Instrument Failure, Stress, and Spatial Disorientation Leading to a Fatal Crash With a Large Aircraft

Arne Tribukait; Ola Eiken

BACKGROUND: An aircraft's orientation relative to the ground cannot be perceived via the sense of balance or the somatosensory system. When devoid of external visual references, the pilot must rely on instruments. A sudden unexpected instrument indication is a challenge to the pilot, who might have to question the instrument instead of responding with the controls. In this case report we analyze, from a human-factors perspective, how a limited instrument failure led to a fatal accident.

CASE REPORT: During straight-ahead level flight in darkness, at 33,000 ft, the commander of a civil cargo airplane was suddenly confronted by an erroneous pitch-up indication on his primary flight display. He responded by pushing the control column forward, making a bunt maneuver with reduced/negative G_z during approximately 15 s. The pilots did not communicate rationally or cross-check instruments. Recordings of elevator and aileron positions suggest that the commander made intense efforts to correct for several extreme and erroneous roll and pitch indications. G_z displayed an increasing trend with rapid fluctuations and peaks of approximately 3 G. After 50 s the aircraft entered a turn with decreasing radius and finally hit the ground in an inverted attitude.

DISCUSSION: A precipitate maneuvring response can, even if occurring in a large aircraft at high altitude, result in a seemingly inexorable course of events, ending with a crash. In the present case both pilots were probably incapacitated by acute psychological stress and spatial disorientation. Intense variations in G_z may have impaired the copilot's reading of the functioning primary flight display.

KEYWORDS: spatial orientation, spatial disorientation, somatogravic illusion, inversion illusion, graveyard spiral, acute psychological stress, drowsiness.

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In this report we analyze, from a human-factors perspective, a case where the response to a limited instrument failure in a large aircraft at high altitude initiated a sequence of events, leading to a crash. The analysis is based on facts presented by the Swedish Accident Investigation Authority.[8] In particular, we have scrutinized graphs from the aircraft's digital flight data recorder (DFDR), data from the cockpit voice recorder and a 3D-graph of the flight path, obtained via wide area multilateration (a system for tracking aircraft via ground-based radio receivers).[8]

Notably, recorded roll and pitch attitude (**Fig. 1**), obtained from the DFDR, represent the malfunctioning inertial reference unit 1; they were presented on the primary flight display 1 (PFD1) in front of the pilot in command, who was pilot flying. For inertial reference unit 2, which most likely was functioning adequately, there are no corresponding recordings. Based on other flight data, estimates of the real attitude, as presented on PFD2 (in front of the first officer, who was monitoring), have been made for $t < 24$ s; limited knowledge about the aircraft's aerodynamics at high speeds makes such calculations increasingly unreliable beyond this point.[8]

The aim here was to give a detailed account of how the pilots may have experienced the sequence of events, hopefully contributing to our understanding of human behavior in similar situations. Spatial disorientation will be a connecting thought

From the Swedish Aerospace Physiology Centre, Department of Environmental Physiology, Royal Institute of Technology, KTH, School of Technology and Health, Solna, Sweden.

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Address correspondence to: Arne Tribukait, M.D., Ph.D., Swedish Aerospace Physiology Centre, Department of Environmental Physiology, Royal Institute of Technology, KTH, School of Technology and Health, Berzelius väg 13, SE 171 65 Solna, Sweden; arne.tribukait@sth.kth.se.

