30, 2016; revised on August 22, 2016; and accepted on November 18, 2016.

automation [65]. Endsley and Kaber [20] suggest that under normal operating conditions automation has been proven to improve human performance, however, in the event of an automation failure, performance decrease is irrespective to man or machine capabilities.

A. *Mode Awareness*

On 25 February 2013, a Boeing 737-838 was conducting a scheduled passenger service from Canberra to Brisbane. As the aircraft approached the descent point for the destination, the autopilot (AP) initiated an unexpected climb. The flying pilot, on recognition of the unintended climb, immediately disconnected the AP and commenced manual flight, descending as directed by Air Traffic Control (ATC) [6]. The ATSB investigation revealed an inadvertent selection of the auto-flight system approach mode resulted in the capturing of the Brisbane instrument landing system (ILS), which shares the same frequency as the Canberra ILS. Once the aircraft was within range of the ILS, the glideslope became the active vertical flight mode and at flight level 390, a climb was initiated to capture the 3^0 glideslope. The aircraft climbed 1,000ft before the pilot intervened and commenced descent to the cleared altitude [6].

The Australian Transport Safety Bureau [4] released an Aviation Research and Analysis Report on a predictive tool for human factors. The report found that while automation is designed to improve human performance, when interacting with mode changes in a flight management system (FMS), unforeseen outcomes can result. 'Mode confusion' may be experienced by the pilot and could result in controlled flight into terrain (CFIT) as a result of human error in decision making [23]. Anecdotal evidence suggests experience and good basic training are key elements in understanding the nuances in automation systems, and most importantly, recognising when automation is no longer required and when to use appropriately. Complying with standard operating procedures (SOPs) and the vigilant operation of the FMS for entering critical data such as V_1 (refusal), V_r (rotate), and V_2 (minimum climb speed with an engine failure) airspeeds are key skills for pilots. In certain situations, inexperienced pilots may be susceptible to not understanding exactly what auto-thrust or other automated modes are doing as the thrust levers, in modern Airbus cockpits, do not physically move when auto-thrust is engaged. This example highlights the criticality of auto-flight mode awareness.

B. *Complexity Creep*

Of the eight enemies of situational awareness, complexity creep features closely with data overload [19]. Automation literature from the 1970s identified the complex nature of automated systems in relation to human limitations, suggesting the greater the complexity, the greater risk to safety from human error [7].

Wiener & Curry [66] reported significant pilot confusion with the automated systems, sometimes not understanding what they were doing or what will happen next. A common question asked by Boeing pilots, when referencing the automation system, is "What's it doing now?". This particular issue is not isolated to junior crew but is also experienced by senior pilots. Training is seen as the solution to the increasing complexity of automation, however, this poses a safety risk on the operator due to an increased level of knowledge required should a system error occur [19][18].

C. *Out-of-the-Loop Syndrome*

It is widely accepted by pilots that automation increases situational awareness (SA) by significantly reducing workload [20]. Another factor for consideration is that the complexity of automated systems can also act to decrease SA via mode errors [19]. Failure by the pilot to maintain SA of what the automation is doing, including mode awareness, can result in out-of-the-loop syndrome (**Figure 1**). This occurs when the automation acts independently of the pilot and without his awareness. The syndrome is magnified when the automation fails and the operator does not detect the problem. Addressing this issue at the design stage is critical to prevent any negative outcomes [19].

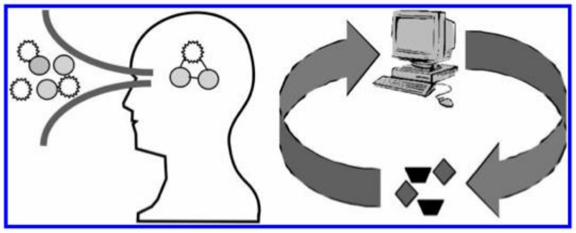


Figure 1 Out-of-the-Loop Syndrome [19]

D. *Optimal Point*

In modern day cockpits, automation plays a pivotal role in maximising safety, efficiency, and sustainability for both the environment and operating costs of airlines. In today's congested airspace, automated flight decks and modern-day ground systems work in unison to improve efficiency and safety in the air, especially in navigation [58][67]. Wiener and Curry [66], interestingly, stated back in 1980 that 'cockpit automation may have already passed its optimum point'. The goal of automation design engineers is to ultimately provide improved capability without the requirement for a human operator. Automation system design engineers strive to improve safety by reducing human responsibility on the automated flight deck. History has shown an unfortunate contributing factor in many aviation accidents has been human error. Is it possible to eliminate human error and develop a safer mode of travel for pilots and passengers? According to Wiener and Curry [66], human error is attributed to more than half of aviation accidents. Since their claim in 1980, many more fatal aircraft accidents have occurred resulting from human error, as a leading contributing factor, even with a modern day flight deck design.

III. HUMAN ERROR

Adams [1] describes human factors in terms of psychology, physiology, medicine, anthropology, and how these human sciences are applied scientifically to systems, operation, and design. Whilst human factors may also apply to other disciplines such as avionics, structures, and materials [27], the interaction of the pilots with the flight deck, ergonomics, provides an interesting insight into psychosocial and performance issues. Numerous studies have identified complacency, automation bias [65][34][45][48], and a decay of manual flying skills [26][12][30][58][2][66], as contributing factors to fatal aviation accidents. A relatively recent aviation accident that exhibited all of these elements was the Air France flight (AF447) accident in June 2009.

According to Kern [31], human error is all too prevalent in daily life and that the rapid escalation of a small or minor error can result in tragedy. Kern adamantly states ‘Anything less than a conscious commitment to understanding and reducing personal error is an unconscious commitment to accepting their continuing presence and all future consequences’ [31]. Hobbs *et al.*[27] affirm that the intent of human error analysis is to determine incompatibilities between the automated system and human ability whilst identifying automation vulnerabilities to the human operator. Analysis tools such the SCHELL model [25], Fault Tree Analysis (FTA), and Human Factors Process Failure Modes and Effects Analysis (HFPFMEA) are used to identify human error factors [27] as a predictive, and/or post-accident investigative tool.

SCHELL Model

The human factors elements in an aviation accident may be determined by a model such as SHEL (Edwards 1972), later modified by Hawkins (1993) [25] to include Culture and an additional Liveware, forming the acronym SCHELL. The model seeks to identify the human factors components and interactions of the human-machine relationship, providing a holistic insight into a complex system.

Figure 2 SCHELL Model (adapted from Hawkins 1993)

The components of the SCHELL model include:

- **Software**: May include checklists, flight manuals, maps, and charts.
- **Culture**: The values, norms, or practices of a particular society or organisation.
- **Hardware**: Tangible items such as radios, navigation equipment, flight control systems, and radar.
- **Environment** Weather, aircraft cockpit, terrain, operational tempo.
- **Liveware** (operator): Stress levels, knowledge, experience, and training.
- **Liveware** (others): The interaction of the crew (CRM), crew-ATC, crew-passengers.

IV. AVIATION ACCIDENTS

Post-accident investigations reveal organisational, workplace, and person factors that have resulted in catastrophic aircraft accidents [14]. The accidents below represent a fraction of incidences that cite automation and human factors as contributing factors.

A. Air France Flight 447

Air France 447, an Airbus 330, departed from Rio de Janeiro, Brasil to Paris, France (**Figure 3**) on the evening of 31 May 2009 carrying 228 crew and passengers. The subsequent accident investigation revealed that the pitot probes filled with ice crystals and ceased to provide airspeed information. As a result, the autopilot disengaged along with a mode change in the fly-by-wire system that provided aerodynamic stall protection [11].

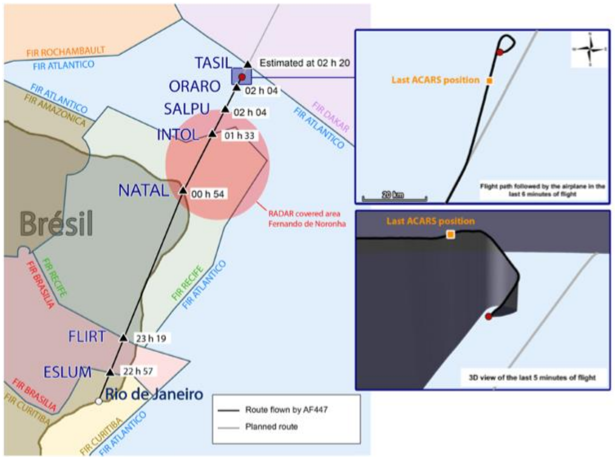


Figure 3 Flight path of AF447 [11]

As a result of the rapid escalation of the emergency, the pilot’s lost spatial and situational awareness, a relatively minor problem became a catastrophic problem. Newman [43] discusses the impact spatial disorientation (SD) has on a pilot. He defines SD as an inability to correctly interpret the aircrafts position in space relative to the Earth or other reference points, namely the aircraft’s airspeed, altitude, or attitude. According to international studies, SD accounts for approximately 15-26 percent of fatal accidents [43].

