ISASI 2017: “**Lost opportunities and thinking illusions**”

Authors: ***Andrew McGregor***, *CPEng; Commercial pilot with 2500 hrs flight experience, owner and director of Prosolve Ltd, a forensic engineering practice based in Auckland New Zealand;*

Captain Simon Tapp*; BSc(Psychology), Airline pilot of 14,000 hrs flight experience, Commander of an Airbus 330 based in Germany for Air China, with a background and interest in human factors;*

Barry Hughes, *PhD; Lecturer in Cognitive Psychology at the University of Auckland and director of the Ringaringa Research Lab, specializing in issues related to perception, cognition and motor skills.*

Contact details: Andrew McGregor +64 27 281 3398; amcgreg@prosolve.co.nz

Introduction

Optical illusions occur when what an observer reports seeing is systematically different from objective reality (lines of equal length are perceived to have different lengths; circles of equal size are seen to be different; straight lines are seen as curved). What makes illusions notorious is that knowing that the perception is in error does nothing to correct the perception (the lines still look bent even when a ruler has confirmed that they are straight). Research in psychology indicates that optical or perceptual illusions may not be the only type to which we are susceptible. People may be subject to illusions of thought. Over the last fifty years, advances in psychological science have revealed striking limitations, distortions, biases in peoples' cognitive capacities. These relate to a broad gamut of cognitive skills, from intuitive statistics to inductive and deductive reasoning to problem-solving. Importantly, these limitations, distortions, and biases are not the burden of the uneducated; they are omnipresent and even those who study them are regular victims. We believe that the benefits of applying lessons from such research to accident investigations, systems engineering and pilot and investigator training will significantly improve air safety. (For example, none of what we describe is discussed in Wiener and Nagel [1].)

In what follows, we argue that aviation accident investigators should be aware of at least some of the more serious of these cognitive illusions and biases which, we argue, have resulted in loss of life, and lost learning opportunities. We demonstrate this by discussing and linking four major incidents and accidents. We do so with reference to the Erebus crash [Air New Zealand; Nov 1979], the Perpignan crash [XL Airways; Nov 2008], the Bilbao incident [Lufthansa; Nov 2014] and the crash of AF447 [Air France; June 2009].

We begin by reassessing the Erebus disaster. We apply Dekker's 'failure drift' model [2, 3] to show how one line of thinking — a pre-occupation with the last stages of the accident timeline—masked important contributing causes of the crash. We discuss why this may have been so. We also assess the various contributing causes in terms of their cognitive origins.

We extend this type of analysis to the Perpignan crash investigation report and those of the Bilbao incident, similar incidents that occurred six years apart. We highlight the thinking illusions to which the Perpignan investigators may have succumbed. This treatment provides some understanding of the illusory thinking that may have preceded the AF 447 crash and which may have weakened the outcome of the many sensor discrepancy incident investigations that occurred before the AF 447 crash and the Bilbao incident, illusions or distortions which resulted in lost opportunities that could otherwise have prevented both of these incidents.

And while it is unlikely that mere awareness will eradicate these types of thinking illusions, such awareness may increase investigators' sensitivity to them and result in investigations whose conclusions may result in more lucrative learning opportunities that really make a difference in terms of reducing future accidents.

Cognitive or thinking illusions

Humans have been referred to as informavores [4]; that is, creatures driven to find meaning in situations. People will seek to find patterns in what they see. They will seek causes for behaviors they observe. They will act in ways that they expect will yield more information and meaning. Our evolutionary success owes much to this ability. But sometimes, this compulsion to seek information leads to anomalies, such as perceptual illusions. And sometimes the struggle for meaning leads to errors of cognition or thinking.

Cognitive or thinking illusions are most closely associated with the Nobel laureate Daniel Kahneman (much of whose work was done in collaboration with Amos Tversky). In his book *Thinking, fast and slow* [5], Kahneman models thinking as the output of two distinct systems. System 1, embedded within the subconscious, is grounded in experiences, emotions and associations and, in short, can be considered the faculty of intuition. System 2, by contrast, refers to our conscious, effortful, deliberatively rational mode of thinking. Kahneman's contribution has been to demonstrate their respective operating characteristics scientifically and via a variety of examples. These two modes of thinking are the essence of the human factor in decision-making. They are not linked to particular individuals; they are not personality traits. Nor do they occur only in certain fields of human endeavor or expertise. As such, these modes of thinking reside in each of us. Their effects are often syncopated: System 1, evolutionarily older and being fast precisely because it is subconscious, often generates an answer, offer a cause or proposes an explanation without beckoning. System 2, on the other hand, entails slower mental effort, typically requires the use of working memory, and often depends on explicit knowledge of probabilities, or more formal logical, rational, scientific precepts. The upshot is that a System 1 answer may be all that a person relies on ("Intuition, grounded in years of experience, told me that this was a case of x"). Or the initial answer may be later audited by System 2 processes and found wanting in some respect ("I know that it looks like x, but the prior probability of this occurring is so low, that I should double-check").

Kahneman argues that while System 1 has its benefits – especially speed and ease in situations where decision-making time or information are limited [6,7, 8]— it is also the basis of serious thinking errors.

System 1 is prone to distortions, biases and an overreliance of mental shortcuts or heuristics. System 1 encourages stereotypes and favors emotional or intuitive decisions. System 1 encourages us to jump to conclusions and prefer simple and 'obvious' explanations rather than factor in complex and latent factors and complex interactions. System 1 accesses information that is defined by its easy accessibility or availability. Self-reflection and self-monitoring of one's reasons and decisions is not a feature of System 1 thinking: these are System 2 operations.

Like optical illusions, cognitive illusions are pernicious, compelling and they persist even when we know they are prone to error. Through many empirical demonstrations Kahneman and colleagues have shown that even when rational analyses indicate that our subconscious decisions may be flawed, we remain susceptible to them and often act on them regardless. Although the literature reveals dozens of distinct distortions and biases [9,10], many of which may be relevant to accident investigations and their implications, we will focus on specific and particular cognitive illusions that may be common to a set of four distinct aviation incidents.