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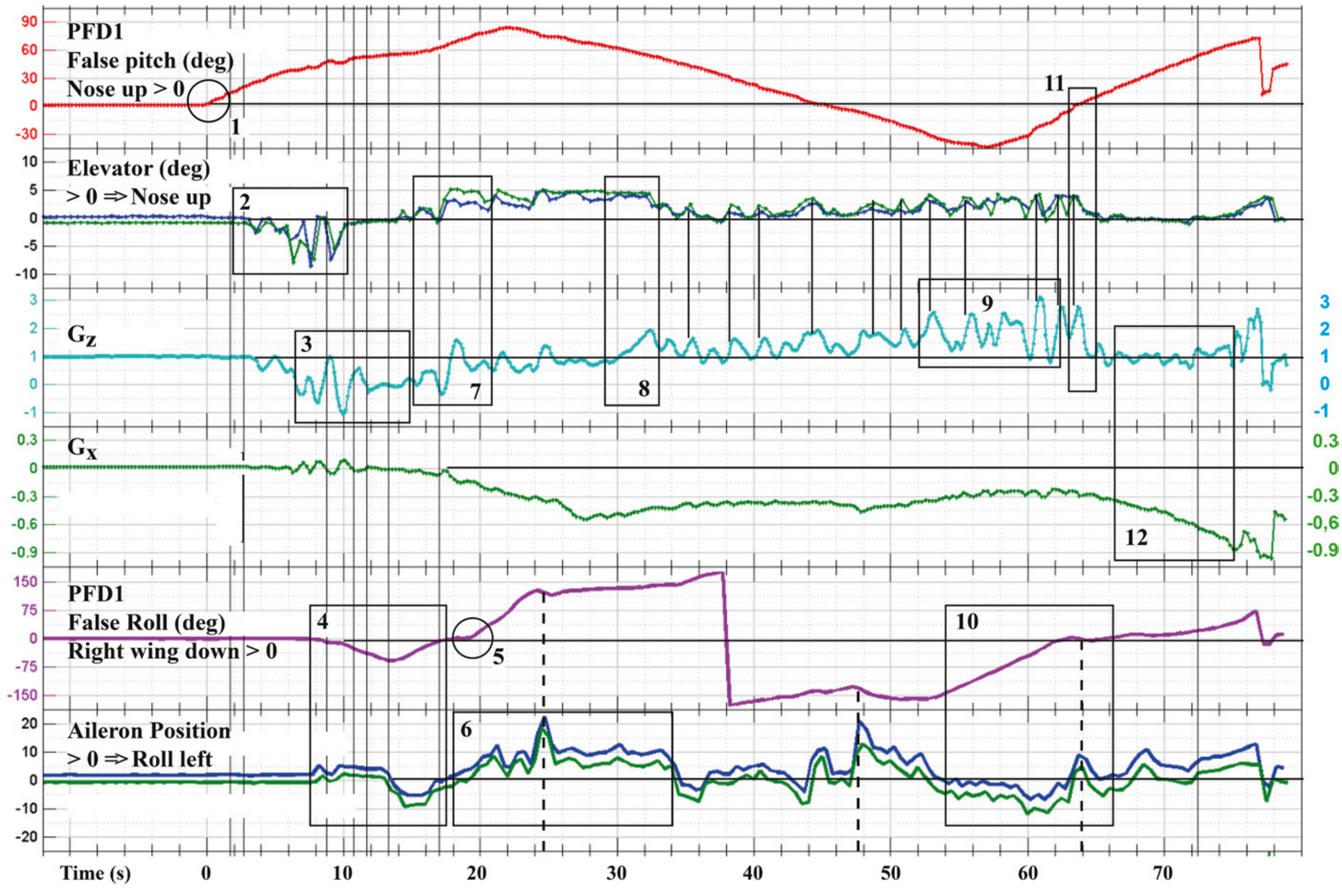