For automation failures, such as those experienced on Air France 447, the pilots need relevant and accurate information to make sound decisions in recovery, including the ability to recognise what is wrong and how to prevent it from reoccurrence. Bainbridge [7] discusses the importance of ‘cognitive skills in on-line decision making’ and how this relates to the operator’s knowledge and awareness of the current condition. The BEA report [11] explicitly stated that only a crew with a ‘good comprehension of the situation’ could have had any chance of recovering control of the aircraft to normal flight parameters. Crew Resource Management (CRM) in the cockpit was inadequate for the two co-pilots to develop a plan of action to resolve the situation, possibly overwhelmed by an automation wrong condition and an exponential increase in germane cognitive loading [65][23][54].

B. China Airlines B-1816

On an approach to land at Nagoya Airport, Japan, on 26 April 1994, an Airbus A300B4-622R with 271 persons on board crashed into the landing zone near taxiway Echo 1 [40]. Whilst conducting an ILS approach to RWY 34 under manual control, an inadvertent selection of the GO lever changed the Flight Director (FD) from LAND mode into GO AROUND mode, causing an increase in thrust. With the autopilot now engaged, the crew did not reselect LAND mode and attempted to override manually by pushing the nose forward with force against the autopilot commands in order to regain glide slope profile. With GO AROUND still selected, the Trim Horizontal Stabiliser (THS) shifted the aircraft nose to a high nose up attitude thus causing an abnormal out-of-trim situation.

Unaware of the abnormal condition, the captain elected to continue, reducing thrust, however the high nose attitude remained and the aircraft was unable to recover the appropriate glide path to land safely. The captain's late decision to cease the approach was futile as the aircraft eventually stalled and crashed, killing 264 persons on board [21][40].

C. Adam Air Flight 547

Adam Air Flight 574, a Boeing 737-400 carrying 102 passengers and crew crashed into the Makassar Strait, West Sulawesi, on 01 January 2007 killing all on board [42]. Due to a navigation error, the two pilots on board became fixated with troubleshooting a failed Inertial Reference System (IRS) to the detriment of flying the aircraft as the priority. The autopilot disengaged and the captain selected ATT (attitude) commanding the autopilot to maintain the selected flight level. Unbeknownst to both pilots the autopilot was not engaged, even with an aural indication as such, and the aircraft commenced a bank to the right. Both pilots were so engrossed in the IRS issue they did not hear the aural warning indicate that the aircraft had exceeded 65^0 AoB (angle of bank) [42]. Greater than 30^0 AoB is considered excessive. The pilots experienced attention tunneling (focused on the IRS) and loss of SA which resulted in the catastrophic accident.

V. SCHELL MODEL CASE STUDY –AIR FRANCE FLIGHT 447

The accident of AF447, registration F-GZCP, highlighted significant human factors issues that can be explored further using the SCHELL Model. Analysing the interaction of the human-machine accord using components of the SCHELL model, exploration of human error as a contributing factor may be solicited and utilised for future prevention of an accident or incident [14]. TABLE 1 provides an insight into the interactions between the human machine and varying elements associated with operating an aircraft and reveals how these factors influence human performance.

A. Software

Relevant elements in the category of software for the Air France accident include meteorological reports/charts, automated alert messages (ECAM), and aircraft communication addressing and reporting system (ACARS).

A.1. Method for processing emergencies

The operational instructions prescribed by Air France dictate the captain is to define the task-sharing between the crew; whereas Airbus prescribes a systematic sharing of tasks. The crew did not comply with the technical standards nor did they identify the cause of incorrect and inconsistent airspeed indications [11].

A.2. Meteorological reports

The pre-flight weather assessment for AF447 predicted no exceptional weather for the intended flight path in the inter-tropical convergence zone (ITCZ). The weather assessment included reports from satellite images (Meteosat 9), significant weather charts (SIGMET and TEMSI), and Tropical-Rainfall Measuring Mission (TRMM) [11]. The crew would not expect any abnormal conditions enroute.

TABLE 1 SCHELL MODEL OF KEY FACTORS OF THE AF447 ACCIDENT

Software	**Culture**	**Hardware**	**Environment**	**Liveware** (Crew)	**Liveware** (Other personnel)
Operational and Technical Instructions - Airbus and Air France	Implicit designation of pilot as relief CPT	Unable to use ADS-C and CPDLC functions	Night conditions and St Elmo's fire	No in-flight training at high altitude for manual handling	Crew Resource Management and HO/TO procedure
Meteorological reports: SIGMET and TEMSI	No instructions to crew from CPT IRT crossing the ITCZ	Flight law change to Alternate 2B (AD stall protection loss)	The ITCZ and CB clusters	Neither pilot identified the deep stall condition	Surprise by pilots of anomaly through AP disconnect
ECAM messages did not display failure - inconsistent airspeeds	No regulatory CRM training for 2 CP's and a relief CPT	Flight envelope departure by PF	Strong condensation - convection phenomena (Ice crystals)	Induced stress and pressure - Aural stall warning	CPT did not delegate command - implicit conveyance
ACARS – SAR response and aircraft monitoring	Percieved provisional failures in analogous environments - flight safety	Pitot probes: Thales C16195AA and C16195AB	Standard atmospheric temperature increases reported at STD+10^{0}C	Ozone, ice crystals, and turbulence	EASA did not mandate probe change

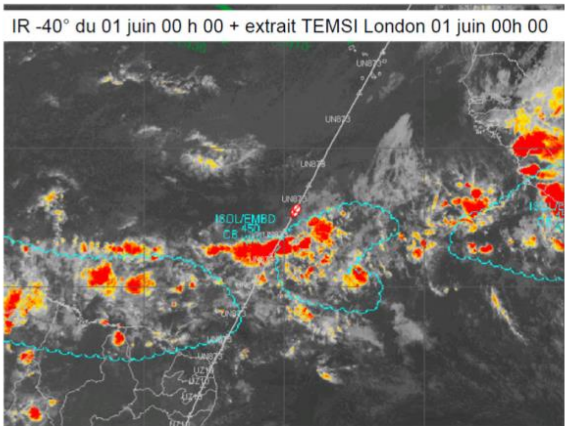


Figure 4 **TEMSI chart with infrarouge overlay [11]**

A.3. ECAM

No failure message was displayed to the aircrew on the electronic centralised aircraft monitoring (ECAM) as the system had not detected an inconsistency in the airspeeds. **Figure 5** represents the ECAM messages viewed by the pilots at the time of the event. The messages did not assist the pilots in failure diagnosis [11]. ECAM can display over 200 checklist items [28].

```
ECAM 02:10:05
AUTO FLT AP OFF
```

```
ECAM 02:10:08
AUTO FLT AP OFF
F/CTL ALTN LAW
      (PROT LOST)
-MAX SPEED.......330/.82
AUTO FLT
REAC W/S DET FAULT
```

```
ECAM 02:10:10
AUTO FLT AP OFF
AUTO FLT A/THR OFF
-THR LEVERS.........MOVE
F/CTL ALTN LAW
      (PROT LOST)
-MAX SPEED.......330/.82
AUTO FLT
```

```
ECAM 02:10:15
AUTO FLT AP OFF                 AUTO FLT
ENG THRUST LOCKED
-THR LEVERS.........MOVE
AUTO FLT A/THR OFF
-THR LEVERS.........MOVE
F/CTL ALTN LAW
      (PROT LOST)
```

```
ECAM 02:10:19
AUTO FLT AP OFF                 F/CTL
ENG THRUST LOCKED               AUTO FLT
 -THR LEVERS.........MOVE
AUTO FLT A/THR OFF
 -THR LEVERS.........MOVE
F/CTL ALTN LAW
      (PROT LOST)
```

```
ECAM 02:10:24
AUTO FLT AP OFF                 AUTO FLT
AUTO FLT A/THR OFF
F/CTL ALTN LAW
      (PROT LOST)
-MAX SPEED.......330/.82
F/CTL
RUD TRV LIM FAULT
```

```
ECAM 02:12:44
AUTO FLT AP OFF                 AUTO FLT
NAV ADR DISAGREE                F/CTL
 -AIR SPD.........X CHECK
•IF NO SPD DISAGREE
 -AOA DISCREPANCY
•IF SPD DISAGREE
  -ADR CHECK PROC...APPLY
```

Figure 5 ECAM screen display at time of incident [11]

A.4. ACARS

Aircraft communication addressing and reporting system (ACARS) is used to provide real-time position reporting from the aircraft to the dispatcher at the Operations Control Centre (OCC), every 10 minutes. Crew can also request SIGMET via ACARS when airborne. The system worked appropriately at the time of the event; however, in the search and rescue (SAR) phase post-accident, the last known position of the aircraft was not passed to relevant SAR authorities [11]. The delay can significantly impede any rescue attempt and SAR asset co-ordination.