Many investigators will be familiar with the research that has been undertaken on human error [11 , 12]. Such research constitutes an important branch of the field of applied cognitive psychology. Does an incident always involve some degree of human error? Is the error made by a single person, or by many? Should the person closest to the incident in time or space be presumed to have a larger causal role than someone more removed? The concept of 'failure drift' introduced by Dekker (2002) is relevant to the claims we make below and serves as an introduction to the more specific claims we offer. Failure drift is a useful concept in accident investigations because it provides an opportunity for more distant acts (of commission or omission) to be assigned causal roles in an accident. Reason's Swiss cheese analogy (1990) also provides this opportunity, but we (like Dekker) believe it assumes that defense failures in the form of 'holes' are visible to the accident participants. However, as is the case with cognitive illusions, the holes are not always visible and the idea that the accident participants should have seen them itself reflects a cognitive bias which Kahneman has referred to as the hindsight illusion. Dekker's failure drift hypothesis provides an opportunity for investigators to consider the failure steps as incremental, imperceptible and insidious, in order to manage the hindsight illusion. That this model is not more widely deployed in accident investigations may also be the result of a cognitive bias and distortion.

In relating the concept of thinking illusions to investigations, we restrict our analysis to four cases or accident contexts, although we contend that many others may be understandable and educative in similar ways. We begin with the Erebus accident.

Erebus

On the 28 November 1979, a DC10 operated by Air New Zealand crashed on the northern slopes of Mt Erebus while conducting a sightseeing flight to the Antarctic. All 257 people on board died instantly. The Erebus accident was first investigated by the office of Air Accidents of the Civil Aviation Division (CAD) of the New Zealand Ministry of Transport, headed by Ron Chippendale. He attributed the cause of the accident to the aircrew descending below the minimum safe altitude of 16,000 ft and continuing the flight below this altitude in poor visibility towards Mt Erebus when they were unsure of their position [13]. Chippendale's report proposed an individual cause: pilot error.

Before the CAD report was published, the New Zealand government commissioned a Royal Commission of Inquiry, headed by Justice Peter Mahon, to more thoroughly investigate the crash. Mahon's findings disagreed with the CAD report and he not only cleared the flight crew of blame but transferred the blame to Air New Zealand, accusing Air New Zealand management of a "litany of lies" [14, p 150].

Mahon's investigation was able to conclude that the weather was fine at the time, atmospheric visibility was 40 km, and Mt Erebus was not shrouded in cloud. Despite this, the pilots who were flying the aircraft did not see the mountain in front of them. They could see a horizon (albeit probably a false one) and were in clear sight of ground and water beneath them, but could not see Mt Erebus.

The Royal Commission of Inquiry found that Air New Zealand altered the course that was programmed into the aircraft's navigational computer without advising the captain of the change. Although this act occurred 6 hours in advance of the accident, Mahon judged this to be the primary cause [14]. Originally, prior to the course being altered, it had them flying down McMurdo Sound instead of over Mt Erebus itself. In sector whiteout conditions, McMurdo Sound looked very similar to Lewis Bay at the foot of Erebus, which they over-flew just before impact. Vette (1999) [15] showed that the visual similarities were such that one or more of the flight crew (mis)interpreted the visible geographical features *as* McMurdo Sound. This uncritical supposition, in conjunction with the whiteout phenomenon that rendered Mt Erebus invisible, allowed them to mistake their true position, and fail to see the mountain before it was too late.

In terms of the history of human factors science, this was significant. Not only did the flight crew not see the mountain, but they had no reason to believe that they *could or would or should* see it. They were unfamiliar and inexperienced with sector whiteout conditions, which provided visual depth perception for only part of their field of view, tricking them into thinking that they could see correctly throughout all of it.

Rather than identify a single cause, Mahon cited ten factors [14, p 157] which contributed to the crash, but for which any one would have prevented the accident. He did not give them equal causal weight. In fact, Mahon judged the primary cause to be the act of the airline in changing the computer track of the aircraft from McMurdo Base to Mt Erebus without telling the aircrew [14, p 158]. But he also uncovered an organisational structure with poor communication and administration procedures. However, all of these contributing factors occurred a few days prior to departure of the accident flight or on the day of the accident itself. In fact, he cited his rationale for deciding on the primary cause because it acted continuously "from the time before the aircraft left New Zealand until the time when it struck the slopes of Mt Erebus" [14, p 158].

This accident rocked New Zealand. Mahon's judgement was challenged by the New Zealand government, which owned Air New Zealand. The New Zealand Court of Appeal found against Mahon and awarded court costs in favour of Air New Zealand. Mahon appealed to the Privy Council, the highest court, as a private citizen but lost. The Privy Council not only supported the Court of Appeal, it also cleared the airline of blame without the corresponding rigor of Mahon's enquiry. This effectively undid much of Mahon's painstaking work and in effect confused the general public. Even to this day, pilots of that era still discuss and may disagree about various causes and issues that the original investigations raised. Erebus also rocked the world. ICAO stated in its *Human Factors Digest No. 10* [16, p 46]

> "The Erebus report... generated violent controversy and remained inconspicuously shelved until recently … In retrospect, if the aviation community --and the safety community at large-- had grasped the message from Antarctica and applied its prevention lessons, Chernobyl, Bophal, Clapham Junction, King's Cross… would not have existed."

Dekker [17] 18, 19, 20] warns of the dangers of *hindsight*, which we now associate with System 1 thinking. Hindsight bias [5, p 201-204] [21] is the propensity, after an event has occurred, to see the event as having been predictable, despite there having been little or no objective basis for predicting it. Dekker's model of failure drift is an explicit attempt to discourage investigators from succumbing to the hindsight illusion.

