Enquiry into the Risk of Cognitive Impairment Due to G Forces

A review into whether or not there is a risk to civil aviation safety from cognitive impairment in pilots experiencing low level G forces at levels, and for durations, likely to be experienced in commercial and recreational, civil air operations

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After graduating from The Medical College of St Bartholomew's Hospital, London Dr Evans qualified as a general practitioner, then worked for British Airways before moving to the UK Civil Aviation Authority (CAA). She was Head of the CAA's Aeromedical Section from 1999 until 2005 and then the CAA's Chief Medical Officer and Head of the Medical Department until 2019.

She chaired the European Union Aviation Safety Agency's (EASA) Medical Group that drafted the European Union aviation medical requirements and was the founder and Chair of the European Aviation Medical Assessors' Council. In 2015 she was a member of the EASA Task Force on Measures Following the Accident of Germanwings Flight 9525. She has been a member of the International Civil Aviation Organization Medical Provisions Study Group, Deputy Chief Examiner for the Diploma in Aviation Medicine, Vice-Chair of the UK Specialty Advisory Committee in Aviation and Space Medicine and a member of the Air Transport Advisory Board of the UK Aviation Confidential Human Factors Incident Reporting Programme and is an Honorary Civilian Consultant Adviser in Aviation Medicine to the Royal Navy, Member of the International Academy of Aviation and Space Medicine and Fellow of the Aerospace Medical Association.

Dr Evans' research interests include incapacitation, mortality and cancer risk in aircrew. She has published on incapacitation and cardiovascular risk in commercial pilots, fitness to fly after chemotherapy and malignant disease, insulin-treated diabetes, colour vision assessment of pilots and medical considerations for spaceplane operations.

Prof David Gradwell BSc, MB ChB, PhD, FRCP, FRCP Edin, FFOM (Hon), DAvMed, FRAeS

Emeritus Professor of Aerospace Medicine, King's College, London, UK

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Prof Gradwell joined the Royal Air Force (RAF) after graduating from the University of Dundee and three years working in NHS Scotland. Appointed a consultant in 1993, he became the Head, Altitude Life Support Division at the RAF Institute of Aviation Medicine, Farnborough and then the Officer Commanding, Aviation Medicine Wing at the RAF Centre of Aviation Medicine, Henlow. He led the practice of the RAF specialists in Aviation Medicine, the delivery of associated research and operational assessments and directed the teaching of Aviation Medicine to military and civilian medical staff and the aircrew of the RAF and Royal Navy. He was the Chief Examiner for the Diploma in Aviation Medicine and a Visiting Lecturer in Physiology for King's College, London and the University of Surrey. International appointments included Visiting Lecturer at the US Air Force School of Aerospace Medicine, San Antonio, Texas, Senior Lecturer for the Flight Medicine Institute of the Luftwaffe, Fürstenfeldbruck, Germany and for the Polish Air Force Institute of Aviation Medicine, Warsaw, Poland. He is the Senior Editor of the standard aviation medicine textbook, Ernsting's Aviation & Space Medicine 5th ed. His principal research interest has been in the physiological effects of acute exposure to high altitude and the means by which protection from those effects may be delivered. He was appointed Professor of Aerospace Medicine at King's College, London in 2012 and set up a National Health Service specialist aeromedical clinic at St Thomas' Hospital, London in 2013.

Mr Chris Kidd BEng (Hons)

Founding Director, Astral Aviation Consulting Ltd, a company delivering aviation consultancy services across a range of aviation disciplines including training, governance, regulation, safety, human factors and just culture and providing support to the UK General Aviation sector.

Chris Kidd gained his Private Pilot's Licence at Dundee Airport in 1994 prior to completing a degree in Mechanical Engineering and commissioning into the RAF in 1998. Following Officer training, he completed flying training, gaining his wings in October 2000 prior to being selected to fly the Tornado GR4 which he flew in multiple exercises and operational deployments. In 2005 he became both a Qualified Flying and Tactics Instructor, and a Qualified Weapons Instructor on the Hawk T1 teaching the advanced, applied flying disciplines of Basic Fighter Manoeuvres, Air Combat Manoeuvring, air to ground weaponry and Simulated Attack Profiles to both student pilots and other members of staff. He returned to the frontline in 2008, once again flying the Tornado GR4.

Whilst posted to a non-flying role in 2012 Chris took this opportunity to complete his Commercial Pilot's Licence before returning to RAF Valley as the commanding officer of 208 Squadron in 2015 where he was responsible for the advanced flying and tactical training of student pilots prior to them moving on to fly the Typhoon. During this time he again flew and taught advanced, applied flying disciplines on the Hawk T1. In 2016, he was appointed as the RAF Aerobatic Team (RAFAT) Senior Operator, responsible to the Duty Holder for safety assurance, the regulatory control environment and the regulatory controls for the Red Arrows. He flew extensively with the RAFAT including supporting and flying with them on their 2017 Far East Tour. In this, his last RAF role, he also learnt to fly a helicopter at RAF Shawbury.

Chris joined the CAA in 2017 where he was appointed as the Senior Manager Operations and Air Display Regulation responsible for the safety and regulation of all UK air displays, the regulation of Civil Aviation Publication 632 aircraft and Safety Standards Acknowledgement and Consent. He subsequently moved into the role of the Head of Regulation and Oversight for the General Aviation Unit before leaving in 2019.

During his career Chris has amassed a total of just over 3,200 flying hours of which 2,900 are either operating or teaching on fast jets.

Prof David Newman MB BS, DAvMed, MBA, PhD, FRAeS, FAsMA, FACAsM, FAICD

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Member of the Board of Editors for the journal *Aerospace Medicine & Human Performance*

Prof Newman did his undergraduate medical training in Victoria, Australia and, as a member of the Royal Australian Air Force (RAAF), undertook postgraduate aviation medicine studies in the USA and UK. Whilst Chief Instructor at the RAAF Institute of Aviation Medicine, RAAF Base Edinburgh, South Australia, he worked towards a PhD on *Postural Baroreflex Adaptation to Repetitive +Gz Acceleration in Pilots of High Performance Fighter Aircraft*. Following his career in the RAAF he was appointed as a Senior Research Fellow to the Faculty of Biomedical and Health Sciences, RMIT University and then as Head of Research in the Department of Aviation, Faculty of Science, Engineering and Technology, Swinburne University prior to joining Monash University, where he founded the Aviation Medicine Unit and became Professor of Aviation Medicine. He is now Visiting Professor of Aerospace Medicine at King's College, London. He is the founder and director of a company that advises on transport accident and safety investigations and the design and delivery of aviation medicine and human factors training programmes. He has written two books on acceleration, 'High G Flight: Physiological Effects and Countermeasures' and 'Flying Fast Jets: Human Factors and Performance Limitations' in addition to publishing more than 50 papers and technical reports many of which are on topics related to acceleration physiology and aviation accident research.