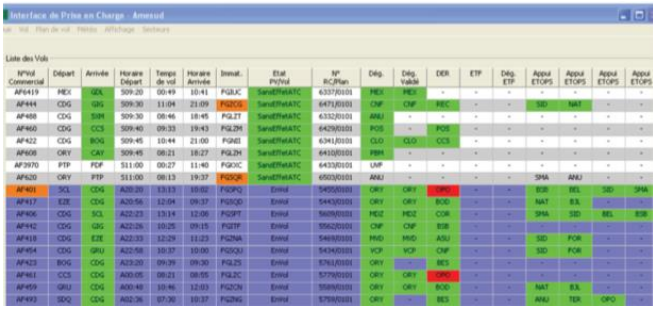


Figure 6 Typical ACARS display [11]

B. Culture

Culture is defined as the values, norms, and practices of a group or society [35]. Evidence of a generative and just culture in an organisation is indicative of a mature safety and training system. Air France and Airbus both retain such a culture, however, human behaviour exposed flaws in the system.

B.1. Pilot-in-Charge

To facilitate crew rest, a co-pilot was augmented to the flight crew. The captain (CPT) left his seat to take rest and did not nominate the pilot flying (PF) as relief captain. The nomination is important as it is the relief captain’s responsibility to take control of any situation and await the captain’s return to hand over command. Between the two co-pilots, confusion on “who’s in charge” may not have been ambiguous as the PF was less experienced than the pilot not flying (PNF), who technically, should have been nominated although it may have been implicitly understood by all three pilots [11]. The lack of formative delegation by the CPT is a sub-standard practice not a typical procedure of modern day flight crews.

B.2. Crossing the ITCZ

The CPT did not provide any instructions for crossing the Inter-Tropical Convergence Zone (ITCZ) to either co-pilot [11]. Again, practices such as this portray a laissé-en faire approach to airmanship and command, setting an unsatisfactory standard for co-pilots. Senior members of organisations set the standard by their actions (or inaction), influencing the cultural practices down through the ranks and into other cockpits.

B.3. CRM Training

Regulatory CRM training was not provided in a situation with a relief captain (two co-pilots at the controls) [11]. The high value placed in the reliability of the automation system by the organisation may potentially be a contributing factor in not identifying a training requirement for analogous situations.

C. Hardware

Flight control systems, instruments, and navigation equipment are critical in the safe operation of all modern day aircraft. Key elements of system hardware that were unannounced or displayed to the crew (liveware) contributed to the aircraft accident.

C.1. ADS-C and CPDLC

Due to the position of the aircraft, in the DAKAR Oceanic Flight Information Region (FIR), Automatic Dependant Surveillance-Contract (ADS-C) and Controller-Pilot Data Link Communications (CPDLC) functions were not available to the ATC operator (see **Figure 3**). Data link services are generally available between the aircraft and relevant ATC authority. ADS-C and CPDLC could have alerted the controller that the aircraft had departed the cleared flight level, thus prompting ATC to challenge the crew regarding the unauthorised climb and subsequent deep stall [11].

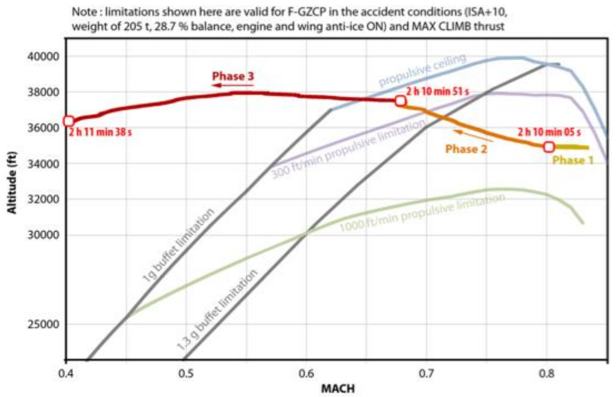
C.2. Flight Law Change

When the three Air Data Reference's (ADR) have been rejected by the flight control computers, a reconfiguration of flight control law occurs. Alternate 2B (a specific flight law reconfiguration) law is associated with a loss of speed limit display and computational loss. High and low speed protection is lost as a result with no explicit indication of the change. The loss of positive longitudinal static stability approaching the stall would not have been evident to the PF [11].

C.3. Flight Envelope Departure

When the AP disconnected and the flying law changed from normal to alternate 2B, incorrect flight control inputs from the PF and subsequent degraded kinetic energy resulted in the A330 rapidly departing the flight envelope.

The flight envelope graph (**Figure 7**) provides a visual representation of the aircraft as the PF initiates climbs at phase 2. At 37,500ft and time 2h 10min 51sec, the aural stall warning commences. The aircraft was still climbing at this particular time reaching a maximum altitude of 38,000ft in phase 3 [11].



Note : limitations shown here are valid for F-GZCP in the accident conditions (ISA+10, weight of 205 t, 28.7 % balance, engine and wing anti-ice ON) and MAX CLIMB thrust

Figure 7 Flight Envelope [11]

C.4. Pitot Probes

F-GZCP, an A330, was equipped with three Thales C16195AA pitot probes. Pilots had reported incidences of temporary loss of airspeed indication as a result of ice crystal obstruction since May 2008. Air France reported these events to Airbus requesting information on the cause and a solution. Airbus replied indicating the cause is likely rapid ice crystal accumulation. Thales developed a new probe (C16195BA), however, the new model is unlikely to clear any ice crystal obstruction since the probe is designed primarily for water ingestion from heavy rainfall. The ice crystal phenomenon was not considered in the C16195BA design or development [11].

From October 2008, Thales was alerted by Air France of increased icing at high altitude. Airbus had suggested that BF Goodrich probes appeared to possess greater reliability in this situation. Two further temporary loss of airspeed indication events occurred in March 2009 and Air France decided to accept an Airbus offer of trialling the Thales C16195BA model under actual conditions. Air France accepted the offer and ordered a fleet-wide upgrade of their A330/340 aircraft with the first batch of pitot probes arriving six days before the AF447 accident [11]. F-GZCP was not fitted with the C16195BA model.

D. Environment

Environmental conditions can significantly influence the safe operation of an aircraft at low and high altitudes. Weather conditions enroute may be predicted as fine and clear, however, rapid developments in cumulonimbus (CB) activity can challenge both crew and aircraft to its limits, especially in the ITCZ.

D.1. St Elmo's Fire

Flight LH507, a B747-400, lead flight AF477 by approximately 20 minutes at coincident flight levels. Due to adverse weather and moderate turbulence they altered their flight path and lowered their airspeed to the recommended turbulence penetration speed. Although no lightning was visible, the crew observed bright St Elmo's fire on the windshield. LH507 continued without further incident. Like LH507, AF447 crew experienced St Elmo's fire and identified adverse weather on their radar, altering course 12^0 West for avoidance (see ACARS inset of **Figure 3**). The captain, however, was not receptive to the concerns of the PF regarding further weather avoidance and did not convey his position clearly. Anxiety was clearly obvious in the PF, evident from the recovered cockpit voice recorder (CVR), due to his insistence for further manoeuvring [11].

D.2. The Inter-Tropical Convergence Zone

The CPT was not concerned with the moderate turbulence or St Elmo's fire, labelling the conditions "normal". The level of turbulence crossing the convective area was acceptable although the PF was concerned and informed the cabin crew of 'imminent turbulence' [11]. There was evidence, via infrared imagery, of the 'existence of powerful cumulonimbi (CBs) along the planned flight path' [11] and may have been at maturity at the time of AF447 flight path crossing (**Figure 4**).