Failure drift refers to the situation in which a succession of decisions, each flawed in an ostensibly minor way can eventually produce a breakdown on a catastrophic scale. Accordingly, for Dekker, the anatomy of an accident investigation needs to assess if and how more distant decisions, even if minor, might have contributed to an incident's occurrence, even if separated by time and distance.

Considering the concept of failure drift, a different causal profile emerges from the one that Judge Peter Mahon concluded. On reviewing the evidence from both the Peter Mahon [14] and the CAD report [13] we find that soon after flights to the Antarctic began in February 1977, the requirement for pilots to have had Antarctic flight experience prior to flying there was cancelled. We also find that the requirement to maintain a Minimum Safe Altitude (MSA) was gradually relaxed. Initially the MSA was 16,000 ft and then this was relaxed to 6000 ft subject to McMurdo ATC clearance and a radar let down in a segment to the South of Scott base, the latter which Mahon found was not always possible due to bad reception. Later the requirement for McMurdo ATC clearance was also cancelled after the McMurdo NDB stopped being serviced reliably and McMurdo ATC reduced their service from 'control' to 'advisory'. Some of these failure drift steps were approved formally by the airline and regulator and some of them were undertaken informally as a result of decisions by individual pilots, with the consent of the airline. The latter included descent down to 1500 feet. Erebus has a summit elevation of 12,448 ft.

We also find that instructions about the hazards of the sector whiteout illusion were never included in the route briefings and this led to a skill illusion that the pilots were better at identifying and managing the whiteout hazard than they really were. The term 'sector whiteout' refers to whiteout conditions in which only parts of the field of view are subject to whiteout conditions, but which are not clearly or obviously so. Compared to complete whiteout where there are no visual cues, sector whiteout is insidious and misleading. Perceiving a specific spatial layout in sector whiteout conditions can be seen as the result of System 1 operations in the service of perception: that is, ones in which the pilots' expectations and beliefs outweighed, or embellished, information from their eyes. Like the victim of a visual illusion, System 1 offered one perceptual conclusion and no information was available to contradict it. Believing their location was one thing --in clear air over McMurdo Sound-- effectively prevented them from seeing Lewis Bay *as* Lewis Bay, because Erebus had become invisible, even with unlimited meteorological visibility. Kahneman and colleagues have shown similar effects in other contexts: "The measure of success for System 1 is the coherence of the story it manages to create. The amount and quality of the data on which the story is based are largely irrelevant" [5 p 85). Jumping to conclusions, using only the information at hand and not being concerned with the information one does not have, having expectations drive perceptions, preferring coherent simplicity over messy complexity, and similar human foibles are so frequent in so many domains that Kahneman collects them under the acronym, WYSIATI, or *what you see is all there is*.

This skill illusion was probably difficult to correct because of another thinking illusion; the hindsight bias. As the CAD report observed [13 para 1.17.48] "those who have not been exposed to whiteout are often sceptical about the inability of those who have experienced it to estimate distance under these conditions and to be aware of terrain changes, and the separation of sky and earth". This type of scepticism is typical of situations in which accident participants are criticised for not being able to prevent an accident when the perception is by some that they should have been able to. This perception is the hindsight bias or illusion.

So under the failure drift analogy, the prominence of the navigation error proposed by Mahon as the dominant cause, is to some extent moderated by other more serious deficiencies. It is in the consideration of these decisions that Kahneman's analysis also proves useful.

Another thinking illusion of relevance regarding Erebus is what Kahneman terms the *illusion of validity*. [5 pp 209-221,22]. This illusion relates to a work process or system of procedures in which the participants know consciously that the system is ineffective or not valid but they continue to believe in it –or at least act on it—regardless of this knowledge. Investigators who are aware that the seeds of an incident may have been planted far earlier than the incident itself, but remain committed to locating the cause only with the most proximal actors and situation, because that explanation coheres (as both Chippendale and Mahon may have succumbed to different degrees), are falling foul of this illusion.

From Kahneman we can also identify a cluster of cognitive biases which may have played a role in Erebus, on the flight deck or in the investigations which followed. Optimism bias, [5 pp 252-265, 23], illusion of skill [5 pp 216-217] and overconfidence bias [5 pp 261-265, 24] all relate to the difference between subjective assessments of risk or probability, skill or ability, and the objective measures of those skills. They refer to the subjective beliefs we are better at some skill than we objectively are. If asked, each of us might claim to be a better-than-average pilot, or investigator, or spouse. But we cannot *all* be better than average; someone or everyone must be mistaken. We may be good pilots; but does this automatically make us good teachers of or investigators of pilots? This is one way in which overconfidence manifests itself. But it also occurs when people underestimate the risk of failure on a project or overestimate the quality of their actual performance, or convey an unwarranted optimism. Confessions of doubt as to one's skill or ability is not, as Kahneman noted, socially acceptable when one is hired and paid for one's expertise.

Perpignan.

The following has been summarized from the English translation of the official BEA report into this accident [25]. On 27 November 2008, an Airbus A320-232 MSN 2500 registered D-AXLA departed from Perpignan–Rivesaltes aerodrome in France on a 'demonstration' flight. The purpose of this flight was to verify that the aircraft previously leased to XL Airways of Germany was suitable for receiving back by its owner, Air New Zealand (ANZ). The aircraft was piloted by an experienced captain (12,709 hrs) [p 21] and an experienced co-pilot (11,660 hrs) [p 22] of XL Airways. The verifier was an experienced captain (15,211 hrs) [p 23] and airline flight instructor. One of the checks that the ANZ pilot requested was to slow the aircraft close to stall speed in order to verify the aircraft's stall protection system. This relied on the aircraft's Angle of Attack (AOA) sensors working properly. The AOA sensor is a rotating vane mounted on the fuselage of the aircraft which measures the angle between the oncoming airflow and the wing. The aircraft will stall if the angle of attack is too high for a given aircraft weight, speed and altitude. The aircraft has three of these devices each of which produce values to the Airbus computers which accept the values on a two out of three voting system. If one AOA sensor is reading differently to the other two, the flight computer uses the values of the two sensors that agree, even if this value is incorrect. The aircraft system has no way of determining if the two values which agree, are correct. Moreover, the values of each of the AOA sensors were not visible to pilots.