Fig. 1. Selection of DFDR variables (adapted from Appendix 1, Ref. 8). Critical events, phenomena, and relationships are highlighted by circles, squares and lines. Pitch and roll represent the malfunctioning PFD1 (there are no recordings from PFD2, which most likely was functioning correctly). 1) Sudden pitch-up indication. 2) The response of pilot flying with the control column. 3) Reduced/negative G_z. 4) Aileron deflection causing temporary left-roll. 5) Erroneous roll-right indication. 6) Pilot flying tries to correct for indicated roll. 7) Due to nose-down trim pilot flying must pull the control column in order to achieve $G_z = 1$. 8) At t_{30-33} nose-down trim is reduced, making it possible to maintain 1 G_z with elevators in neutral position. 9) Pronounced increase in G_z as the aircraft enters a right-turn; fluctuations might interfere with reading functioning instruments. 10) PFD indicates that the aircraft is approaching level flight from an extreme left-bank; aileron deflections suggest that pilot flying tries to facilitate this roll movement and to stop it at 0°. 11) When indicated pitch is 0° elevators return to neutral position and G_z to 1.0. 12) The situation at t_{63} has similarities with that at t_0, but now pilot flying does not respond to the indicated pitch up; while G_z is constant, there is an increasing negative value of G_x, possibly inducing a sensation of forward tilting from upright position. Continuous vertical lines show how peaks in G_z are preceded by peaks in elevator position. Dashed vertical lines highlight the association between extreme aileron deflections and marked reductions in indicated roll-right rotation.

through the discussion, but also drowsiness and acute psychological stress are important elements.

CASE REPORT

A twin-engine jet airplane (length 26 m, width 21 m, weight 19 tons), had departed from Oslo for a cargo flight to Tromsö. It was a midwinter night with clear weather but there was no moonlight. The aircraft was flying straight-ahead by autopilot at 33,000 ft. Indicated air speed was 275 kn. There was no turbulence.

Pilot flying (PF) had commenced approach briefing and pilot monitoring (PM) was confirming when, shortly after midnight, DFDR recorded a sudden increase in the aircraft's pitch attitude (Fig. 1;1). This erroneous information was presented on PFD1 (in front of PF) but not on PFD2. The discrepancy between the PFDs automatically disengaged the autopilot, generating acoustic warning signals (**Fig. 2**). After 2 s (at t_2) the pitch-up, indicated by PFD1, was 15°, but altitude and speed remained unchanged. PF uttered an exclamation of astonishment and reacted instantaneously by pushing the control column; at t_3, the elevators were deflected in the nose-down direction and the stabilizer was trimmed nose-down (Fig. 1;2). Notwithstanding, the indicated pitch-up increased, exceeding 30° at t_5. In addition, red arrows, calling for a nose-down input, appeared on PFD1 (probably also on PFD2, but pointing oppositely). A high rate of descent followed. G_z (the component of the gravitoinertial force vector acting in the head-to-seat direction) declined; during approximately 10 s it was ≤ 0, with a minimum of -1.0 (Fig. 1;3). In conjunction with transitions between positive and negative G_z, irregular sounds from lose objects in the cockpit were recorded by the cockpit voice recorder. Registered roll displayed a left-banking with a maximum of 50° (Fig. 1;4); acoustic bank-angle warnings sounded and PM said "Turn right." At t_{17}, maximum operating speed (315 kn) was exceeded, activating the overspeed warning. At t_{18}, the aircraft's roll position was again 0°. So far, PFD1 was correctly indicating the roll attitude.

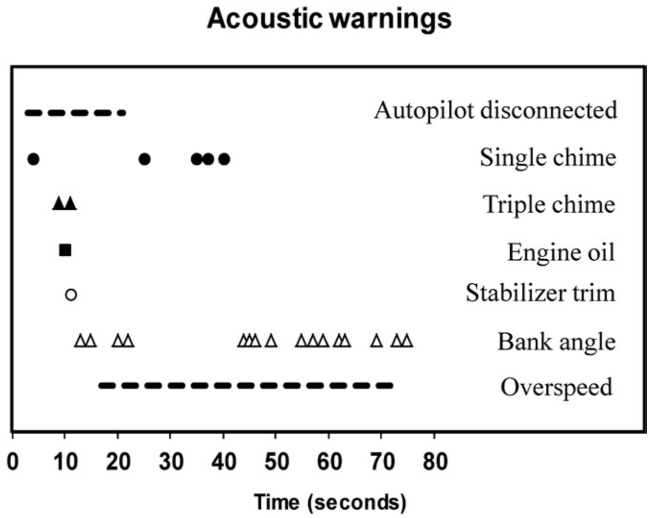

Fig. 2. Acoustic cautions and warnings during the course of events.