D.3. Convection Phenomena

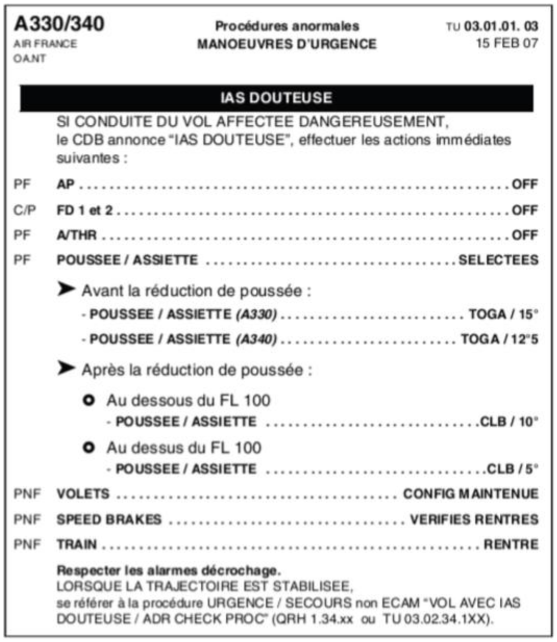
Evidence of strong condensation near the flight path of AF447 may be associated with convection phenomena. In areas of profound convection, extreme concentrations of ice crystals may be found (typically at high altitudes above 30,000ft), and it is highly probable the pitot probes became obstructed as a result of the ice crystals in the tropopause [11].

E. Liveware (the Pilot)

The AF447 accident revealed deficiencies in manual handling skills at high altitude and an overload of cognitive resources to comprehend the situation, or to gain situational awareness [11][19][25]. Stress and confusion by each pilot were evident via information received from the CVR and the flight data recorder (FDR) that indicated abnormal control inputs and speech tone [11].

E.1. Manual Handling

Manual flying skills are imperative for pilots to maintain, and simulator training tends to concentrate efforts on the terminal area during arrivals and departures. Training for high altitude manual handling for the 'vol avec IAS douteuse' (flight with Indicted Airspeed (IAS) doubtful) was absent at Air France and is identified as a contributing factor to the accident [11]. EASA made the assumption Air France provided basic handling skills and any training relevant to aircraft type so that aircrew may apply appropriate checklists and procedures in accordance with (IAW) flying manuals.



A330/340 Procédures anormales TU 03.01.01. 03
AIR FRANCE MANOEUVRES D'URGENCE 15 FEB 07
OANT

IAS DOUTEUSE

SI CONDUITE DU VOL AFFECTEE DANGEREUSEMENT,
le CDB annonce "IAS DOUTEUSE", effectuer les actions immédiates suivantes :

PF **AP** .... **OFF**
C/P **FD 1 et 2** .... **OFF**
PF **A/THR** .... **OFF**
PF **POUSSEE / ASSIETTE** .... **SELECTEES**

➤ Avant la réduction de poussée :
- **POUSSEE / ASSIETTE *(A330)*** .... **TOGA / 15°**
- **POUSSEE / ASSIETTE *(A340)*** .... **TOGA / 12°5**

➤ Après la réduction de poussée :
○ Au dessous du FL 100
- **POUSSEE / ASSIETTE** .... **CLB / 10°**
○ Au dessus du FL 100
- **POUSSEE / ASSIETTE** .... **CLB / 5°**

PNF **VOLETS** .... **CONFIG MAINTENUE**
PNF **SPEED BRAKES** .... **VERIFIES RENTRES**
PNF **TRAIN** .... **RENTRE**

Respecter les alarmes décrochage.
LORSQUE LA TRAJECTOIRE EST STABILISEE,
se référer à la procédure URGENCE / SECOURS non ECAM "VOL AVEC IAS DOUTEUSE / ADR CHECK PROC" (QRH 1.34.xx ou TU 03.02.34.1XX).

Figure 8 IAS Douteuse procedure [11]

The abnormal procedures checklist for flight with IAS doubtful, **Figure 8**, indicates the existence of such a checklist, however, crews did not practice the procedure at high altitudes [11].

E.2. Stall Condition

Airspeed indications showed a dramatic fall in airspeed from 275kt to 60kt, prompting the AP and auto-thrust to disconnect at approximate time 2h 08min. The PF took manual control of the A330-203 and commenced climbing, inadvertently, from 35,000ft, raising the attitude to 11^0 nose up within 10 seconds. Several excessive control inputs from nose down to nose up were made by the PF with a resultant nose up input of 6^0 AoA (angle of attack) and increasing.

At time 2h 11min 42sec, at an altitude of 37,000ft, the PF maintained a high nose attitude and the AoA was recorded as exceeding 40^0 with a RoD (rate of descent) of 10,000 ft/min. The pitch attitude did not exceed 15^0 nose up [11]. A fundamental technique for manual flying is most relevant in this situation: Power + Attitude = Performance. Basic pilot skills may have assisted the aircrew.

E.3. Aural Stall Warning

At time 2h 10min 51sec (**Figure 7**) the stall warning was triggered and remained active until the aircraft impacted with the Atlantic Ocean at time 2h 14min 28sec. The aural stall warning ("STALL, STALL") sounded continuously for 54 seconds. The PF did not recognise the control inputs he was applying contributed to the deep stall condition of the A330 [11]. It is highly likely the PF and PNF were overloaded with information, some of it valid, some invalid, causing loss of SA and saturation of cognitive resources resulting in confusion [11][19].

E.4. Unique Environment

As the crew were passing the ITCZ at high altitude the PF did not recognise the unusual smell in the cockpit as Ozone. The sound of ice crystals impacting the windshield and the turbulence contributed to the decay of information processing ability via sensory overload [19][11][25].

F. Liveware (Other Personnel)

The influence that other personnel have on the pilot can be significant. From raising stress levels and depleting situational awareness, other pilots, air traffic controllers, and organisational influences, can all have a negative impact on the way in which the pilot manages an airborne emergency and aviation safety.

F.1. Crew Resource Management

At time 2h 11min 37sec, the senior CP (PNF) had assumed manual control of the aircraft. Without the standard HO/TO procedure of declaring control of the aircraft (internationally recognised practice), the PNF took manual control and priority to fly the aircraft. The junior CP, without a callout, immediately took back priority and proceeded to fly. The failure to declare who has priority is in contradiction to CRM training and SOPs for multi-crewed cockpits [11].

F.2. Unexpected Situation

The PF and PNF responded with surprise when they detected an anomaly through the AP disconnect warning. During the cruise phase of flight, the system failure was not expected by the crew resulting in abnormal and excessive control inputs. The pilots became progressively de-structured not comprehending that they were faced with a relatively simple airspeed information error [11].

F.3. Hierarchical Structure

When the CPT left his seat for crew rest he did not nominate the relief CPT, instead implicitly designating it to the PF in the right hand seat (the less experienced of the two co-pilots). The CPT left his seat to rotate with the more experienced co-pilot and did not conduct a handover brief or delegate authority to his replacement [11]. BEA report that the PNF (senior CP) naturally asserted his authority over the PF (junior CP) once in the left hand seat. The PF accepted the strategies proposed by the PNF in weather avoidance and at the time of AP disconnect, the PNF demonstrated leadership despite no verbal formalisation of command.

F.4. The Regulator

The icing issues with the Thales pitot probe (C16195AA) were assessed by the European Aviation Safety Agency (EASA). EASA made the decision to not make the pitot probe change mandatory, despite awareness of the severity of the failure. The decision by EASA may have resulted in an acceptance of risk by the operators outside of their normal limits considering the area of operation in question (high altitude in the ITCZ) [11].

VI. COMPLACENCY

Complacency is often described as a 'failure to be vigilant in supervising automation prior to the automation failure' [65]. It does not directly imply that the failure will be a failure to provide advice at all (omission error). However, complacency has been associated with an assumption that 'all is well' when in fact a dangerous condition may exist [45]. Such complacency is considered an omission error. Furthermore, the term complacency is most typically invoked in the concept of alerting systems rather than decision aids [46][41], although it has been invoked in the latter context as well [34].

A. Automation Bias

Mosier and Skitka [41] define automation bias as

> "The tendency to use automated cues as a heuristic replacement for vigilant information seeking and processing [which] results in errors when decision makers fail to notice problems because an automated fails [*sic*] to detect them (an omission error) or when people inappropriately follow an automated decision aid directive or announcement (a commission error)".

In a study of complacency and automation bias, Parasuraman and Manzey [45] found no delineation in degree of complacency between the novice and expert individual or teams. Clearly a new approach to address the divide is long overdue, but how is this ideally managed?

Wickens *et al.*[65] determined that 'automation wrong' reflected automation bias and proved the greater automation error than if automation had simply failed ('automation gone'), reflecting a complacency in the automation. Errors of commission (overcompliance) are when the aircrew receive false alerts, and errors of omission (overreliance) relate to inappropriate action from the decision maker [65][48], or misuse of automation [34].