Two AOA sensors iced up and although their values were in agreement, their values were incorrect in a way that endangered the aircraft. This caused the stall protection system to fail which, in turn, allowed the aircraft to set itself a minimum protection speed far below what was needed for the aircraft to safely fly above the real stall speed. As the aircraft slowed, the pilots did not monitor the table of safe speeds that was available to them. Moreover, the aircraft system did not warn the pilots of discrepancies between the three AOA sensors, and did not clearly warn of a possible failure of the stall protection system which was instead indicated as a low priority 'check gross weight' on the MCDU scratch pad. The aircraft stalled and the pilots were not able to recover, resulting in the aircraft crashing into the Mediterranean Sea near Perpignan.

Three days before the flight the aircraft was rinsed with water following a re-paint into ANZ livery. The AOA sensors were not shielded or protected during the water rinsing process. From a simulation exercise alone, the BEA report concluded that this caused water to penetrate the AOA sensor mechanisms which later froze as the aircraft climbed, causing the AOA sensors to malfunction. The report did not consider the possibility that environmental factors, more severe than what the sensors were tested or certified to, could have contributed to water leaking into the AOA sensors. It also concluded that there was a lack of consistency in the airplane cleaning procedure related to rinsing tasks.

The BEA report concluded that the demonstration flight was carried out at too low an altitude to recover in the event of the stall and formal flight test procedures were not properly followed by the pilots. Moreover, it stated that the pilots ignored a low priority warning message on one of the airbus computer displays advising the pilots to 'check GW', meaning 'Gross Weight' of the aircraft.

The BEA report also identified that the demonstration flight did not comply with other procedural requirements for flight-testing the aircraft. This would have required the stall protection test to have been performed at a minimum of 14,000 ft rather than the height of 4,000 ft that was undertaken on the day of the accident. The Airbus test flight procedure would also have required the pilots to have been adequately trained for such a test and for the demonstration flight to have been carried out in more orderly and controlled operational conditions than was possible on the day of the accident flight. To prevent this recurring in the future, the BEA report recommended that EASA require the operator concerned to specify the type of non-revenue flights that it is able to perform.

The BEA report also criticized the pilots' management of the stall recovery process, referring to the poor management of the strong increase in pitch up moment generated by full thrust and the horizontal stabilizer being at the pitch-up stop position. To correct this, the engine thrust needed to have been reduced and the trim wheel needed to have been actioned manually to rotate the horizontal stabilizer to the pitch down position. To prevent this from recurring in the future, the BEA report recommended that EASA, in co-operation with manufacturers, improve training exercises and techniques in order to ensure control of the aircraft in the pitch axis during the approach-to-stall. The BEA report also recommended that EASA undertake a safety study to improve warnings and instructions to crews when flight control systems change during a flight sequence.

Sometime before the Perpignan report was released on 17 November 2010, Airbus altered its stall recovery procedure so that the application of power is applied only after the nose is lowered. Had the Perpignan pilots been trained in this procedure, the accident may have been prevented.

However we believe that it is important for pilots to be given the opportunity to train and practice recovery from not only at the stall buffet, as is the industry standard, but also during a fully developed (deep) stall. Those initiatives do not appear to have been pursued by many airlines. One reason for carrying out fully developed stall training, is not just to train pilots on how to recover from a fully developed stall, but also to demonstrate how difficult it could be, particularly in the unlikely event of speed or (AOA) sensor failures. The stall training would help to better calibrate objective performance and subjective confidence that their pilots have regarding their skills in such situations, and indeed the aircraft capability of unstalling. This is also relevant to our next case study, the crash of Air France flight AF 447.

It is significant that the BEA report does not recommend that the system design of the aircraft be modified so that all AOA sensor values are communicated to pilots in order to improve their situational awareness of the stall protection system, together with high priority alarms should the integrity of the stall protection system be in doubt.

Air France 447.

The following has been summarized from the English translation of the official BEA report into this accident [26]. On 31 May 2009, Air France flight AF 447 departed Rio de Janeiro bound for Paris. At approximately 2 h after departure, while in straight and level flight at an altitude of 35,000 ft, the captain left the cockpit for a rest break, leaving the aircraft in the control of two co-pilots. Approximately eight minutes after this, the pitot probes of some of the airspeed sensors were likely obstructed by ice, causing temporary discrepancies between the speed sensors, which in turn disconnected the aircraft's autopilot, placing the control system in Alternate Law which provides no automatic stall protection. However, this event did not generate a warning on the ECAM identifying the airspeed sensor discrepancies to the co-pilots. Nor did the pilots work through the specified Airbus procedure for managing airspeed discrepancies. The pilots were unable to fully comprehend the situation and lost control of the aircraft. Apparently, they were unable to identify the approach to the stall and despite hearing an audible stall warning and likely experiencing buffeting at onset of the stall, they could not prevent the aircraft from stalling. The captain returned to the cockpit while the stall warning was sounding but was unable to recover the aircraft and the aircraft crashed.

The BEA report acknowledged that the co-pilots had not undertaken any in-flight training at high altitude, either for manual airplane handling or for managing airspeed discrepancies [p 198]. The report also identified an industry-wide deficiency in stall training [pp 185, 200], noting evidence of possible confusion between a high speed buffet and the stall buffet [p 183]. The report also observed that trainees did not understand that during high-level straight and level flight, the angle of attack at cruise and at the stall is very similar (in the order of 1.5 degrees) and did not appreciate the proximity of the stall warning threshold [p 44]. The report recommended that angle of attack values be visible to pilots to improve their situational awareness of proximity to the stall at high altitude. [p 205].