At t_{20} PFD1 began to display, erroneously, a rapid right-wing-down roll rotation (Fig. 1;5); exceeding 110° at t_{24}. This indicated roll motion continued, with irregularities, during the remaining course of events (exceeding 400°). At t_{20-23}, bank-angle warnings sounded and PM said "Turn left." During t_{20-34}, DFDR recorded aileron deflections of great magnitude, as for rolling left (Fig. 1;6). The effect was, according to calculations,[8] that the aircraft, whose roll position at t_{20} was close to zero, at t_{24} was tilted left-wing down 140°. At this moment the aircraft was, according to calculations, pitched nose-down by almost 40°, but PFD1 indicated a pitch-up of 80°.

The aircraft's subsequent movements cannot be established with certainty. The interval t_{24-50} is characterized by increasing speed, aileron deflections as for performing left-wing down roll maneuvers, bank-angle warnings, increasing G_z (with pronounced fluctuations) and height loss. The 3-D graph of the flight path does not reveal any deviations from a straight course. At t_{30}, indicated airspeed exceeded the aircraft's maximum design speed (400 kn); the altitude was then 24,000 ft. During t_{30-33} the nose-down trim of the stabilizer was reduced (Fig. 1;8), at t_{44} engine thrust was reduced to idle.

After t_{50} there was, according to the 3-D graph, a right-turn with decreasing radius. During t_{52-64}, G_z was approximately 2, with vigorous fluctuations and peaks of 3 G (Fig. 1;9). The graphs representing the malfunctioning attitude indicator of PFD1, elevators, ailerons and G_z display certain noticeable relationships. PFD1 indicated that the aircraft at t_{54} had a very large left-bank, but that there was a rightward roll rotation. Aileron deflections are compatible with an intention of PF to perform such a movement, with a brief counter-action when indicated roll was 0° (Fig. 1;10). The indicated roll rotation was, in fact, stopped at that very moment. For a short while (t_{63-64}) also indicated pitch was 0°, and PF saw on his attitude indicator that the aircraft was horizontal in pitch and roll. Concomitantly, the elevators returned to the position of straight-ahead level flight and G_z abruptly decreased to 1.0 (Fig. 1;11), remaining nearly constant until the aircraft hit the ground, at t_{77}.

Radar data show that the aircraft's course had been deflected 75° to the right. The impact site was found in horizontal terrain, 722 m above sea level, in a desolate valley. The appearances of the crater, spread of wreckage, and localization of the wings indicate a steep trajectory with the aircraft inverted.

The pilots' calls and exclamations indicate that they initially were astonished and that the level of stress soon became very high. PF asked PM for help several times. PM sent distress calls. There were, however, no rational communication about the situation, and it appears that the pilots never compared the PFDs or checked the standby attitude indicator. In **Table I** the pilots' communication is related to DFDR data. The pilots were exposed to a large number of acoustic cautions and warnings (Fig. 2).

As to the maneuverability of the aircraft at high speeds (for which aerodynamic knowledge is limited), two observations suggest that the aircraft was, in fact, maneuverable until the end. Firstly, peaks in G_z were preceded (with a fraction of a second) by peaks in elevator position (Fig. 1). Thus, variations in G_z were due to activities of the pilots and the elevators were functioning adequately. When the nose-down trim of the stabilizer was reduced at t_{30-33}, G_z increased (Fig. 1;8). The increasing trend of G_z and the fact that G_z was +1 during the last inverted phase implies that the wings gave their usual lift. Secondly, at moments when the ailerons displayed particularly large left-wing-down deflections, there were notable reductions in the roll-right rotation indicated by PFD1 (Fig. 1). Thus, even if inertial reference unit 1 did not provide correct information on the aircraft's attitude it was not insensitive to roll movements, and the aileron deflections had an effect in the direction desired by PF.