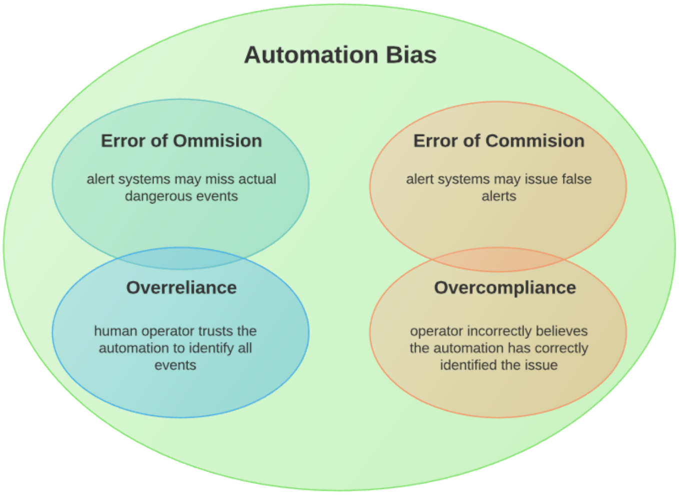


Figure 9 Automation Bias (adapted from Wickens *et al.*[65])

It is plausible that resistance to cognitive loading, as a result of the sudden increase in workload from a benign automation monitoring state to an "adverse one", may support the over-reliance and over-compliance theory [65][44]. Attempting to alleviate the resultant stress of the "adverse" situation, the condition of automation bias may exist to provide a perceived homeostatic mental model for the individual. Gil *et al.*[23] identified a potential reduction in cognitive loading from 'novel NextGen-style flight concept of operation(s)'. Research results may advance the understanding of the cognitive behaviour of pilots, and provide a prediction tool for future automation in regards to workload and performance. A review of numerous academic papers on automation and human factors dating back over three decades reveals continued findings that validate the psychosocial issue, yet no proposed solutions appear to remedy the root cause. After a significant contribution to resolving the human condition of complacency and automation bias by academia and subject matter experts, is a panacea likely to exist or does the infallibility of human psychology destine that the same errors are repeated?

B. Cultural Considerations

Any novel attempt to address complacency must consider a culturally intelligent solution as values, norms, and practices vary significantly between cultures, even when operating identical aircraft types. Procedurally, an automated platform will generally be operated the same for all flight conditions as prescribed by the aircraft manufacturer. In any solution to minimise or eliminate complacency, the key elements to address are the psychosocial factors. For example, it is widely understood that Crew Resource Management (CRM) is a fundamental practice for aviation safety, especially in the multi-crewed environment, however, not all pilots are practitioners [36]. One suggested reason is the cockpit authority gradient. This cultural norm, in some countries, refers to the lack of assertiveness of junior pilots when detecting an error, reluctant to raise the concern or issue with the captain. Even in some modern day societies, pointing out someone's error(s), especially your supervisor's (captain), can have career ending consequences.

Threat and Error Management (TEM) forms part of the CRM training for the Air Force, and focuses on the recognition of a threat that may lead to an error prior to the error occurring. Analysis of errors by aircrew in greater detail are required to assist in identification post error occurrence [14][15]. A just culture is imperative to ensure tools such as CRM and TEM are used efficaciously. If the cultural practice of an airline accepts latent psychosocial conditions like authority gradients, Reason Model elements such as the organisation and workplace conditions that mitigate an accident are already effaced. This situation leaves minimal defensive barriers for accident prevention [14].

VII. COGNITIVE LOAD THEORY

During learning and problem solving, our cognitive resources are focussed on managing and completing a task(s). Human operators may experience lacklustre performance as a result of an inability to process interactive elements of information simultaneously to produce meaning [51][57]. The term "element" may refer to a procedure that needs to be learned, such as conducting an instrument flight procedure (IFP) in instrument meteorological conditions (IMC), or something as simple, yet critical, as confirming the airspeed being within limits prior to gear or flap extension. Additionally, an element may be attributed to a learned concept such as airworthiness. Elements are reflected in the proposition of cognitive load theory by Sweller [52][54]. Sweller introduces three components of cognitive load theory; germane, intrinsic, and extraneous.

A. Germane Cognitive Load

When one is attempting to commit to permanently memorise a theory or checklist, say aerodynamics or pre-take off vital actions (PTVAs), he/she will utilise germane cognitive load. Germane load is also referred to as working memory. Current theory proposes instructional design should look to promote germane load, or schema development, whilst simultaneously reducing extraneous load as to allow greater working memory resources to intrinsic cognitive load [54]. Germane cognitive load is inherently different to intrinsic or extraneous cognitive load as it is not, in terms of cognitive load, an independent source. Simplistically, germane load is a working memory resource from which intrinsic cognitive load manages element interactivity [54].

Germane load is also defined in terms of intrinsic load, where element interactivity is imperative to the task. Sweller [54] adds that the learner's knowledge level will determine the degree of difficulty in the application of working memory. An example of element interactivity and its relation to germane cognitive load for a pilot's knowledge level would be the co-pilots ability at entering a flight route into the FMS. As proposed by Bainbridge [7], one would expect the captain to make the minimum number of actions to complete the data entry into the FMS where the junior co-pilot is likely to require the maximum.

B. Intrinsic Cognitive Load

Considered to be immutable, intrinsic cognitive load 'is concerned with the natural complexity of information' [54]. The way in which the information is to be learned must be free from methods associated with delivery or how to maximise the learning experience. Sweller [54] reports that the only technique to manipulate intrinsic load is to influence the act of learning or transforming the material to be learned. For a particular knowledge level and task, element interactivity determines the extent of intrinsic cognitive load. If an element is able to be learned in isolation, or limited reference, of another element then a low imposition to working memory will result [53][54]. Learning the alphabet is a simplistic example of low element interactivity as each element can be learned independently.

C. Extraneous Cognitive Load

Suboptimal didactic procedures combined with intrinsic complexity of learned material have greater demand on working memory load. This amalgam imposes on working memory, and defines extraneous cognitive load [53][54]. As there may be a limited or finite cognitive resource in the human operator, any application of this resource to processing extraneous load will diminish the human's capacity to learn or to solve problems. Both germane and intrinsic cognitive load will be reduced.

Using an aviation related example for extraneous cognitive load, an ab initio student on pilot's course is learning how to fly a circuit for the first time. One method of teaching the student is to describe the circuit verbally. Another method would be to show the student a diagram of the circuit with appropriate labelling. Consider the four sensory modalities of learning: visual, auditory, read/write, and kinaesthetic (VARK). Whilst both methods described may be successful,, far less effort is required by the student to comprehend what the instructor is communicating in the latter example.

D. Information Sources

Varying sources of information can increase the cognitive load, especially when dealing with a new task. As a result of multiple experiments, Chandler and Sweller [13] hypothesised that the human operator performed better due to a single integrated source of information, ultimately using less cognitive load to complete the task. In the context of piloting an automated flight deck, an automation wrong scenario whilst flying may overload the human operator. This may inhibit the information collection process for timely and appropriate decision making, potentially resulting in an aviation accident. Conversely, automated flight deck ergonomics embraces information integration via systems such as electronic centralized aircraft monitor (ECAM) on Airbus, or engine indicating and crew alerting systems (EICAS) used by Boeing [49]. Chandler & Sweller [13] found that disparate information sources resulted in poorer cognitive load performances.

In cockpit ergonomics terms, non-automated flight decks are very closely aligned to disparate sources of information as raw data from altimeters, airspeed indicators, vertical speed indicators, attitude indicators, and compass, are processed independently by the pilot. Learning any new skill, either operating an automated system or mentally processing raw data instruments, the user relies on individual working memory abilities to maximise germane capacity, minimise intrinsic and extraneous cognitive loads [53][57][54][55], and workload management [24][63]. This is required for optimal performance and safe operation of the aircraft. One could reasonably argue that automated flight decks mitigate the human infallibilities cognitive load theory purports, especially cognitive processing capacity [51].

The complex nature and operation of fully automated flight decks is circumvented via simplistic user interface systems such as ECAM and EICAS. The user simply "follows the bouncing ball" for the rectification of an airborne issue captured by the automated system, thus aiding or eliminating the decision making process of the pilots. Where the relatively benign failure spirals out of control, however, is when the automated system is wrong. Wickens *et al.*,[65] described the 'error of commission' and identified 'overcompliance' as an automation bias, highlighting that when the automation is wrong, the user inputs irrelevant and inaccurate actions into the system due to an incorrect belief that the automation system has identified the fault correctly [65].