Prof David O'Hare BA (Hons), PhD

Professor of Psychology, Department of Psychology, University of Otago, New Zealand

Associate Editor, Pacific Rim, The International Journal of Aviation Psychology (now International Journal of Aerospace Psychology),

Regional Editor for Australasia, The International Journal of Human Factors and Ergonomics

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After obtaining a PhD from the University of Exeter, Prof O'Hare lectured in Psychology at the University of Lancaster and the Open University and then moved to the Department of Psychology at the University of Otago in New Zealand. His research expertise includes cognitive science, occupational health and safety, psychology, cognition, motivation and performance. He has undertaken an extensive number of international research projects with expert decision making and performance, including pilot decision making, being central to many of these. He acts as a consultant in human factors training and examinations and has acted as an advisor on accident investigation and for the Advisory Board of the New Zealand Confidential Aviation Safety Reporting System. He was a co-founder of the New Zealand Ergonomics Society (now NZ Human Factors and Ergonomics Society).

His research on aeronautical decision making and flight safety has been funded by numerous agencies including the Federal Aviation Administration and National Aeronautics and Space Administration. He has published and edited books on human performance in general aviation and flight deck performance and contributed chapters to books on aeronautical decision making, cognitive ability determinants of elite pilot performance and cognitive task analysis. He has published extensively on aviation psychology, human factors and aviation safety.

Mrs Anna Vereker MA (Hons), CPsychol, Aviation Psychologist (EAAP), MRAeS

Human Factors Programme Specialist, UK Civil Aviation Authority

Registered Psychologist, General Scope (NZ), New Zealand Psychologists' Board (2008-2015)

Chartered Occupational Psychologist, (from 2016) including Psychometric Test User (Occupational and Personality), British Psychological Society and Health and Care Professions Council

Registered EuroPsy Psychologist European Federation of Psychologists' Associations

Aviation Psychologist European Association for Aviation Psychology

Anna Vereker has a Master of Arts degree in Psychology with a focus on the Industrial /Occupational (I/O) field. Her thesis was on 'Person-Organisation fit with respect to personality and behavior in a medium-sized New Zealand Company'. Anna has worked across a broad range of I/O, Aviation Psychology and Human Factors domains. After a period with the New Zealand Police in selection (non-uniformed), she was commissioned into the Royal New Zealand Air Force as a Psychology Officer where she supported operational deployments, training development and delivery, assessment, selection, individual readiness and wellness and advised military operations. During this time, she attended the short course on the Fundamentals of Accident Investigation at Cranfield University. Subsequently she joined NATS in Scotland and became a Senior Human Factors Specialist. During this period, she conducted eye tracking and electroencephalogram research with live-operation air traffic controllers. Finding objective measurement options remains a research interest for her. Since joining the CAA as a Human Factors Programme Specialist in 2018, she has worked within strategy and policy sections to embed robust human factors considerations through the regulatory approach and across industry.

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Executive Summary

Introduction

On 22 August 2015 a Hawker Hunter T7 aircraft (G-BXFI) crashed on the A27 in West Sussex, England, during an air display at the Shoreham Air Show, causing the deaths of 11 people and injuring 12 others plus the pilot.

The Shoreham pilot was subsequently prosecuted and found not guilty of gross negligence manslaughter. During the criminal trial it was suggested that the G forces (+Gz) the pilot had been exposed to may have affected his cognitive abilities and hence his ability to fly the aircraft.

The Civil Aviation Authority (CAA) considered that it was necessary to conduct a review of the potential risk of cognitive impairment in pilots experiencing G forces at levels, and for durations recorded by accident investigators as having been experienced by the Shoreham pilot that are also likely to be experienced in commercial and recreational, civil air operations and to assess any consequent safety risk to civil air operations and the public.

The CAA set out in its Terms of Reference that the Review Team was to consider whether the nature, degree and duration of acceleration experienced by the Shoreham pilot poses a risk for the safety of other civilian flights where a pilot may experience the same nature, degree and duration of acceleration as in the accident flight.

The objective of the review was to determine whether any basis could be found in the scientific literature to support the proposal that cognitive impairment occurs with lower level G forces below that known to cause an alteration of consciousness.

Whilst the Review Team was informed by events at Shoreham, including access to the published accident investigation reports and material disclosed to the CAA by the pilot, many of the documents relied upon during the criminal trial were not available. The lack of access to this material is not considered to have materially affected the review process or the ability of the team to fulfil the objective in delivering their conclusions as set out in this report. The Review Team focused on the body of scientific literature that is currently available and did not analyse the 2015 Shoreham accident.

The Review Team included experts in the specialist fields of aviation medicine, acceleration physiology, altitude physiology and aviation psychology. Information was gathered from the scientific literature and aviation authorities, experts and publications.

Background Information

The review has been written for the CAA Board in the knowledge that the audience is likely to be broader. The aim has been to provide sufficient explanation of terms used and the physiological processes for a general readership whilst preserving academic content for the aviation medical and scientific community. In particular, the chapters on ‘Acceleration’ and ‘Hypoxia’ provide an overview of the physiological processes relevant to this review.

G Force

When the body is subject to an applied acceleration in the foot to head direction, as when a pilot undertakes a banked turn or loop in an aircraft, a force is experienced in the opposite, head to foot direction, commonly referred to as +Gz. The Air Accidents Investigation Branch (AAIB) provided estimates of G force experienced by the Shoreham pilot which reached ‘a maximum’ of +4 Gz during the loop manoeuvre ‘and remained above 3g [+3 Gz] for about 4 seconds’. Other estimates did not exceed these levels or durations which therefore formed the basis for the review.

Whilst alteration of consciousness is a recognised effect of high levels of G force analysis of the effects of high levels of G forces on civil pilots is not within the scope of this review. Where reference is made in this report to almost or actual loss of consciousness (known as A-LOC and G-LOC respectively) it is done for comparative purposes i.e. to emphasise the distinction between the effects of low level G force and those experienced at higher levels of G force.

Physiological Responses to G Force

The effects of G force on the body depends on the rate of onset, duration and maximum level of G. The most immediate effect is one of changes in hydrostatic pressure within the circulatory system and there is redistribution and alteration of blood flow. There are autoregulatory mechanisms that assist in maintaining an adequate perfusion to the brain and sensors (baroreceptors) in the main vessels supplying the brain that will be triggered to effect changes in the peripheral circulation if the pressure in the arteries reduces and blood flow to the brain is compromised for more than a few seconds. At low levels of G a pressure gradient is maintained across the blood vessels supplying the brain with oxygen compared with those returning to the heart and this differential acts as a siphon to draw blood through the cerebral vessels.

There are some changes in blood flow and ventilation to different areas of the lungs with +Gz that result in a reduction in the oxygen bound to haemoglobin on the blood cells; this is known as reduced oxygen saturation. At low levels of G force this effect is not marked as oxygen is released from blood cells when it arrives in tissue with a low oxygen tension which serves to preserve the oxygen supply.