The BEA report also made a startling observation: that the severity of icing to which the sensor probes may be subjected in some climatic conditions may exceed those for which the probes were tested and certified, and that this could lead to a 'temporary' deterioration in pressure measurement [p 40]. Therefore, under these conditions the accuracy of speed measurement will be in doubt.

The report mentioned other airspeed discrepancy incidents and accidents. Twenty eight incidents of airspeed discrepancies were identified and of these, thirteen were studied closely [pp 85, 106]. The maximum duration of airspeed sensor discrepancy was 3 minutes and 20 secs. [p 86] The procedure for managing airspeed discrepancy was rarely utilized by the flight crews who experienced these incidents, though many admitted that managing the situation was difficult. Although the stall warning was triggered in nine of the incidents, many crews considered the stall warning as an inconsistent feature of the incident. Two crews concluded that their incidents were caused by inconsistent AOA sensor readings.

The difficulty of addressing the problem of airspeed sensor discrepancies was well known: between 1998 and 2008 Airbus facilitated ten presentations on this subject [p 148]. The BEA report briefly described three previous accidents caused by airspeed sensor discrepancies on Boeing aircraft. These were not caused by icing but by insects and other issues. In all cases, the aircraft crashed due to the aircraft stalling.

Despite knowledge that icing conditions could be worse than those which the sensors are certified to withstand, the occurrence of three fatal accidents, at least 28 incidents and 10 industry presentations about the problem of airspeed sensor discrepancies, the system of design, training, incident feedback and correction was unable to prevent the crash of AF 447. Information from the incident reports suggest that crews did not find the procedures set by the system helpful, and their procedural inadequacy was confirmed by the comprehensive human factor analysis of the AF 447 BEA report which criticized poor training and inadequacy of cues such as absent or unclear ECAM warnings and unavailable AOA information. Many of the AF 447 BEA recommendations have not been implemented and airspeed discrepancy incidents still occur to this day [27, 28, 29], although without extensive research, we have no way of determining the exact number of these incidents, or their nature.

The AF 447 story has all the hallmarks of an illusion of validity. Despite an overwhelming collection of factual evidence in the form of incident reports questioning the effectiveness, safety and ability of the whole aviation system to address airspeed sensor discrepancies, people still believed –or acted as if they believed-- that it was satisfactory. The circumstances under which System 1 thinking is most useful and least prone to cognitive distortion are those in which the work environment is considered to be of high validity. By this it is meant that (a) the work environment contains valid, specifiable, reliable information as to the system status, and (b) the users have extensive opportunity to use this information under these conditions [30]. The low validity environment that results from flight at high altitudes in transonic flow close to the stall when critical sensors fail does not provide appropriate failure cues to pilots. This, together with an unavailability of adequate opportunities for training, has resulted in a low validity environment. It may therefore have generated discrepancies between objective and subjective skill levels, and/or between optimism and realism, not only in the case of flight instructors but of incident investigators. These distortions, which reside in cognition, have contributed to the illusory belief that the system was and is valid which, in turn, contributes to the system's continued use.

The BEA report into the Perpignan crash [25] which we have briefly discussed and that occurred approximately six months before AF 447 provides some clues as to how investigators perceived critical sensor failures at this time. However, to more fully understand the Perpignan crash, we need to first consider the Bilbao incident [2014] that resulted in a temporary loss of control in the pitch mode due to failure of AOA sensors. Unlike that suggested in the Perpignan report this was not caused by sensor washing following a paint job. The Bilbao incident occurred in November 2014, approximately six years after the Perpignan crash.

The Bilbao incident.

The following has been summarized from the interim report published by the German investigation agency BFU report No. 6X014-14. [31]. On 5 November 2014, an Airbus 321 departed from Bilbao, Spain. Soon after takeoff while still in the climb, the captain noticed indications of the Alpha protection band increasingly unusually rapidly. This meant that the safety margin between the speed at which the aircraft might stall and the actual speed of the aircraft was diminishing. The co-pilot stated that he reduced the rate of climb from 800 ft/min to 500 ft/min using vertical speed mode in order to allow the aircraft to accelerate, although in this autopilot mode unless the aircraft was below its target speed, this would only have resulted in a reduction in thrust, and would not have helped maintain a separation between climb speed and the increasing stall protection speed termed 'V alpha prot'. Soon after this, the co-pilot disengaged the autopilot to lower the nose further. But, unexpectedly, the nose of the aircraft continued to lower and the aircraft persisted in a descent at a rate of 4000 ft/min and at a pitch angle of -3.5 deg. Maximum backward sidestick was required to arrest the rate of descent and this had to be maintained. Airline technicians were contacted and, through the ACARS system, were able to determine that one of the angle of attack sensors was reading differently to the other two. To manage the situation, one of the ADRs (Air Data Reference Units) had to be turned off and this changed the flight control system to Alternate Law, which has no stall protection system, allowing the pilots to resume normal control of the aircraft under Alternate Law. This control action formed the basis of a Flight Operations Transmission (FOT) and Operational Engineering Bulletin (OEB) that was promulgated by the manufacturer after the incident both of which remain in effect.

The investigation concluded that two of the AOA sensors had frozen or jammed at a lower altitude earlier in the climb. When the co-pilot reduced the vertical speed of the aircraft the lower angle of attack generated by this action was not detected. The aircraft continued climbing to a higher altitude/Mach No, approaching the stall threshold of the aircraft (V alpha prot) eventually activating the stall protection which, in turn, lowered the nose of the aircraft into an aggressive descent. The reason why this configuration placed the aircraft above the stall threshold is because of the effects of compressibility and increasing Mach No as the aircraft climbed. The BEA Bilbao report discusses this on pages 6 and 7. A related discussion can be found in the AF 447 report [26 pp 44,150]

From these BEA report discussions it is possible to conclude that the stall characteristics of various Airbus models differ at Mach values above 0.75 [26 p 44].This has implications for training and emergency procedures set up to manage situations when AOA and airspeed sensors fail or freeze over. The AF 447 report also refers to possible confusion on the part of the pilots between the high speed buffet and the buffet that occurs at the stall. The AF 447 report recommends the need for better training to support flight at high altitudes. [26, p 204].