The graph at **Figure 10** indicates, for the automation wrong group, the diagnostic accuracy of the automation failure decreased dramatically for the first fault (FF) from the baseline, assessed at only approximately 20% accuracy. The second fault (2F) exhibits an improvement in accuracy, however, is only identified at being approximately 55% accurate [65]. In addition, Wickens *et al.*[65] report evidence of complacency in both the automation wrong and automation gone groups for the experiment. Complacency was identified by the user taking shortcuts in the resolution of the failure (fault diagnosis and management), actions generally performed by the experienced operator in selecting the minimum number of steps in the process [7].

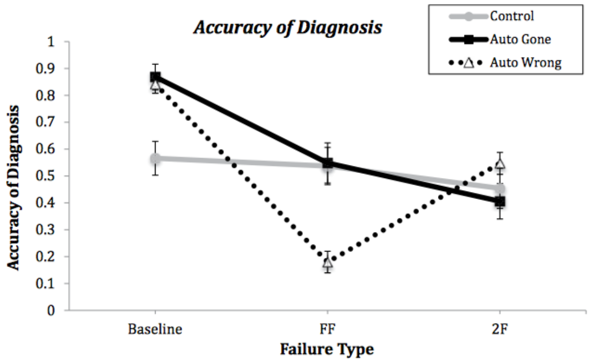


Figure 10 Accuracy of Diagnosis [65]

VIII. INFORMATION PROCESSING

How we receive, store, and retrieve information for its application is described by Harris [25] in terms of a system model and information processing theory. Harris contends that workload and situational awareness both intimately interact with human information processing, representing cognitive load on working memory. The interaction of human information processing elements associated with the flight deck is represented at **Figure 11**.

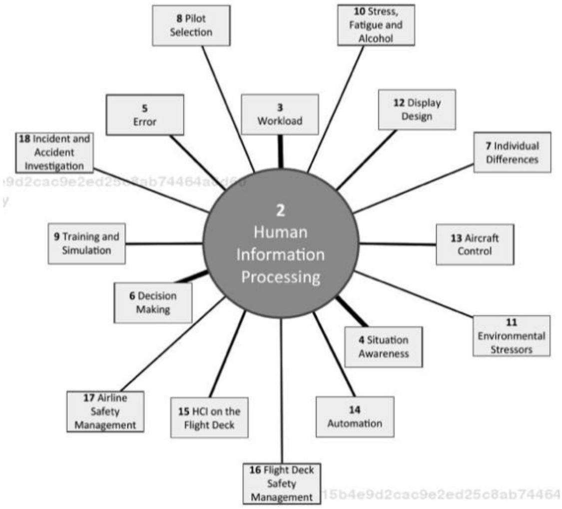


Figure 11 Human Information Processing [25]

A. *Workload*

Cognitive processing includes workload (high or low), ability to learn, and the processing of errors for recognition and prevention. In the context of piloting a highly automated aircraft, this relates to the process efficiency [8]. Measurement of workload associated with the processing of information can be both subjectively and objectively assessed. Subjective methods include the NASA task load index (TLX) and the Bedford workload scale. Objective methods measure psycho-physiological responses and can produce an empirically determined result by assessing an individual's autonomic balance. The assessment determines the degree of dominance of the sympathetic nervous system (SNS) and the parasympathetic nervous system (PNS) [59][60][3].

In an experiment to determine the normal distribution of a random sample of individuals, Wenger [59][60] found an autonomic balance average of 70. Individuals that scored above 70 were considered PNS-dominant, and those below were SNS-dominant. The greater the score from the average, the greater the imbalance. Studies conducted by Wenger and associates resulted in a hypothesis suggesting the differences in autonomic balance and response patterns could be used to predict individuals who may respond positively to stressful environments and those who may develop a psychosomatic disorder [62][61][3].

B. *Attention Tunneling*

In airborne emergency situations, the operator may be bombarded with information, and may become fixated on a single element of the complete environment they are seeking to comprehend, a condition known as attention tunnelling [19]. As a result, they cease to be effective in scanning behaviour, and SA rapidly decays [25].

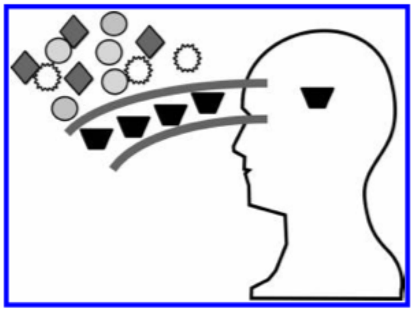


Figure 12 Attention Tunnelling [19]

Whilst attention tunnelling may be perceived as appropriate for certain situations, fixating on altitude during descent for example, provided the pilot continues scanning all relevant information sources for SA maintenance, then there may not be any negative consequence. Where the scanning behaviour fails to incorporate other key elements for the safe operation of an aircraft, catastrophic results may ensue [19]. A well-known example of attention tunnelling, with fatal consequences, occurred in 1972 when an Eastern Air Lines Lockheed L-1011 carrying 176 passengers and crew crashed near Miami International Airport, killing 94 passengers and 5 crew. The National Transport Safety Board (NTSB) [42] Aircraft Accident Report revealed all 3 pilots had become fixated on a problem with the nose landing gear indicator light and failed to monitor the flight instruments, resulting in controlled flight into terrain (CFIT).

C. Data Overload

The ability of the pilot to process data can be exceeded by the rapid rate of information that flows from an emergency, such as a double asymmetric engine failure after take-off. Having a visual horizon can alleviate the requirement to extract raw data to aviate the aircraft before any navigation, communication, or administration (ANCA) can occur. In IMC, however, the data overload condition is increased and the pilot may start to lose SA.

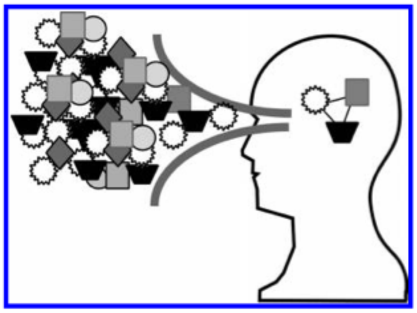


Figure 13 Data Overload [19]

If an increase in visual messages or auditory alerts that may not be related to the initial emergency is delivered to the pilot, and they are not received, an outdated SA picture will result and may adversely impact the safe recovery of the aircraft [19].

D. Perception

Perception is defined by Harris [25] as the interpretation of the human information processing system from the sensory inputs, converted to meaning by the recipient. In high workload environments of flight like manually flying an instrument approach procedure in IMC, the Sensory Register receives data and converts to something meaningful (radials, altitudes, on profile) to be processed further into a physical action (adjust power lever changes, control inputs etc.).

Harris [25] suggests that memory plays a significant role in perception. Visual illusions result from what is learnt to be fact, thus perceived to be factual, that may indeed be false. Mental images of how a typical runway on final approach should look is learnt from pilot training and reinforced from continued flying experience. The visual illusion can occur when the perceived, or learnt picture “looks right” but is actually incorrect due to an up sloping runway on flat terrain. Human error occurs when the pilots incorrectly perceives they are high on profile and increases rate of descent (ROD) to recapture the “correct” flight path [25].

IX. EFFORT

It is proposed that a benign airborne environment (low workload) has a greater probability of being the source of boredom and fatigue due to inactivity. Phases of flying such as the cruise are typically low workload periods, and pilots may only perform a monitoring role of performance parameters including systems, navigation, and air traffic control reporting. With automated systems performing most of these duties, the effort required by the pilot is very minimal. It is this very situation where pilots can quite easily slide into germane cognitive load decay, potentially negatively affecting information processing and construction ability [54][52]. When an abnormal automated system situation presents itself whilst airborne, extraneous cognitive load may overload working memory [54][55][65].

When one is “pretty sure” of their memory recollection, the expenditure of effort to confirm the information is not always considered worth the effort [64]. Kern [31] states that not all negative actions, or inactions, result in negative consequences. When an operator experiences success in following a path of least resistance (low effort option) to achieve an outcome, normalisation of deviance or practical drift emerges. Unless the behaviour is changed, the outcome of the human error(s) whilst airborne can be acute.

Wickens [64] offers a representation of effort in terms of high and low risk, **Figure 14**. The decision tree offers a quantitative outcome of one’s decision to select either the low or high effort path. In selecting the path of least resistance for a given issue, the operator has exposure to a higher risk outcome. This choice could result in a serious or catastrophic accident or, as Kern [31] would state, the start of practical drift.