There is an interval of 4-6 seconds before loss of consciousness occurs even with a complete failure of blood flow to the brain because of the oxygen reserve that is within the brain.

Effects of G Force on Vision and Consciousness

Impairment of visual function can start to occur at relatively low levels of acceleration, typically in the +3 to +4 Gz range, as the blood supply to the eye has to be able to match the pressure within the eye.

+Gz-induced impairment of cerebral function can occur with high G, beyond +4 Gz, presenting as a wide array of cognitive, physical, emotional and physiological signs and subjective symptoms, known as almost loss of consciousness or A-LOC. G-LOC results when, on exposure to high G, the blood pressure becomes insufficient for blood flow through the brain. A-LOC and G-LOC do not occur at low G levels in experienced pilots and are not, therefore considered in any detail as part of this review.

G Tolerance and Protection

Individuals can tolerate different levels and durations of G force from one day to the next and compared with other individuals. Low levels of G are generally well tolerated for periods of many minutes, even up to an hour.

Protection against the physiological effects of G force can be achieved through the use of a straining manoeuvre (an extra +3 Gz), wearing an anti-G suit (an extra +0.5 Gz uninflated, +1 Gz pressurised) and other means such as body positioning.

International and Military Experience

A considerable number of international aviation organisations were contacted, for the purpose of this review, to ask for any information or concerns they may have been aware of relating to cognitive impairment with G force. No respondents described cases that fitted the criteria of acceleration-induced cognitive impairment at relatively low G force. The RAF Centre of Aviation Medicine informed the review that following consultation with international colleagues and experts ‘no consulted expert or organization recognises the existence of a low-G impairment syndrome’ and that ‘the total unanimity and unambiguous nature of expert opinion and long-term international experience offers significant reassurance’.

G Forces in Civil Aviation

In civilian commercial flying operations, pilot exposure to excessive G force is not encountered during normal flight, with any exception, for example during turbulence, being limited to less than a second. No circumstance was found of exposure to more than +2.7 Gz.

Most recreational pilots will be taught how to recover from a spin and pull up out of a dive where they will experience some increase in G. Many will also be taught basic aerobatics including how to undertake an inside loop. An aerobatic training syllabus is followed prior to undertaking solo aerobatics and some pilots may progress to enter aerobatic competitions.

Only three accidents were identified through the UK National Occurrence Reporting Database (1976 to January 2020) that included comment on G force experienced during the flight; one was due to G-LOC, one was likely to have been related to a medical condition and the other was the accident at Shoreham in 2015.

The only type of civilian flying where a significant amount of G, above +2 Gz, is regularly experienced is display flying and aerobatic, particularly competition aerobatic, flying.

Whilst flying aerobatic manoeuvres in an air display a pilot can be exposed to a high level of G, often sustained for many seconds, and may include negative G manoeuvres in their routine which can exacerbate subsequent physiological changes from +Gz.

A review of all aircraft types on the UK General Aviation Civil Aircraft Register was undertaken to establish the amount of +Gz of which each is capable. Each type was categorised according to its +Gz capability and likely operating environment.

Cognitive Performance with Low G Force

A pilot flying an aircraft needs expert decision-making abilities, memory and other cognitive processes to maintain safe flight, especially when also exposed to the physiological stresses of an increase in +Gz.

Few studies have been undertaken on higher mental functions with low G force. In part this is due to the difficulty of accurately measuring these functions in a +Gz environment. Varied study designs, methodologies, differences in choice and experience of participants, individual differences between participants and levels of Gz have been employed in studies and this lack of consistency makes comparisons challenging. The majority have been undertaken in the centrifuge and their applicability to the in-flight environment is not known. The duration of G exposure representative of a real-world scenario is generally too short to enable a quantitative measurement of cognitive function. It is not considered currently possible to obtain performance measures on the centrifuge during ‘short’ duration +Gz exposures of 1-3 seconds. Even up to and around 20 second exposures there are severe restrictions on what can be measured and measurements of motor performance become difficult due to mechanical disturbance which affects manual dexterity, hand-eye co-ordination, speech, control inputs and reaction times. The available research does not mimic the likely brief conditions that general aviation pilots may experience; most aerobatic sequences involve a series of short-duration accelerations in succession and this is very difficult to simulate in circumstances where valid and reliable cognitive testing can be done.

Eight studies are described that investigated lower +Gz levels, between +2 to +5 Gz. The results suggest that cognition may be affected at levels even below +3 Gz when the G force is sustained for more than 3 minutes, but exactly how performance may be degraded, and after what period of time, is not easily identified in the research. It may be difficult to differentiate between impairment of performance due to +Gz and fatigue. It may also be difficult to distinguish errors in reading aircraft instruments from a mechanical effect on visual or auditory acuity, or sensory perception or response issue from an effect on cognition. Being distracted or preoccupied with G forces could have significant effects on the resources available for all cognitive processes. In one series of studies up to +5 Gz, of eleven tasks only one, short-term memory, showed any decrement at the +3 Gz level. This suggests that a range of other cognitive tasks show some resilience at levels up to +5 Gz.

It is the prolonged nature of these experiments, with exposure to sustained acceleration, that is the key point and means that it may not be valid to translate the results of these studies to G force exposure that is much shorter in duration.

The majority of identified studies ran very small numbers of participants and would have consequently lacked statistical power to detect any real differences. In many studies, the information needed to assess the significance of any findings, such as means and standard deviations, was not reported. Even where statistically significant differences in performance have been reported, these may be within diurnal variation and the practical, operational significance of the performance decrement may be limited.

Aerobatic Flying

Pilots who fly aerobatics, whether for recreation, sport, display or competition need to apply not only their basic flying skills but in addition manage to accurately fly the aerobatic routine and cope with the physical demands of G forces.

It has been widely acknowledged since the very early days of aviation that if an individual exceeds their G tolerance their performance could be affected and flight safety could be compromised. Some medical conditions predispose pilots to low G tolerance. Pilots intending to undertake aerobatic manoeuvres need to be aware of the possibility of altered consciousness due to G force that can compromise motor and cognitive function.

Hypoxia

The wide range of methodologies used in the studies of cognitive performance and inadequate oxygen in the tissues (hypoxia) made it difficult to make many comparisons between the literature on acceleration and cognitive performance, and hypoxia (without acceleration) on cognitive performance.

Day-time flying of well-practised aerobatic manoeuvres at very modest altitudes has not been reported in the literature reviewed to pose specific hypobaric hypoxic challenges.

Conclusions

Risks from G Force

All flying carries some degree of risk to the participants and to people on the ground in the vicinity of the flight. Good cognitive function is essential for piloting an aircraft in normal flight conditions.

When a pilot is exposed to increased G forces additional physiological stresses may be encountered. Training and experience are required to be able to make decisions and solve problems rapidly whilst remaining alert to cues in their environment to maintain a high standard of flying and the necessary executive functions at all times. Aerobatics require a high degree of mental agility and concentration.