All this suggests that recovery from a fully developed stall at high Mach speeds and high altitudes may be difficult, or at least may be more difficult than is commonly understood. This is concerning. This gap in understanding may encourage the formation of a suite of cognitive illusions regarding pilot skill: illusions of optimism, of skill, of confidence. -that well-trained pilots ought to know it, and therefore do know it. Moreover, pilots will know what do if it occurs, and that their skills will permit success even under these conditions, and therefore they do know how to respond. This suite of distortions can be encouraged by acceptance, rightly or wrongly, that systemic procedures are valid and reliable.

From an industry wide perspective, we may continually believe that the present training regimes and practice schedules for flying at high altitudes in the transonic speed range is acceptable to address sensor failures. But the evidence suggests otherwise. Compounding the cognitive illusions related to skill, optimism and confidence, which pilots are implicitly not discouraged from adopting, we suggest that more systemic or organizational decisions may each contribute a small but significant degree to creating an illusion of validity. The evidence may be ignored because of beliefs that the whole system in the most general sense is robust and piloting skills are sufficient even if they is not. Although the ICAO process for investigating a single accident or incident is systematic, open and transparent, there is not a similar process to facilitate the collation of several similar accidents and incidents. We have neither the space nor the resources to collate all the relevant incidents that have occurred since Bilbao, AF 447 and Perpignan. But as mentioned, we are aware of speed sensor failure incidents occurring in recent years [27, 28, 29].

The Bilbao incident report does not suggest that the AOA sensor failure occurred due to a jet of water from a wash down process, as concluded in the Perpignan report. The Bilbao weather information included thunderstorm activity but this was not exceptional in character. Under 'AOA sensor reliability' the BFU Bilbao report indicates that, in the past, individual AOA sensors had provided inappropriate constant values during a flight. But the report states that the "algorithms and context of these analyses differ and the BFU has no comprehensive knowledge of them." [31 p 11] The BFU Bilbao incident report of interim status advises that "it is part of the further investigation to determine the probability of occurrence of a similar serious accident." However two and a half years after the Bilbao incident report, there is still no update on the Bilbao report; it remains of interim status.

In safety management we like to believe that accidents are normally preceded by incidents from which learning opportunities can be accessed to prevent the accidents. It is therefore useful and necessary to investigate and track incidents as an accident prevention tool. But the more serious Perpignan accident happened first and then the less serious Bilbao incident followed six years later. Moreover, the Bilbao report suggested that several similar incidents had occurred previously and that AOA sensor issues were widely known. Is not something wrong? The Bilbao incident should have been preventable by the lessons available from Perpignan but it was not and this was despite the fact that the Perpignan pilots deliberately went looking for these lessons.

The interim findings of the later Bilbao incident and the comprehensive BEA report into the AF 447 crash highlight questions that were not addressed in the Perpignan report, possibly suggesting that the Perpignan investigation did not take advantage of all the learning opportunities available to prevent further accidents and incidents including the AF 447 accident and the Bilbao incident itself. In the light of these later incidents and the discussion about thinking illusions, it is perhaps useful to now return to the Perpignan report to examine these lost opportunities. This may also shed some light on the type of thinking about sensor discrepancy failures and incidents that existed around the time of the AF 447 crash.

Lost opportunities

The Perpignan accident was the first of the three sensor failure incidents studied in this paper. As it occurred prior to the tragic accident of AF 447, re-examining the Perpignan crash may provide clues as to how investigators considered sensor failures before AF 447; why there had been 28 earlier speed sensor discrepancy incidents with 10 presentations to discuss the problem and why no system improvements had occurred that could have prevented AF 447.

Let us reconsider the hose washing of the Perpignan AOA sensors. Although there was no direct evidence from the wreckage that could positively confirm that the Perpignan AOA sensors had ingested water from the hose washing, the report concluded that this was the case without any doubt. In the light of AF 447 and the Bilbao incident, other alternatives appear credible.

The Bilbao report suggested that there have been many failures of AOA sensors, and without causes related to hose washings. The AF 447 report [26 p 40] also concedes that atmospheric conditions can occur which exceed those for which speed sensors have been qualified to. If this is possible with airspeed sensors, could it have been possible with AOA sensors? However this question was not addressed in the Perpignan report.

The Perpignan report stated that the AOA sensors fitted to the Airbus were certified to a category R of the RTCA DO 160 C standard. Category R [25 p 39] requires the sensor to withstand a jet of water 2.5 m from the sensor with an exit pressure of 200 kPa and the rate of flow of 450l/hr. This is only 7.5 liters per minute and is less than the flowrate of water typically expected from a domestic garden hose. This flowrate of water passing through a hose of 12 mm internal diameter would generate a velocity of approximately 1 m/sec or 2 knots. This appears too trivial for representing a transonic jet passing through areas of heavy tropical precipitation and thunderstorms. It was worthy of a question in the Perpignan report.

The flowrate of water that was applied to the Perpignan AOA sensors was 5,500 l/hr [25 p 71) or 91 l/min. A hose with 12 mm internal diameter would generate a water velocity of 14 m/sec or 28 knots. While significantly greater than the flowrate and velocity used to test the sensors to category R, it still appears insufficient to properly represent driving precipitation that the AOA sensors could be subject to in transonic flight.