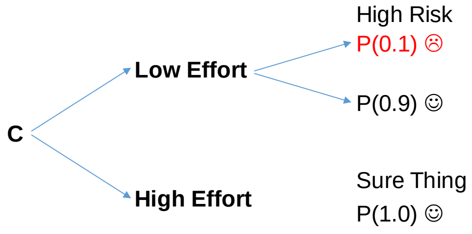


Figure 14 Effort and Risk (Wickens [64])

Over-confidence in a captain's or co-pilot's mental ability in the cockpit can have similar consequences. In this case, effort to ensure the accuracy of the proposed answer or question is confirmed is most certainly worth it. In their paper on neuroergonomics, Mehta and Parasuraman [39] discuss effort expenditure in terms of physical and cognitive ergonomics where the neckline delineated the ergonomics of cognition (above) and physical (below).

It is evident that greater effort is required to validate our memory, thus ensuring us to take that extra step beyond being "pretty sure". Cognitive laziness or social loafing contributes to choosing the low effort option [48]. A low workload airborne environment is generally where military pilots will discuss aircraft systems knowledge including abnormal system operations (hydraulic issues, electrical failures, etc.). Additionally, problem solving activities such as reasoning and mental calculations greatly assist pilots in decision making, maintaining cognitive sharpness, and addressing any latent fatigue or boredom associated with low workload periods of flight.

Reasoning

Human intelligence encompasses varying elements such as reasoning, decision making, and problem solving [32]. All of these elements overlap within the human intelligent framework and reasoning is important for the process requires the interpreter to solve beyond the information given [10]. Reasoning is a critical skill for the pilot in automation wrong or gone situations as reference to raw data is required to draw conclusions and resolve the abnormal event. The question posed at **Figure 15** is an example where inductive reasoning is required to solve the problem rather than deductive.

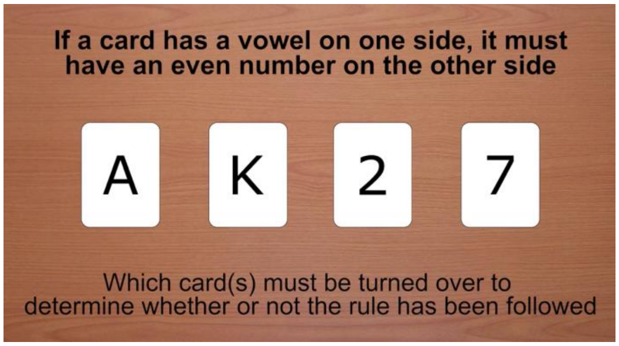


Figure 15 Reasoning question (adapted from Johnson-Laird & Wason [29])

Lohman and Lakin [32] cite evidence of repeatable laboratory demonstrations where humans act irrationally and display pervasive biases that negatively impact rational decision making. The key to solving the reasoning question is to affirm the antecedent "A" (Modus Ponens) and deny the consequent "7" (Modus Tollens). Johnson-Laird and Wason [29] found only 4% or participants correctly answered the question with 46% selecting "A and 2"; 33% selecting "A" only; and 7% selecting "A, 2, and 7"; with 10% other. The correct answer is "A and 7". The pattern of progression for both inductive and deductive reasoning is viewed at **Figure 16**. Inductive reasoning has greater relevance in the cockpit as the primary role of a modern day pilot is monitoring (observing) the automated system. Any deviations from the norm would require the pilot to Observe, determine any Pattern, deduce a Hypothesis, then form a Theory for resolution [29].

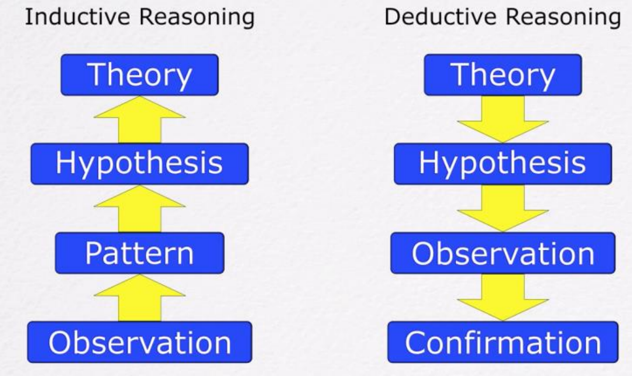


Figure 16 Reasoning theory (adapted from Johnson-Laird & Wason [29])

Any relevant activity or task created for pilots whilst in a low workload environment (cruise phase) will go a long way in combating fatigue and boredom whilst contributing to neural reinforcement of learned skills, problem solving, or systems knowledge.

X. NEUROPLASTICITY

A student on pilot's course with the Royal Australian Air Force (RAAF) will develop the majority of the skills for manual flying over the duration of pilot training. During this period a student will create new neural pathways that will be "strengthened" as he or she progresses through the course and consolidates manual flying techniques.

A. Neurogenesis

A new environment, such as flying, provides mental stimulation where neurogenesis can occur. The new learning environment can spark 'anticipatory proliferation' where rapid growth of neurons in the hippocampus materialise, forming memory [16]. Unless new skills are repeated constantly, and they must be completed accurately, as "*perfect* practice makes perfect", the neural connections formed in the process will remain weak and are rapidly reversed [16]. New skills, or disciplines, for the modern day pilot on a fully automated flight deck may include accurate data entry into the FMS; autopilot and auto-thrust mode awareness; and flight director mode awareness. The new skills mentioned have limited, if any, connection to the neural pathways used for manually flying. So what happens to the manual flying neural superhighways if we cease manual flying?

Doige [16] suggests that competition exists for brain processing power and cognitive resources and unless a particular skill (neural superhighway) is maintained, 'use it or lose it' principles apply. This statement is consistent with numerous academic papers on the assessment of pilots in their manual flying skills and the adverse impact of enduring automation use [26][12][44][30][33][58]. Creating permanence and improvement in skills requires constant effort by the operator as some will pick it up faster than others by nature of cognitive ability, termed the 'tortoise-and-hare effect' [16]. An important point is made by Doige in that the 'hare', or quick study, may not end up in front of the 'tortoise' as establishing strong neural pathways requires sustained effort that solidifies the skills learnt and provides opportunity to master the new skills.

B. *Visualisation*

Chair flying is a visualisation technique practiced by nearly all RAAF pilots, especially under training. It involves the student flying the procedure (checklist actions or flying circuits) in his or her mind, placing the hands and feet as you would if you were actually in the cockpit whilst sitting in your chair. This technique allows an opportunity for constant repetition of a particular skill or procedure to consolidate the neural pathways in the brain (muscle memory), thus strengthening them and increasing SA for improved germane cognitive function. This skill is important in the handling of an emergency, especially in single pilot operations. Mentally practicing what you would do allows you to increase germane load resources when compared to an actual emergency.

Human experimentation has asserted the benefit of visualisation when compared to learning a new skill physically. In an experiment conducted in the 1990s using transcranial magnetic stimulation (TMS), Dr Alvaro Pascual-Leone demonstrated that the same physical changes in the motor system were evident in the visualisation group as the group learning by physical means only [16]. Studying the cognitive finger maps of people learning to play the piano, Pascual-Leone taught a sequence of piano notes to two separate groups that had never played piano previously, one conducting "mental practice", the other "physical practice" [16]. The experiment indicated that visualisation, along with a brief period of physical consolidation, can result in an effective performance equal to those that physically practiced on a continuous basis.

This result suggests that modern day pilots flying fully automated aircraft may achieve, with the use of visualisation (chair flying), an appropriate retention of manual flying skills when supplemented with occasional manual flying. The combination of mental and physical manual flying will satisfy the principles of "use it or lose it" and ensure the enduring nature of the neural superhighway. Conversely, if chair flying is not supplementing the limited exposure to manual flying, the relevant neural pathways may eventually decay. The concept of neuroplasticity is that the brain exhibits plastic-like properties where it can recover old or not regularly-used information or skills, however, the neural pathways will be weak and the sensation of feeling a bit "rusty" on the controls may be evident.

In a high workload and dynamic environment, for example an aircraft emergency in IMC, the cognitive resources allocated to resolving the emergency may adversely impact the manual handling of the aircraft and can also cascade into a loss of situational awareness, information processing, and decision making. It is suggested that most, if not all, pilots that spend a period of time out of the seat have experienced the feeling of being a little rusty when converting or undertaking a refresher back on the controls, which is to be expected. The "rust" sensation, however, can be minimised with a time and effort investment in chair flying.