DISCUSSION

Several conditions of the present case are known to increase the risk of spatial disorientation (SD): lack of external visual references, possibly reduced wakefulness, stress, instrument failure, and the episode with negative G_z.[7] We will discuss the course of events focusing first on somatogravic illusions and, thereafter, on the significance of drowsiness and acute psychological stress.

The first mechanical event is the response of the pilot flying (PF) to the erroneous pitch-up indication. Why did he respond so rapidly, pushing the control column forward, although there had been no other sensation of change in attitude? If an aircraft maintains constant velocity, throttle and altitude, a pitch up will, however, be accompanied by longitudinal deceleration. The posteriorly directed component of the Earth gravity force will be balanced by an inertial force acting forward. Therefore, the pilot will not receive any vestibular or somatosensory impression of backward tilt.[2] Consequently, it is reasonable to trust the attitude indicator even if you do not have any corresponding bodily impression. It might be argued that a rapid pitch up must generate a tangible increase in G_z. Nevertheless, the autopilot was engaged and PF was active with briefing; if he had not watched PFD1 for a while he might have got the idea of having failed to notice a slow pitch-up rotation.

Table I. View of the Course of Events with Relevant Flight Data Related to Calls and Exclamations by the Pilots.

TIME	CONDITIONS	PILOT FLYING	PILOT MONITORING
13s	Pitch (malfunctioning PFD1) +50°		Come up
	Pitch (calc) -10°, Roll -50°, $G_z \approx 0$		
15s		Come on, help me, help me, help me	Turn right (i.e., *roll* right)
17s	Pitch (PFD1) +60°	Help me, help me	
	Pitch (calc) -30°, Roll ≈ 0°		
18s	G_z: Rapidly increasing		Yes, I'm trying
20s	Pitch (PFD1) +75°, Roll (PFD1) +25° Pitch (calc) -35°, Roll (calc) -10°,		Turn left
	G_z 0.7		
23s	Pitch (PFD1) +80°, Roll (PFD1) +110°		Turn left
	Pitch (calc) -40°, Roll (calc) -105°		
24s	Roll (PFD1) +120°		No
	Roll (calc) -140°, G_z 1		
46s	Bank angle warning		Turn left, turn left
47-52s	Large aileron deflections as for making a roll to the left		
54s		We need to climb, we need to climb	
55s			Yeah, we need to climb
55s	Bank angle warning		
56s			Turn left, turn left
57s	Bank angle warning	No, continue right, continue	
	Roll (PFD1) -100°, decreasing		
59s	Bank angle warning	Continue right	
	Roll (PFD1) -70°, decreasing		
62s	Bank angle warning, Roll (PFD1) 0°	No, help me,	
	$G_z \approx 2$, with vigorous fluctuations	help me please	
63s	Bank angle warning, Roll (PFD1) 0°		I don't know,
	$G_z \approx 2$, with vigorous fluctuations		I don't see anything
64s	Pitch (PFD1) 0°, Roll (PFD1) 0°		I think you are the right to correct
65s	Pitch (PFD1) +10°, Roll (PFD1) 0°	OK	
	$G_z = 1$		
71s	Pitch (PFD1) +45°, Roll (PFD1) +20°		What (!)

For the first 24 s calculated roll and pitch are given in addition to the values indicated by the malfunctioning PFD1.