Any manoeuvres which expose the pilot to more than +3 Gz for a sustained duration of longer than four seconds have a potential risk of adverse physiological effects. There are a very small number of references to G tolerance below +3 Gz in the literature. These appear mainly to relate to novice subjects not previously exposed to high G and are likely not to be representative of the G tolerance of experienced pilots.

A pilot flying an aircraft capable of a high G onset rate should be aware of the potential for alteration of consciousness without premonitory visual symptoms and, when flying with a rapid G onset rate, to keep strictly to flying bursts of a few seconds of high G with recovery time in between to ensure consciousness is maintained.

The risk of A-LOC or G-LOC is relatively low in civilian display flying which can be planned to ensure the G onset rate is kept at a level where warning signs of grey out give sufficient time to offload G and/or execute an escape manoeuvre where applicable. Planning of manoeuvres should have sufficient contingency to allow for offloading G if vision becomes impaired.

Manoeuvres that first expose a pilot to negative G and are then followed by a high positive G load (push-pull) pose a particular risk for alteration of consciousness.

Aerobatic pilots should be aware of their personal G tolerance level and undertake training on mitigations that protect against the effects of G force.

Cognitive Impairment from Low G Exposure

Capturing quality performance measurements in response to a highly transient phenomenon such as +Gz is challenging and it is considered not currently possible to obtain performance measurements during short (approximately 3 second) exposures at +2 to +3 Gz so the evidence does not and could not exist.

Cognitive impairments become evident in well-trained healthy participants at around +5 Gz with some changes setting in as low as +3 Gz albeit that these have only been demonstrated in studies with sustained G and are unlikely to be of practical importance.

Cognitive function seems to be largely protected at low to moderate G levels, especially with low onset rates. Notwithstanding the impairments that can occur with sustained exposure at lower levels, the average human can tolerate up to +4 Gz with little cognitive compromise.

There is no evidence to support the existence of cognitive effects prior to a level of G where grey out or blackout affects vision.

In the absence of direct evidence there remains the possibility that some aspects of pilot performance could be affected at levels of +Gz lower than those associated with effects on vision and consciousness, though these may only relate to longer durations of exposure. It is not possible to state from the data available whether any of the impairments would have occurred at much shorter durations than those reported in the literature.

There is no evidence to suggest that cognitive effects can be demonstrated at low levels of G force when experienced for the short period of time associated with aerobatic displays.

The overwhelming weight of available scientific evidence does not show any demonstrable, practical and meaningful cognitive impairments under +4 Gz that would point to impaired flight safety.

The Review Team concludes that there is no identifiable risk of cognitive impairment in civil pilots experiencing G forces at levels, and for durations, consistent with those stated by accident investigators as having been experienced by the Shoreham pilot.

This review makes 7 recommendations which may be considered by the CAA.

None of the recommendations are considered to be urgent safety recommendations.

Abbreviations

Abbreviations	
AAIB	Air Accidents Investigation Branch
AGS	Anti-G Suit or Anti-G System
AGSM	Anti-G straining manoeuvre
A-LOC	Almost loss of consciousness (or Acceleration-induced near-loss of consciousness)
AME	Aeromedical Examiner
ANO	Air Navigation Order
BBMF	Battle of Britain Memorial Flight
CAA	Civil Aviation Authority
CAP	Civil Aviation Publication
CBF	Cerebral Blood Flow
CO_2	Carbon Dioxide
CPP	Cerebral Perfusion Pressure
CRT	Continuous Recognition Task
DA	Display Authorisation
DAEs	Display Authorisation Evaluators
ECCAIRS	European Co-ordination Centre Accident and Incident Reporting System
EASA	European Union Aviation Safety Agency
EU	European Union
FAA	Federal Aviation Administration
G-LOC	G-induced loss of consciousness (or Acceleration-induced loss of consciousness)
Gno	Normal Operating G
Hb	Haemoglobin
KIAS	Knots Indicated Airspeed
LAPL	Light Aircraft Pilot’s Licence
MAA	Military Aviation Authority
MAP	Mean Arterial Pressure
MEP	Multi Engine Piston
mmHg	Millimetres of Mercury
MORS	Mandatory Occurrence Reporting Scheme

Abbreviations	
NHS	National Health Service
NIRS	Near-Infrared Spectroscopy
NTSB	National Transportation Safety Board
O_2	Oxygen
OBOGS	On Board Oxygen Generating System
PBG	Pressure Breathing for G
pCO_2	Partial pressure of Carbon dioxide
PhD	Doctor of Philosophy
RAF	Royal Air Force
RAFAT	RAF Aerobatic Team
RAF CAM	Royal Air Force Centre of Aviation Medicine
rCBF	Regional Cerebral Blood Flow
rSO_2	Regional Cerebral Oxygen Saturation
SaO_2	Oxygen Saturation level
SEP	Single Engine Piston
SERA	Standardised European Rules of the Air
TUC	Time of Useful Consciousness
US	United States of America
USAF	United States Air Force
Vne	Velocity Never Exceed

Glossary of Terms and Definitions

+Gz. A lower case ‘z’ is used to describe G force acting in the vertical direction. Head to foot inertial G force is termed ‘+’ or ‘plus’ G force and in the opposite direction ‘-’ or ‘negative’ G force.

Acceleration is the rate of change of velocity of an object where velocity describes both the rate at which an object is travelling and the direction of travel. In this document the term ‘acceleration’ is used as a synonym for ‘long duration acceleration’. Long duration acceleration acts for a period of longer than one second whereas ‘short duration acceleration’ acts for a period usually less than 1 second and is associated with impacts.

Air Accidents Investigation Branch is the UK government organisation responsible for the investigation of civil aircraft accidents and serious incidents within the UK, its overseas territories and crown dependencies.

Aircrew and **pilot** tend to be used interchangeably in this report as in the civilian world it is very rare for a non-pilot to act as aircrew. Some of the studies referenced differentiate between pilots and non-pilot aircrew.

Blackout is complete loss of vision.

Cognitive impairment is a change in an individual’s capacity to acquire, interpret, process or otherwise utilise information.

g is the acceleration on the body due to the earth’s gravity.

G force is the resultant effect on the body from an applied acceleration and is expressed as a multiple of the Earth’s gravity. It refers to any level of acceleration above or below gravity and is expressed in ‘Gs’.

G onset rate is the rate of change of acceleration in G per second (G/s).

Grey out is a perception of darkening or dimming of the outer visual fields.

Hypoxia is inadequate oxygen supply for normal tissue function.

Ischaemia is inadequate blood supply for normal tissue function.

Low G vs High G. There is no accepted definition of low G or high G. ‘High G’ tends to be used when referring to +4 Gz and above and ‘low G’ below this level but there is no threshold described in the scientific literature and ‘high G’ is sometimes used to mean anything above +1 Gz.