It remains possible that hose washing could have contributed to water which leaked into the Perpignan AOA sensors, but in the light of this discussion, other sources of AOA water ingress were also possible. These other causes were from normal operational conditions. It is therefore possible that contrary to the Perpignan report, the 'demonstration flight' by XL airways and Air New Zealand that uncovered the AOA sensor discrepancy problem may have exposed a systemic issue and was not purely the result of standard operating procedures being breached following the painting of the aircraft into ANZ livery. Whether or not the causes and contributing factors were due to environmental effects, sensor defects, or unmasked hose washings, compliance with JAR25.1309 required the aircraft designers to consider and address the consequences of blockages of one, two or three sensors resulting in a false stall warning [25 pp 40, 41). The Perpignan report does not address this apparent shortcoming which the Perpignan pilots unwittingly demonstrated at their own peril. The Perpignan accident also provided an opportunity for the designers to consider the case of an aircraft climbing with frozen AOA sensors, as occurred in the Bilbao incident. Regrettably this does not appear to have been addressed and is another example of a lost opportunity.

The next part of this discussion relates to the approach to stall and the failed recovery. As the pilots approached the stall, the normal stall protection was unavailable to them because two AOA sensors had frozen, causing them to indicate lower values than actual. It is regrettable that the pilots did not refer to the table of speeds for the given aircraft weight in their QRH/FCOM as they approached the stall. But it is also regrettable that the aircraft system, whilst able to produce an ECAM message alerting a sensor heating failure of a given AOA, was unable to indicate the AOA discrepancy values to the pilots. The Perpignan report considered this flight 'atypical' and therefore not conducive to learning safety lessons, [25 p 219]. However the AF 447 report issued at least two recommendations that were relevant to the Perpignan investigation; that the AOA values be indicated to the pilots and that more comprehensive stall training should be provided to pilots. [26 pp 204,205] Had the Perpignan investigation resulted in the implementation of these recommendations, the outcome of the AF 447 may have been quite different. But it is also clear that with AOA information, the Bilbao pilots would also have had the tools to better understand and manage their situation.

Many airline pilots would probably agree that carrying out a stall protection test and approaching a stall below the manufacturer's recommended height without a proper test procedure would be courting disaster. But consider an aircraft flying at 37,000 ft. The AF 447 report advises [26 p44] that the margin between the angle of attack in the cruise and the angle of attack of the stall warning is of the order of 1.5 degrees, or in terms of indicated airspeed, approximately 40 knots. These are small margins in thin air at transonic speeds. In the event of a sensor failure, these margins can quickly disappear and so to, the aircraft's built in protections. And together with the lack of training and routine hand flying practice at high altitude to address these situations, it is possible to see real difficulties in a pilot being able to manage them safely.

Yet we still see this situation as much safer than the Perpignan pilots' improvised flight test. This is an illusion of validity. And like optical illusions, everyone succumbs; it gets investigators as well as pilots.

We conclude the Perpignan analysis with a return to the hindsight illusion. The report discloses that the low priority warning message 'check GW' indicated on the pilots' scratch pad could have alerted the pilots to an AOA sensor discrepancy. However the German BFU noted on the last page of the Perpignan report that many line pilots would not have understood the significance of the message as being applicable to an AOA sensor problem. It is only after exhaustive investigation that the trigger for this MCDU scratch pad message becomes obvious. This is an example of the hindsight illusion being expressed by the investigator in charge and corrected by an accredited representative partner in accordance with the ICAO investigation process.

The factors common to the Perpignan crash and AF 447 are as follows:

1. Critical flight sensors failed to provide correct readings due to the obstruction or formation of ice crystals within the sensor apparatus.
2. Although the sensor types were different, the discrepancies caused inconsistent flight information to be sent to the flight computers. It was necessary for this information to be consistent and correct for the flight computers to maintain control of the aircraft in the minutes leading up to the accidents.
3. The pilots of both accident aircraft lacked a clear display in the cockpit of the sensor discrepancies. In the Perpignan crash, these were AOA sensors; in the AF447, these were airspeed sensors.
4. In both accidents, there was not a straight forward procedure available to the pilots for identifying, evaluating and addressing sensor anomalies.
5. Both the humans and the machines were unable to properly manage the conflicting information from the sensors in the different situations that they encountered.
6. Following the sensor malfunctions, both aircraft stalled after which the stall became fully developed.

7. The flight crews of both accidents were not able to apply effective inputs to recover from the fully developed stall.

So the circumstances that led to the Perpignan accident, are perhaps not so 'atypical' as its report has suggested. As this accident occurred before the AF 447 crash, it provides an indication of thinking that was around at the time leading up to the AF 447 crash. It is possible to see the illusions and biases that discouraged investigators from comprehensively addressing the problems that would likely have been apparent from the 28 speed sensor discrepancy incidents that occurred prior to the AF 447 crash.

It is clear that many of the recommendations that arose out of the AF 447 crash could have been issued as a result of the Perpignan investigation. These include not only the AF 447 recommendations relating to the need for individual AOA sensor values and more comprehensive fully developed stall training but more relevant ECAM messages to be displayed to the pilots [26 p 211] together with improved simulator fidelity [26 p 210]and improved resources for analyzing in-service and operational events [26 pp 190-191, 212]. Had only some of these recommendations been implemented following the Perpignan accident, the outcome of AF 447 could have been prevented.

Conclusions and Suggestions.

The ICAO investigation protocol Annex 13 provides a well-established protocol that facilitates comprehensive and open investigation procedures and conventions for a single accident. The assumption is that the recommendations from this process are sufficient to prevent further incidents or accidents occurring from the learning opportunities provided by the accident or incident under investigation. But this is not the case. The Perpignan accident was one of 29 incidents that preceded AF 447 which offered specific lessons, if only these could have been accessed. Is there a need for a process that methodically collates and interprets common factors and features of many accidents and incidents with similar features or characteristics? Do we need to do a better job of 'joining the dots' across accidents and incidents? Who is charged with the responsibility for doing this at the moment?

It may be a thinking illusion that the existing ICAO investigation protocol which caters for only a single investigation is adequate. We all believe that it is adequate but the evidence suggests that it is not. We concede there have been lost opportunities because we cannot ignore the evidence that there have been similar accidents and incidents preceding the large accident in question, but we all think this is the best we can do. Advances in the digitization of databases, search engine efficiency and statistical and analytic techniques which make information available to System 2 thinking are now more available and should be utilized to collate and assess factors that may be common to a range of similar incidents.