The second question is similar: Is it reasonable that the pilot did not feel the forward tilt of the aircraft resulting from his movement with the control column? Here, a longitudinal acceleration generates a backward inertial force (**Fig. 3A**) balancing the forward component of the Earth gravity force.[2] In the present case, the longitudinally oriented G_x (Fig. 1) did not deviate notably from the value during straight-ahead level flight until t_{18}, when the aircraft, in reality, was pitched down 25°. Thus, while the pilot observed an increasing pitch up on his PFD, he could not feel any forward tilt.

The pilot's attempt to counteract the indicated pitch up resulted in a curved trajectory with an inertial force directed upwards. The magnitude of this force soon exceeded the Z component of the Earth gravity force (Fig. 3B), and during approximately 10 s G_z was ≤ 0, with a minimum of -1.0. In this situation pilots may experience an illusion of being upside-down,[2,6] hanging in the seat belts while loose objects fall to the ceiling. A plausible response to this inversion illusion is a roll maneuver. In the present case, there was a temporary left-bank with a maximum of 50° shortly after the nadir of G_z. This might have been due to an involuntary movement with the control column. PF asked for help and pilot monitoring (PM) replied: "Turn right"; a corrective aileron deflection followed and the aircraft's roll attitude was soon 0° again. By the end of the period with $G_z \leq 0$, PF asked for help again. The answer was "Yes, I'm trying!" followed by "Turn left, turn left!", although the real roll attitude of the aircraft was 0°. The idea that a corrective roll movement should be performed may have been an effect of perceived weightlessness. Further, PM's reading of PFD2, whose artificial horizon was in the uppermost position, was probably impaired by vigorous variations in G_z.

The situation was aggravated at t_{20} when PFD1 began to indicate, erroneously, a rapid roll-right rotation. PF responded immediately with large left-wing-down aileron deflections. That PFD1 was now indicating 80° pitch-up should, perhaps, have made him reject it, in particular as the overspeed warning sounded. It might also seem strange that PM, whose PFD2 was, most likely, functioning correctly, at t_{20} and t_{23} said "Turn left!".

The pilots had, however, only 2 critical seconds ($\approx t_{18\text{-}20}$) for reflection over the situation since G_z returned from near-zero values. An unexpected period with $G_z \leq 0$ can be stressful and it is not unlikely that a sensation of weightlessness or inversion had a lingering effect on the pilots' spatial orientation. Again, the aircraft was pitched-down 30–40°; the horizon on PFD2 was at its highest level and variations in G_z might have interfered with reading it. Further, pilots may, when confronted with unexpected roll indications, correct in the wrong direction (roll-reversal error).[7] A coincidence that could have strengthened