Oxygen saturation is the percentage of haemoglobin that is combined with oxygen (the oxyhaemoglobin) relative to the total haemoglobin in the blood.

Oxygen tension (also known as **oxygen partial pressure**) is the partial pressure of oxygen in a liquid.

Partial pressure of a gas is the pressure that a single component of a gas mixture would exert if it alone occupied that total space.

pH is the acidity or basicity of a solution.

Sustained G tends to refer to acceleration maintained for a duration of at least several seconds but there is no accepted definition in the scientific literature and it may vary from one paper to another.

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Preface

The review has been written for the CAA Board in the knowledge that the audience is likely to be broader. The aim has been to provide sufficient explanation of terms used and the physiological processes for a general readership whilst preserving academic content for the aviation medical and scientific community.

The CAA reserves the right to re-open this review if further relevant information or material evidence becomes available that was not available at the time the review was concluded.

All spellings in this review are UK English unless they are direct quotes from published material or international organisations in which case the original spellings are retained.

Chapter 1
Introduction

Background

1.1 On 22 August 2015 a Hawker Hunter T7 aircraft (G-BXFI) crashed on the A27 in West Sussex, England, during an air display at the Shoreham Air Show, causing the deaths of 11 people and injuring 12 others plus the pilot. The Air Accidents Investigation Branch (AAIB) undertook an investigation of the crash and published its report on 3 March 2017.[1]

1.2 The pilot was subsequently prosecuted for gross negligence manslaughter and on 8 March 2019 the jury at the criminal trial returned not guilty verdicts on all counts. It was suggested that the pilot may have been subject to a physiological effect during exposure to varying levels and duration of G forces affecting his cognitive abilities which led to a reduced ability to operate the aircraft safely.

1.3 The criminal trial highlighted a perceived risk to civil aviation safety from pilots who suffer from cognitive impairment due to low levels of G forces they experience during flight.

1.4 Consequently the CAA considered that it was necessary to conduct a review of the potential risk of cognitive impairment in pilots experiencing G forces at levels, and for durations recorded by accident investigators as having been experienced by the Shoreham pilot that are also likely to be experienced in commercial and recreational, civil air operations.

1.5 The CAA Board set out Terms of Reference for the review in August 2019 and the review commenced in October 2019 (**Appendix A**).

1.6 This review does not comment on potential causes of the 2015 Shoreham accident or the subsequent investigation by the AAIB. The AAIB original and supplementary reports were used to provide the Review Team with information about the accident and the flight profile of the accident aircraft.

Aim of the Review

1.7 The CAA set out in its Terms of Reference that the Review Team was to consider whether the nature, degree and duration of acceleration experienced by the Shoreham pilot poses a risk for the safety of other civilian flights where a pilot may experience the same nature, degree and duration of acceleration as in the accident flight.

1.8 The objective of the review was to determine whether any basis could be found in the scientific literature to support the proposal that cognitive impairment occurs with lower level G forces (+Gz) below that known to cause an alteration of consciousness.

1.9 Cognitive impairment refers to a change in an individual's capacity to acquire, interpret, process or otherwise utilise information.

1.10 This review seeks to determine whether this suggested physiological effect has any consequences for civil aviation in the UK and whether any operational or regulatory action needs to be taken to safeguard the public and those involved in such aviation activities.

Scope

1.11 This review is not a re-investigation of the crash that occurred on 22 August 2015, nor does it seek to apportion blame on any party. Its sole purpose is to determine whether a risk of cognitive impairment exists with exposure to the G forces likely to have been experienced by the pilot prior to the accident at Shoreham. All regular civil aviation activities, both commercial and recreational, were considered as part of the review to determine whether there is a consequent risk to flight safety.

1.12 Acceleration forces due to impacts, vibration and buffeting were not considered relevant to this review and were therefore out of scope.

1.13 As the review does not relate to the individual circumstances of the pilot involved in the accident, the experts did not request permission to access or consult the pilot's medical file or flying records.

1.14 Military aviation activities are out of the scope of this review.

Levels of G Force in Scope

1.15 The AAIB produced a broad estimate of the accident flight profile in its original Aircraft Accident Report stating that 'a high g load was not present at any point in the left turn preceding the entry to, or in the upward half of, the accident manoeuvre. The peak g force calculated for the turn was 2.7 g…'[1] It was noted that 'action camera recordings appeared to show that throughout the flight the pilot was conscious and that the aircraft was responding to his control inputs'.

1.16 The AAIB undertook a further review between June and October 2019 to determine whether additional information they had been asked to consider contained new and significant evidence of cognitive impairment.

1.17 The AAIB confirmed verbally to the CAA on 14 October 2019 that the levels of G that had been derived for the Supplementary Report (which had not yet been published) were not significantly different from the figures they had originally derived and their findings did not change the original report. Thus the experts utilised the acceleration estimates in the original report as the baseline for their work.

1.18 The AAIB published its Supplementary Report in December 2019 which included more detailed estimates of acceleration experienced by the pilot in the manoeuvres preceding the accident based on additional modelling techniques.[5]

1.19 The ‘Summary of Gz analysis’ in the AAIB’s report describes the +Gz exposure as follows:

> ‘The additional modelling indicated that +Gz during the positioning turn was briefly about 3.8 g, four seconds after the start of the positioning turn, falling within three seconds to approximately 2.2 g, then rising slightly to a level predominantly around 3 g before falling again to around 1g over the final six seconds of the turn.
>
> The review also estimated +Gz exposure in the first part of the loop. This indicated that a maximum +Gz of 4 g occurred about five seconds after the start of the manoeuvre and remained above 3 g for about 4 seconds. The +Gz load then reduced in a linear manner to a value of approximately 1.6 g some four seconds later.’

1.20 The Supplementary Report also estimates that in the first part of the loop ‘The G-onset rate peaked at 0.8 g/s.’

1.21 The scope of this review encompasses levels of G above which physiological symptoms attributable to G forces greater than gravity alone can be experienced and below those associated with Almost-loss of consciousness (A-LOC) or G-induced loss of consciousness (G-LOC).

1.22 Video evidence cited in the AAIB reports, but not seen by the Review Team, suggested that G-LOC had not occurred in the accident flight. G-LOC was therefore considered out of scope. It is acknowledged however that G-LOC is associated with failure of cognition and its physiological mechanism is explored where appropriate.

1.23 The review is of the physiological effects of G force (+Gz) greater than that of gravity so the physiological effects of G force less than that due to gravity are considered out of scope.

1.24 +Gz onset rate is considered where appropriate but calculations of +Gz onset rate in specific aerobatic aircraft require aerodynamic calculations that are outside the scope of this review.

UK Civil Aviation Activities

1.25 UK civil aviation encompasses a wide range of aviation activities involving both fixed wing (aeroplanes) and rotary wing (helicopters). As well as commercial air transport there is a significant volume of other commercial activities and leisure flying.