C. *Manual Skills*

In a review of several studies on manual control skills, Edwards and Lees [17] revealed that an experienced operator conducts the minimum number of steps to complete a task, whereas an inexperienced operator, as one would expect, makes several more. Wiener and Curry [66] argue that, for rote learned manual tasks, automation will possibly decrease skill level. Onnash *et al.*[44] found that long periods of non-use of manual handling resulted in decay. During initial phases of operation, the training literature suggests that effective and complete acquisition of the skill set can be achieved by 'part-task operation (with the other tasks automated)' [66].

Bainbridge [7] argues that an experienced operator that may be monitoring an automation process, for example the cruise phase of flight, may have degraded manual control skills as a result and function similar to an inexperienced operator.

Developing simulator scenarios for a modern day platform where crews are measured in operational environments with unfamiliar navigation and air traffic control directions, with aims similar to those found in Ruffell-Smith [47], may permit further understanding of pilot error and decision making. Wiener and Curry [66] found similar results as Ruffell-Smith [47] from inadequate feedback from input to control systems, automation versus manual control respectively, thus indicating evidence of human errors.

A significant issue faced by many automated flight deck pilots is an apparent lack of manual hands and feet flying skills, especially when it comes to stall recovery and energy awareness. Some airlines require or encourage pilot employees to use automation as often as possible, resulting in some pilots never hand flying an approach to land, subsequently contributing to the decay of their manual flying skills [12].

XI. FUTURE OF AUTOMATION

The logical, and inevitable, end state of automation in aviation is the fully autonomous and pilotless passenger jet. Technology will not be the limiting factor in its achievement. Convincing the general public and their perception of intrinsic safety regarding the automated systems will be the challenge. Understanding how a system works and the facts surrounding the technology such as failure rates (mean time between failure (MTBF)), system redundancy, and regulation will be fundamental in managing the process and addressing public concern.

Alleviating public apprehension may be achieved by the incremental introduction of automated devices in our own motor vehicles. Current automated features, such as Volvo's Collision Warning with Brake System, use forward facing cameras and or radar to scan potential hazards and automatically activate the braking system to prevent an accident [56].

Confidence in automated systems is a gradual process. Car technology that improves safety and eliminates human error can only have a positive impact on managing public perception towards an autonomous passenger aircraft. The leaders in fully autonomous vehicles, driverless, are technology giants Alphabet Inc. Google car division and the automobile industry's Tesla Motors Inc. [50]. They lead the way for autonomous vehicle transportation with prototypes such as the Tesla Model S P90D.

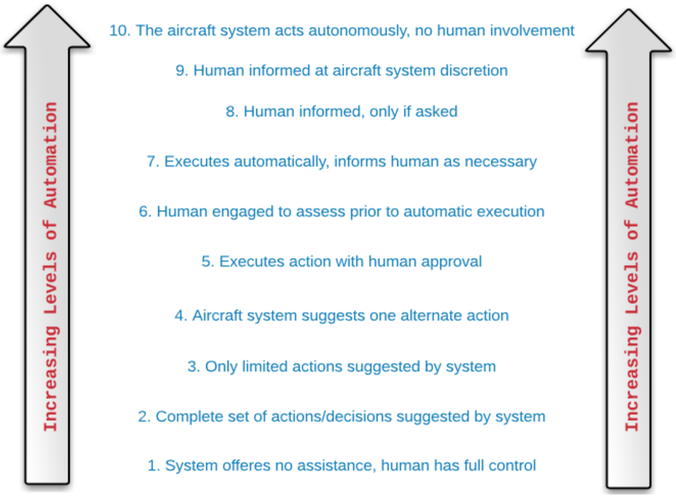


Figure 17 Levels of Automation
(adapted from Parasuraman et al. [46]; Billings [9])

Classifying the varying levels of automation, with complete autonomy at the highest level, has been established for both the automobile and aviation industries. Parasuraman *et al.*[46] defined a 10-point scale to illustrate the varying levels of automation, **Figure 17**.

Currently, the most advanced automated flight decks function with relative autonomy, from gear up after take-off through to the landing roll for a CAT III - Instrument Landing System (ILS) instrument approach. The human operator maintains complete oversight of the system with the ability to override and operate manually at any stage, in the unlikely event of a failure. Using the automobile industry as a guide for autonomous vehicle advancements, industry experts originally estimated the year 2035 as an appropriate timeframe for driver-less vehicles. Given the advancements in technology, led by Silicon Valley corporations, a revised deployment of autonomous vehicles has been suggested as early as 2020 [50]. Depending on one's perception of the technology, the introduction into society of driver-less cars in the very near future, may pave the way for fully autonomous aircraft into our skies.

A single aviation incident on 4 November 2010 that potentially resulted in the loss of 469 lives, due to an uncontained engine failure, was rescued by sole human intervention and basic flying skills. Qantas Flight 32, an A380-842 departing Singapore, was fortunate to have several experienced pilots on board to problem solve and effect a safe recovery of the large passenger jet [5]. A significant incident such as QF32 may always challenge the concept of a completely autonomous passenger aircraft in the eyes of the flying public, until such a time when technology can successfully overcome, with confidence, an identical situation.

XII. NOVEL APPLICATION FOR PROFESSIONAL PILOTS

Consider an interactive software application for smart phones and tablets that may be uploaded to a personal smart phone or tablet devices that challenges pilot boredom, fatigue [39], and complacency. During the cruise phase of flight, the captain and co-pilot can utilise the low workload environment to maintain and/or improve flying skills and knowledge. The application presents a series of randomly selected short systems knowledge questions, determined by the platform type being operated, including mental calculations directly related to flying such as fuel burn, distance, time, and velocity. Both the captain and co-pilot can discuss the presented problems and solve collaboratively or individually. Cultural sensitivities may be addressed by individual training only, where any errors or gaps in knowledge are not evident to colleagues.

Options such as specific aircraft systems, emergency procedures, and problem solving questions that promote decision making (inductive reasoning), can be selected and individual logins can track performance to assist in identifying strengths and weaknesses. The aim of the application is to promote pilot cognitive sharpness and how it relates to flying such as assessing raw data and problem solving in four dimensions (x, y, z, and time). The application aims to address complacency in automation, via mode awareness questions and discussion topics, assisting team building and leadership development by collaborative problem solving. Given the frequency of crew changing, especially in commercial aviation, exercises such as this will promote crew cohesion and junior pilot development whilst directly addressing the phenomenon of complacency and automation bias.

XIII. CONCLUSION

The relevance of literature on automation issues and human factors since the 1970s continues to remain valid today. The problems identified, researched, and discussed nearly four decades ago continue to be contributing factors in aircraft accidents and topics of academic research. Aviation accident investigations continuously identify human error as a contributing factor and whilst recommendations for elimination or amelioration are made at the organisational level, personal responsibility to minimise or eliminate error account as a significant mitigating treatment. Kern makes a compelling point that each pilot must make a conscious commitment to reduce personal error. Having greater understanding of information processing ability and what can overload cognitive resources may assist in how we manage our strengths and weaknesses when it comes to skills and knowledge. Simulator check rides, manually flying an approach to land, and examinations provide an insight into where we can or need to improve. However, the frequency of these events may be inadequate to remain at our optimal peak.

Models like SCHELL provide accident investigators and the wider aviation community a valuable insight into human factors and performance. It is critical we learn from our mistakes and respond proactively so that we can improve training, procedures, and technology to keep us safer in the air. Using the techniques suggested, along with access to the novel application proposed, pilots may work through system knowledge quizzes and chair flying procedures, including emergencies. Ideally, these are best utilised during low workload periods of a flight, thus greatly assisting in the maintenance or improvement of cognitive sharpness in the event of an emergency whilst combating boredom.

Regaining situational awareness in an emergency is difficult, especially in time-critical situations. Investing time in the techniques may ensure neural superhighways remain strong therefore alleviating cognitive load in the event of an emergency where SA easily deteriorates. Professionals acknowledge “perfect practice equates to perfect performance”; this requires time and effort, individually and as an organisation. The evidence saliently reveals, complacency and automation bias is a significant human factor concern requiring further, novel research in order to minimise the contribution to aviation incidents and accidents.

ACKNOWLEDGEMENTS

The author would like to thank Associate Professor Agus Budiyono, RMIT, for his support as supervisor for this paper. In addition, I would like to thank Richard Court, Chris Jeansch, Mike Read, and Glenn Salmon, all who provided valuable information in relation to operating highly automated platforms as professional pilots. Their experience greatly assisted in validating some of the academic concepts of automation operation and bias.

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