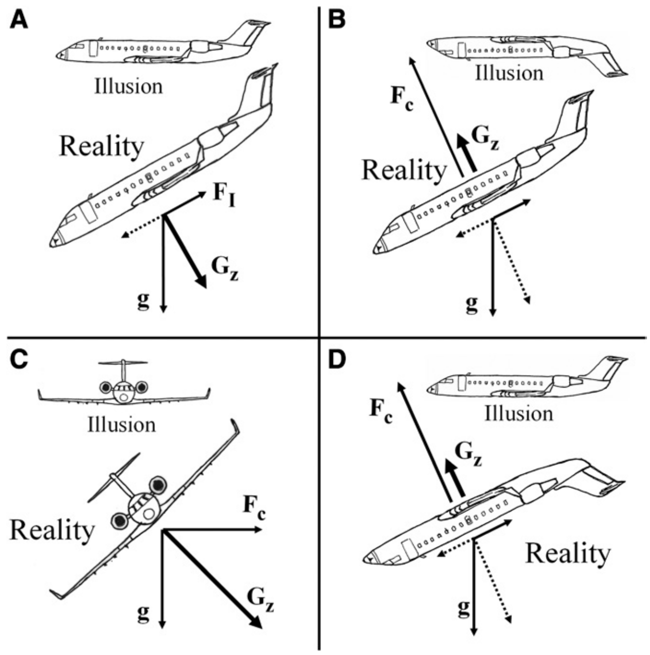

Fig. 3. Four cases of somatogravic illusion, illustrating the difficulties encountered by the pilots because of the equivalence between gravity and inertia. The Earth gravity force is represented by the vector g; the x and z components of g are dotted. Inertial forces caused by longitudinal accelerations are denoted F_I, centrifugal forces F_C. The resultant G vector acting in the pilot's head-to-seat axis is denoted G_Z. A) Illusion of level flight while actually being tilted pitch-down. The forward component of g accelerates the plane; because of F_I the pilot feels as if flying level. B) When the magnitude of an upward F_C exceeds the z-component of g, G_z will be negative (pointing upwards), causing an illusion of inversion. C) During a coordinated turn G_z remains in the pilot's median plane, making it difficult to perceive the direction and magnitude of roll tilt. D) By the end of the course of events, the aircraft was inverted, but since an upward F_C exceeded the z component of g, G_z was pointing in the head-to-seat direction.

the tendency of PF to perform the roll-left maneuver is that the roll-right indication of PFD1 was accompanied by PM's utterance "Turn left!" and an acoustic bank-angle warning.

Simulations of the aircraft's movements during t_{20-24} suggest a 140° roll to the left.[8] This is a strong semicircular-canal stimulus. Why did PF not realize that the indication of PFD1 was in contradiction to the real roll rotation? Firstly, humans underestimate roll angular displacements if the canals are contradicted by graviceptive information.[9] Secondly, vibrations, stress, and PF's attention on PFD1 might have further interfered with his ability to sense that the aircraft was in a rapid roll opposite to that indicated by PFD1. The situation here is analogous to that in the beginning; it can be very difficult to perceive, based on somatosensation and the sense of balance, whether an indicated change in roll or pitch attitude is real or false (Fig. 3C). The pronounced aileron deflections during t_{24-34} make a barrel roll appear likely; to the ground-based observer this maneuver seems dramatic, but because of the positive G_z it might not be perceived by a pilot devoid of visual references.

During t_{50-64} the aircraft entered a right-turn with decreasing radius and increasing G_z. Both pilots realized the necessity of climbing but it appears that they had different opinions as to whether they were in a right-turn or a left-turn. The exclamation of PM "Turn left, turn left!" at t_{56} is compatible with observing that the functioning PFD2 indicated a right-turn; the reply of PF "No continue right, continue!" can be related to the fact that PFD1 now showed that the aircraft was approaching level flight from an extreme left-bank. It thus appears as if none of the pilots had still, after 1 min, compared the PFDs. Mechanically, this phase is reminiscent of the so-called graveyard spiral – if a pilot, flying without instruments, loses visual contact with the ground, he/she is likely to enter a turn with increasing bank angle (Fig. 3C).[7] A pilot realizing the height loss might be tempted to pull the control column, which worsens the situation. Pilots without experience of aerobatic maneuvering may find $G_z = 2$ distracting or physically demanding. When PF at t_{62} asked for help, PM answered "I don't know. I don't see anything!"—a response suggesting that the vigorous fluctuations in G_z made it very difficult to read the instruments.

At t_{63-64} PFD1 happened to indicate that the aircraft was horizontal in roll and pitch. A moment later the elevators returned to the neutral position and G_z declined to 1.0. Apparently, PF was still maneuvering the aircraft guided by his malfunctioning PFD1. Unfortunately, the aircraft's real attitude at this moment deviated sharply from that indicated by PFD1. It seems likely that the aircraft approximately at t_{65} ended up in an inverted position with steeply declining trajectory. Because of the positive G_z, the pilots did not realize that they were upside-down (Fig. 3D). After 5–6 s with $G_z = 1.0$, PM exclaimed "What" and an expletive. It is as if he now, since the fluctuations of G_z had ceased, suddenly realized that PFD2 was indicating that the aircraft was upside-down, strongly contradicting the intuitive impression dependent on the sense of balance and somatosensation.