1.26 The UK has an active flying display community and many recreational pilots undertake aerobatics that exposes these pilots to levels of +Gz not experienced in commercial air transport operations.

1.27 All UK civil aviation activities are within the scope of the review.

Availability of Material

1.28 The bundle of documentary evidence and many documents cited during the criminal trial were not made available to the Review Team.

1.29 On 27 August 2019, the CAA wrote to the AAIB, Sussex Police, the Crown Prosecution Service and the pilot seeking disclosure of material potentially relevant to this review, including expert reports and any research, studies, theses, tests, experiments, academic publications or other similar material. All parties confirmed their willingness to assist the review by providing potentially relevant material but indicated that there were various legal restrictions on the disclosure of much of the material, including those arising from Regulation (EU) 376/2014, the Criminal Procedure and Investigations Act 1996 and an earlier High Court Order of Mr Justice Edis restricting the dissemination and use of protected material. The AAIB further confirmed that much of the material they held was specific to the investigation of the accident involving Hawker Hunter G-BXFI at Shoreham in 2015 though they were able to provide a list of academic references potentially relevant to the review. The pilot also subsequently provided material to the review.

1.30 The cockpit image recording cited in the AAIB reports was not available to the Review Team.

1.31 The Review Team was able to determine that, despite not having access to much of the evidence submitted to the Court for the purposes of the criminal trial, it would not be necessary to take steps to obtain that evidence in order to fulfil the review objective. This decision was reached after consideration of the overall objective, the availability and analysis of relevant, available scientific literature and information available to the Review Team from the accident investigation reports.

1.32 The lack of access to the protected material is not considered to have materially affected the review process or its conclusions.

1.33 The CAA reserves the right to re-open this review should any relevant new publications or evidence that is considered to be material to the scope of this review become available.

Chapter 2
Methodology

First Stage – Collation of Relevant Material

Background Material and Accident Reports

2.1 Background information was obtained to provide context for the review. This included the AAIB report on the Shoreham accident (AAIB report 1/2017) and the AAIB Supplementary Report (1/2019).[1,5]

2.2 The AAIB provided the citations of the scientific and academic literature that they had used in the preparation of their reports (**Appendix B**).

2.3 Flight profile information, which was necessary to understand the levels and duration of G forces to which the accident pilot was likely to have been exposed, was obtained from the original and supplementary AAIB reports.[1,5] It is acknowledged that the levels of G in these reports were estimates, however, in the context of the review, as it was necessary to consider all levels of G above 1G but below levels known to be associated with G-LOC, this was not considered to be an issue.

2.4 The CAA's Flight Operations Department was asked to obtain Flight Data Monitoring information to enable an overview of the levels of G force encountered in both fixed wing and rotary commercial aviation.

2.5 An expert in high-performance, fast jet aviation and the governance and regulation of air displays was engaged to provide data about the performance of all aerobatic aircraft on the UK General Aviation Civil Aircraft Register to identify all those with high G capability and to act as a specialist reviewer.

2.6 The CAA's UK National Occurrence Reporting Database was interrogated for specific reports of accidents and incidents that were concerned with pilot loss of consciousness or almost loss of consciousness as a result of G force experienced during flight.

Scientific Literature

2.7 The first stage of the review entailed forming the question to be answered and collating relevant scientific literature. It was decided that a formal systematic review was not appropriate as the volume of papers identified by the methodology of a systematic review was likely to prove unwieldy and the key papers should be readily identifiable through specific literature searches. It was considered that by engaging acknowledged experts in the specialist fields of aviation medicine, acceleration physiology, altitude physiology and aviation psychology the vast majority of relevant papers would be identified.

2.8 It is difficult to obtain unpublished literature and the Review Team acknowledges the difficulties associated with referencing unpublished literature, particularly as it represents lower scientific credibility in the hierarchy of evidence. The team therefore concentrated on obtaining peer-reviewed papers published in scientific journals.

2.9 Some of the information obtained had been published as an institutional report, guidance issued by a specific organisation or an advisory circular; for these types of publications the level of peer review was sometimes unclear. Much of the early work on acceleration was performed by military or governmental institutions and the reports produced had a specific circulation rather than being published in the open literature. These references can be identified by the publishing institution to which they are attributed in their citations in the reference list which serves to distinguish them from externally peer-reviewed papers. Other potentially non-peer-reviewed literature that was consulted included articles published on the Skybrary web site and in Aerospace, the journal of the Royal Aeronautical Society.

2.10 Electronic searches for potentially relevant papers, publications, and reviews were undertaken using PUBMED, PsychSource (EBSCO database), Google Scholar and other internet search resources using combinations of the following keyword search terms:

- acceleration induced loss of consciousness
- acceleration induced near loss of consciousness
- acceleration and aviation
- almost loss of consciousness
- pilots
- aircrew
- acceleration
- GLOC

- Gz and aviation
- +Gz
- hypoxia and aviation
- cognitive impairment
- cognitive testing
- psychological testing
- cerebral physiology
- cerebral perfusion

2.11 A number of papers were highlighted by the Review Team as being significant as the review progressed and these then yielded further potentially relevant papers.

2.12 Papers that were reviewed but have not been specifically cited in this report are listed in **Appendix C**.

2.13 Some papers were available from searches previously undertaken as part of the CAA's Air Display Review.

2.14 Standard reference textbooks, mainly published in the UK or US, covering aviation medicine and aerospace physiology were consulted and are listed as references.[17,88,99,192]

2.15 The closure of library facilities in March 2020 due to the Covid-19 pandemic meant that some older papers, only held in hard copy in archives, were not available. The Review Team managed to obtain all but two of the papers from the reference list provided by the AAIB. A very small number of other papers were also unobtainable but none of these were thought to be of key importance to the review.

Consultation with Other National Aviation Authorities and Institutions

2.16 A total of 38 national aviation authorities and aviation regulatory bodies were contacted to inform them that the review was being conducted, explain the reason for, and purpose of, the review and to enquire whether they had any experience of cognitive impairment in a pilot subject to lower level G forces below that known to cause an alteration of consciousness (**Appendix D**). They were specifically asked for any experience of such a phenomenon in aeromedical research, commercial or recreational flying, accident investigation reports or safety reviews and were asked to share any information, data or analyses with the Review Team. The organisations were chosen according to their close links with the UK, whether they were English speaking and whether their country had produced literature relevant to the review.

2.17 The Royal Air Force Centre of Aviation Medicine (RAF CAM) contacted the Review Team with their view as to the existence of a low G cognitive impairment syndrome including opinion from international colleagues.

2.18 Some external parties asked for specific information to be considered as part of the review. These references are listed in **Appendix E**.

2.19 The CAA members of the Review Team reviewed all the abstracts of papers that had been identified to determine which were relevant. External experts were then asked to check the list, to ensure that all relevant papers had been captured. They were also asked to provide the citations of any other papers they considered should be reviewed.