We need an open process for examining several incidents and accidents, for identifying common features and trends linking several accidents, because without the data that this will provide, we cannot justify investing significant resources to improve safety. Also, we need these data to offset our cognitive biases; we have no other device to address our human inadequacies.

We can only improve our systems with the understanding that it takes more than one incident or accident to do so. The evidence that we cannot and must not ignore is that our human condition requires many chances to learn. We are pretending if we think that we can learn after only one fright or accident. We need several. Therefore, if we truly believe in the process of investigation, we need a new process to help us evaluate accidents and incidents collectively. But this will only come with greater sensitivity to the cognitive distortions and biases to which we are all prone.

The distinctions between System 1 and System 2 are well established in the scientific literature. We believe that it is time for these distinctions to be known in applied fields such as the investigation of aviation incidents and related fields.

References

1 Wiener, E. L., & Nagel, D. C. (Eds.). (1988). *Human factors in aviation*. Gulf Professional Publishing.

2 Dekker, S. (2016). *Drift into failure: From hunting broken components to understanding complex systems*. CRC Press.

3 Dekker, S. (2004). *Ten questions about human error: A new view of human factors and system safety*. CRC Press.

4 Miller, G. (1983). Informavores. In F. Machlup & U. Mansfield (Eds.), *The study of information: Interdisciplinary messages* (p. 111-113). Wiley-Interscience.

5 Kahneman, D. (2011). *Thinking, fast and slow*. Macmillan.

6 Gigerenzer, Todd & ABC Research Group (1999). *Simple heuristics that make us smart*. Oxford University Press;

7 Gigerenzer & Gaissmaier (2011). Heuristic decision making. *Annual Review of Psychology*, *62*, 451-482.

8 Gigerenzer (1991). How to make cognitive illusions disappear: Beyond "heuristics and biases". *European Review of Social Psychology*, *2*, 83-115.

9 Haselton, Nettle & Andrews (2005). The evolution of cognitive bias (pp. 724–746). In Buss (Ed.), *The Handbook of Evolutionary Psychology*. Hoboken, NJ: Wiley

10 Ariely (2008). *Predictably Irrational: The Hidden Forces That Shape Our Decisions*. New York, NY: HarperCollins.

11 Senders & Moray (1991). *Human error: Cause, prediction, and reduction*. Hillsdale, NJ: Erlbaum

12 Reason, J. (1990). *Human Error*. Cambridge: Cambridge University Press.

13 Aircraft Accident Report No 79-139; Air New Zealand McDonnell Douglas DC10-30 ZK-NZP Office of Air Accidents Investigation, Ministry of Transport, Wellington. Reproduced by NZ Transport Accident Investigation Commission.

14 Report of the Royal Commission to inquire into the crash on Mt Erebus, Antarctica of a DC 10 aircraft operated by Air New Zealand Ltd 1981..

15 Vette, G., & Macdonald, J. (1999). *Impact Erebus two*. Auckland: Aviation Consultants.

16 ICAO circular 247-AN/148 1993. *Human factors digest No 10*; Document sales unit, ICAO.

17 Dekker (2002). Reconstructing the human contribution to accidents: The New View of human error and performance. *Journal of Safety Research, 33*, 371–385;

18 Dekker (2006). *The Field Guide to Understanding Human Error*. Farnham: Ashgate;

19 Dekker (2011). *Drift Into Failure: From Hunting Broken Components to Understanding Complex Systems*. Farnham: Ashgate;

20 Dekker and Pruchniki (2013). Drifting into failure: Theorising the dynamics of disaster incubation. *Theoretical Issues in Ergonomics Science*, *15*, 534-544

21 Fischhoff, B (2003). "Hindsight ≠ foresight: The effect of outcome knowledge on judgment under uncertainty". Quality & Safety in Health Care. 12: 304–312.

22 Kahneman & Tversky (1973). On the psychology of prediction. *Psychological Review*. 80 (4): 237–251

23 Weinstein & Klein (1996). Unrealistic optimism: Present and future. *Journal of Social and Clinical Psychology*. 15 (1): 1–8.

24 Moore & Healy (2008). The trouble with overconfidence. *Psychological Review*. 115 (2): 502–517.

25 BEA Report; Accident on 27 November 2008 off the coast of Canet-Plage (66) to the Airbus A320-232 registered D-AXLA operated by XL Airways Germany; English translation of the French version. Published by Bureau d'Enquetes et d'Analyses pur la securite de l'aviation civile

26 BEA Final Report; Accident on 1 June 2009 to the Airbus A330-203 registered F-GZCP operated by Air Fance flight AF 447 Rio de Janeiro – Paris; English translation of the French version. Published by Bureau d'Enquetes et d'Analyses pur la seceurite de l'aviation civile

27 AAIB Bulletin 9/2013; Incident on 20 April 2012, involving G-EUXM in the Lambourne hold near London Heathrow airport.

28 Pasztor, Andy; *FAA Issues Safety Directive concerning Airspeed sensors on Boeing 787 Jetliners.* Wall Street Journal (online) New York, N.Y. 31 Mar 2016

29 Serious Incident Investigation Report No 05/2013 Unreliable airspeed Airbus A340-600 Etihad Airways on 3 February 2013, Published by General Civil Aviation Authority, United Arab Emirates, 21 March 2013.

30 Kahneman & Klein (2009). Conditions for intuitive expertise: a failure to disagree. *American Psychologist*, *64*, 515-526.

31 BFU Interim report NO BFU 6X014-14, of incident that occurred on 5 November 2014, at 12 NM NW of Pamplona, Spain; published 17 March 2015 by Bundesstelle fur Flugunfalluntersuchung. www.bfu-web.de