Two general questions remain. Firstly, why didn't PF postpone his reaction to the erroneous pitch indication for a brief overview of other instruments, for reflection or communication? Secondly, why was it so difficult to regain control over the aircraft during the minute to follow? Drowsiness and acute psychological stress are factors of possible significance.

Sleep restriction can impair several cognitive functions,[10] from attention to the ability of inhibiting automatic responses.[3] Therefore, a drowsy pilot is more likely to respond inadequately to misinterpreted information.[2] Further, the ability of shifting attention is impaired when arousal is low.[5] In the present case, PF was on his fifth consecutive evening/night shift, PM on his fourth. No circumstances had motivated particular vigilance or frequent instrument scanning. Thus, it is possible that the pilots, due to sleep restriction and low stimulus level, were less prepared to cope with unexpected problems.

Following the initial maneuvering response the pilots must have experienced intense psychological stress, a state where cognitive functions can be severely impaired. Under normal conditions, the prefrontal cortex plays a pivotal role not only in attention and thinking but also in the regulation of action, including our ability to inhibit inadequate responses of instinctive or habitual character.[1] During acute stress, activation of more primitive brain structures leads to release of dopamine and noradrenaline in the prefrontal cortex. This rapidly reduces the activity of the prefrontal cortex, while brain regions controlling habitual motor responses are stimulated. Acute psychological stress thereby switches the control of behavior from the top-down cognitive level to the bottom-up level mainly constituted by sensory cortices and subcortical structures. The scientific study of these mechanisms was, in fact, initiated by observations, during World War II, that skilled pilots often crashed their planes due to mental errors when exposed to the stress of battle.[1]

It cannot be excluded that PF's first response to the initial pitch-up indication was governed by a stress-induced shift in the regulation of behavior. Then, instead of rejecting PFD1, he was soon focusing all attention on the deceiving attitude indicator, becoming engaged in an intense struggle for attaining satisfactory indications. The instrument's weird functioning made this an extremely difficult and stressful task, further impairing his capability of shifting attention. The term "coning of attention" denotes a stress-induced restriction of the field of attention, which can make even experienced pilots focus entirely on one single instrument.[7]

The period with negative G_z is another critical event, impairing spatial orientation and, possibly, cognition. Pronounced variations in the magnitude of the G-vector are physically tangible and probably stressful to pilots without experience of aerobatic flight maneuvers. The many warning signals, as well as the movements of lose objects in conjunction with changes in the sign of G_z, may have contributed to the level of stress.

To summarize, a limited instrument failure in a large airplane at high altitude led to a fatal crash within slightly more than one minute. Save for the lack of external visual references, flight conditions were benign. Notwithstanding, certain predisposing factors and critical events dramatically impaired the pilots' control over the aircraft. Obviously, acute psychological stress and SD were closely interrelated. Although the pilots must have experienced the problems from different viewpoints, they were both highly incapacitated throughout the course of events. This is a strong indication as to the difficulties of the situation, including the forcefulness of brain functions likely to direct human behavior during unexpected or threatening conditions.

After fatal accidents there is, typically, a lack of evidence regarding the pilot's experiences. Therefore, factors like SD might not be mentioned in accident investigation reports even in cases with no other possible explanation. Presumably, this underreporting impedes development of overall flight training techniques, hence impairing the prevention of SD accidents.[4] In the present case SD was discussed in the report (we were consulted during the investigation) but not mentioned as a cause or contributory factor. According to the Swedish Accident Investigation Authority "The accident was caused by insufficient operational prerequisites for the management of a failure in a redundant system."

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Authors and affiliations: Arne Tribukait, M.D., Ph.D., and Ola Eiken, M.D., Ph.D., Swedish Aerospace Physiology Centre, Department of Environmental Physiology, Royal Institute of Technology, KTH, School of Technology and Health, Solna, Sweden.

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