2.20 At the start of the review, the Review Team did not have access to the written evidence provided to the Court for the purposes of the criminal trial by the medical expert witnesses, the medical evidence submitted by both the Crown Prosecution Service and the Defence or any other evidence related to the actions of the pilot during the accident flight, such as cockpit image recordings.

2.21 At a later stage some of the oral evidence taken from expert witnesses during the criminal trial was considered in conjunction with the AAIB accident reports and information disclosed to the CAA by the pilot in order to determine whether any of the underlying evidence would be relevant to the review.

2.22 Ultimately the Review Team relied upon the data provided in the AAIB original and supplementary reports and focused on the central topic of cognitive impairment due to G forces with a view to fulfilling the objective and producing a report for the CAA Board to enable the members to decide whether further action is warranted to both protect the public and improve flight safety.

Second Stage – Review of Literature

2.23 Members of the Review Team read and analysed the identified literature and described their findings. Individual chapters of the draft report were sent to internal and external experts for comment and review.

2.24 As the review progressed it became clear that the evidence provided to the Court described in the Terms of Reference would not become available to the Review Team. It was determined that for the purposes of this review it was not necessary to seek access to potentially protected material not already publicly available or made available through the coronial inquest. The AAIB reports provided an estimate of the acceleration levels experienced by the pilot during the accident flight. The Review Team determined this was credible source information, sufficient for the purposes of considering the general issue of the potential for cognitive impairment with low levels of G force without reference to the material relied upon for the purpose of the trial.

Third Stage – Peer Review and Publication of Report

2.25 Once the drafting was completed it was distributed to all members of the Review Team and one additional internal expert for peer review.

2.26 The CAA's Group Director, Safety and Airspace Regulation, as sponsor of the review, also provided input prior to the report being published.

2.27 Amendments were agreed and made prior to the publication of the Final Report.

Chapter 3
Acceleration

Introduction

3.1 In aviation some aircraft are capable of producing an acceleration (positive or negative) that will lead to the application of forces that can exert substantial physiological effects. At a constant speed these effects may not be observed, such as when travelling rapidly but at a constant velocity in a car or train. In these situations the body is exposed to effects similar to those experienced when stationary and the effects of linear forces will only be felt when accelerating or decelerating. Aircraft have the capacity to make turns that generate radial acceleration at a constant speed and pilots and passengers in high-performance aircraft will feel the effects of radial acceleration in this situation. These accelerative forces are commonly expressed in multiples of the force of gravity experienced on the Earth.

Acceleration and ‘G Forces’

What is Acceleration?

3.2 Acceleration is defined as ‘the rate of change of velocity of an object’ where velocity describes both the rate at which an object is travelling and the direction of travel.[113]

3.3 The most commonly experienced acceleration, familiar to all of us in everyday life, is that due to the Earth’s gravity (expressed as ‘g’). In this case, the body is experiencing a force towards the centre of the Earth.

What are ‘G Forces’?

3.4 When we are subject to an applied acceleration, this is expressed as a multiple of g (the Earth’s gravity). The resultant effect on the body is referred to as ‘G force’. The expression ‘G force’ is used throughout this review as this is the term with which most pilots are familiar. The normal environment for a person on the Earth’s surface can thus be described as an applied acceleration equal to the Earth’s gravity, or 1 G (1 multiple of the force of the Earth’s gravity). Expressing acceleration as multiples of the Earth’s gravity is intuitive, as the force generated by the Earth’s gravity is familiar to everyone. Multiples of this force can be readily understood, i.e. a 3 G acceleration is simply 3 times what is routinely experienced by a person on the Earth’s surface in daily life.

Direction and Magnitude of G Force

3.5 The force producing the acceleration is in the opposite direction to the sensation of its effect.

3.6 The acceleration most commonly encountered by pilots in flight is experienced as a head to foot inertial G force. This is the sensation experienced in response to a radial acceleration where the pilot's head is directed to the centre of the circle being described. This vertical G force in the head to foot or foot to head direction is known, by convention, as the 'z' axis. Pilots are subjected to higher levels of Gz force depending on the aircraft they fly and how that aircraft is operated. The other axes that can be encountered are the front to back (or back to front) 'x' axis and the side to side 'y' axis. However, while take off in a conventional aircraft will produce some increase in +Gx, and landing may give rise to -Gx. Gx and Gy forces are much less physiologically relevant for the purpose of this review.

3.7 The accepted nomenclature for a head to foot inertial force is a positive ('+') G force. A force in the opposite direction is termed a negative ('-') G force. G force in the head to foot axis is sometimes referred to as 'vertical G' by pilots. Negative G force is also called 'push' and positive G force is called 'pull' as this describes the action on the control column or stick that the pilot makes to initiate the manoeuvre that creates the acceleration.

3.8 Negative Gz is encountered less often in flight than positive Gz and is generally sustained for only short intervals. Negative Gz arises during a radial turn when the aircraft is inverted to the radius of the turn. Aircraft are commonly not designed to be exposed to the same value of negative G as they are to positive and are not flown to the same multiples of accelerative forces in both directions. Exposure to -Gz is potentially significant, however, as it is understood to potentiate the effects of any subsequent immediate exposure to +Gz. This is known as the 'push-pull' effect.[113,275]

3.9 There is no accepted definition of low G or high G. Colloquially 'low G' tends to be used when referring to up to +4 Gz and 'high G' as +4 Gz and above but there is no threshold described in the scientific literature that differentiates between these ranges and 'high G' is even sometimes used to mean anything above +1 Gz.

Acceleration in Flight

3.10 Pilots are exposed to G forces when flying whenever they change the speed or direction of travel of the aircraft. This may occur when taking off, landing, undertaking a banked turn or an aerobatic manoeuvre. An aerobatic manoeuvre is defined in Schedule 1 of the Air Navigation Order 2016 as including 'loops, spins, rolls, bunts, stall turns, inverted flying and any other similar manoeuvre intentionally performed by an aircraft'.[6]

3.11 In a banked turn or loop a pilot is exposed to centrifugal force from the radial acceleration produced by the aircraft. The lift generated by the aircraft's wings tends to pull it towards the centre of the turning circle and the resultant G force is the inertial force pushing the pilot in the opposite direction i.e. the aircraft is being pulled towards the centre of the circle whilst the pilot is being pushed into their seat by the resultant inertial G force. It is the inertial G force that is perceived by the pilot.

3.12 All G forces in this review refer to positive G force in the z axis unless otherwise specified.

Acceleration Physiology

3.13 The Earth's gravity exerts a downward force on the body which influences its physiological systems i.e. the way the body systems work. These effects include pressure gradients in the circulating blood down the length of the body. This makes it essential that there are structures and processes in place to facilitate the circulation of the blood around the body despite the influence of gravitational force. Examples in the circulation are the valves found in the veins of the limbs and the siphoning effect of normal respiration on blood returning to the heart (the venous return). The distribution of blood in the lungs is also influenced by normal gravitational force and is affected by posture. Sudden changes in posture can, in some vulnerable individuals, even cause fainting (syncope) as the normal flow of the circulation may be interrupted for a short time.

3.14 The pressure in the arteries supplying blood to the brain 'forces' the blood that is pumped out of the heart by each heart beat against gravity up to head level. This pressure maintains blood flow through the carotid and vertebral arteries which supply the head and the cerebral vascular bed that supplies the brain.

3.15 When subject to an increase (or decrease) in +Gz there is the potential for adverse effects on the body. With a very rapid increase in G leading to a high G level there can be an abrupt cessation of blood flow to the head and the brain.

3.16 The G forces caused by acceleration are important as they cause a number of physiological changes, in particular redistribution of blood and alteration of blood flow. These effects are well known, have been extensively documented in the medical literature, experienced by pilots and taught to student pilots since the earliest days of human flight.

3.17 Large commercial aircraft are generally flown so as to maintain an approximately 1 Gz force on the occupants (i.e. a normal, routine G exposure). Military fast jet aircraft, and some high-performance aerobatic light aircraft, are capable of generating significantly greater levels of Gz and can be flown in such a manner that the pilot and/or crew may be exposed to higher levels of Gz. These higher G forces can have physiological effects on the heart and circulatory (cardiovascular) and breathing (respiratory) systems and cause deleterious consequences. Aerobatic light aircraft can generate high Gz levels but these are rarely sustained as the aircraft does not have the power available to do so.[158,192] Military combat aircraft are more likely to have the thrust to sustain high Gz-generating manoeuvres.

3.18 An explanation of much of the effect of Gz on human physiology can be derived from considering the body as a fluid-filled entity. The force of the acceleration influences the pressure within the fluid. At +1 Gz the heart exerts a force during contraction (systole) that ejects blood around the circulation. For a seated individual the pressure in the arterial blood vessels above the heart is lower than within the heart. This is related to the hydrostatic effects on the fluid column involved. Similarly the arterial pressure below the heart becomes greater with increasing vertical distance from the heart. Blood returning to the heart through the veins has to move ‘uphill’ against the pressure gradient, making the role of valves in the limb veins (to prevent backflow) and the siphoning effect of reduced intra-thoracic pressure during inspiration essential to keep blood flowing through the circulation.

3.19 When the seated occupant of an aircraft is exposed to G force greater than +1 Gz the associated force is detected as a downward pressure, increasing the force applied by the buttocks on the seat. As +Gz increases the body feels increasingly heavy and actions such as lifting an arm requires more and more effort.

3.20 For a comprehensive, general overview of the physiological effects the reader is referred to Ernsting’s textbook of Aviation and Space Medicine and Gillingham’s 1988 paper.[88,104]

Cerebral Blood Flow

3.21 The brain is very sensitive to the interruption of a continuous supply of oxygen by the blood and the initial response to an increase in G force is to protect the head level blood pressure to preserve the oxygen supply. The blood flow through the brain, the Cerebral Blood Flow (CBF), is normally high relative to the mass of the brain tissue and generally fairly constant through a wide range of arterial blood pressures. Despite this there are some regional variations within the brain to direct blood flow to active local areas. The cerebral perfusion pressure is the difference between the pressure in the blood vessels supplying the brain (arterial blood pressure) and the pressure in the blood vessels taking blood away from the brain (cerebral venous pressure). Thus the arterial pressure must exceed the venous pressure for there to be a continuous supply of oxygenated blood to the brain.[124]

3.22 The mean cerebral arterial blood pressure range over which normal cerebral blood flow is maintained is wide. However there are limits to what is known as the autoregulation of this blood flow that can be reached and beyond which blood flow becomes affected. At extremely low arterial blood pressures (hypotension) the blood flow falls as the perfusion pressure falls and cerebral hypoxia will occur. Rapid onset of such significant under-perfusion and even sudden cessation of perfusion does not, however, cause an immediate loss of consciousness. Instead there is a short interval, of the order of 4-6 seconds, before loss of cerebral function occurs. This is due to the presence of oxygen, dissolved in the brain tissue, which acts as the only source of energy for the brain cells during this period. This oxygen supply acts as a buffer and temporarily maintains neurological function. This oxygen is depleted within 4-6 seconds (the ‘cerebral hypoxia reserve time’) and loss of consciousness ensues unless blood flow is restored. This time immediately prior to G-LOC has been described as the ‘functional buffer period’.

3.23 What is not immediately apparent is whether very modest Gz exposures have any subtle effects on physiological mechanisms or function. There is some evidence that even +1.5 Gz may cause a modest reduction in cerebral blood flow although the implications for function were not explored by the authors of the 2011 study in which this was postulated.[136]

Siphon Effect

3.24 At moderate levels of G force (+3 to +5 Gz) the difference in pressure across the walls of the cerebral blood vessels remains unchanged. This is due to the pressure of the fluid surrounding the brain and spinal cord (cerebro-spinal fluid) mirroring falls in arterial pressure. There is also dilation of the small arteries in the brain. In the same way that the increased +Gz causes a fall in the pressure of the arterial vessels, the same effect is seen in the venous vessels. The pressure in the jugular neck veins becomes negative (sub-atmospheric) instantaneously with rapid onset acceleration.[127] This acts as a siphon and helps to draw blood through the cerebral circulation from the arterial side. These changes all help to maintain blood flow to the brain.

3.25 An arteriovenous pressure gradient is maintained under +Gz, even when arterial pressure falls to zero.[127,237] Henry's seminal work on this issue showed that Mean Arterial Pressure (MAP) at around +4 Gz was 30 mmHg. While MAP falls almost linearly with the application of +Gz, mean cerebral venous oxygen saturation 'stays materially unchanged'.[127] Some actual increases were seen in the +2 to +3 Gz range. Oxygen saturation at a minimum was 42%. Henry's work documented a negative jugular venous pressure (up to -60 mmHg) with only mild visual dimming reported by the subject.

3.26 Significantly, Henry concluded that venous pressure changes follow arterial changes, and the arteriovenous pressure differential was never less than 50 mmHg. The jugular siphon effect thus appears to be completely intact at the +4.5 Gz for 15 seconds duration used in Henry's study. G levels higher than this are likely to be a problem; once higher levels of +Gz force are reached (more than +5 Gz) the veins in the neck collapse and blood flow through the vessels supplying the brain ceases.

Arterial Blood Pressure and Baroreceptor Response

3.27 The pressure effects described above are passive and mechanical due to the forces acting on a fluid (blood) in a semi-rigid pipe (blood vessel). Physiological processes controlling blood pressure involve arterial pressure receptors (baroreceptors) in the main aortic arch and carotid sinus.

3.28 Inertial G force in the head to foot direction increases the hydrostatic pressure in the main arteries, lowers resistance to blood flow in the peripheral arteries (by them expanding), leads to a reduction in cardiac output and redistributes blood from the head to the lower part of the body.

3.29 The body responds to an increase in G force by the action of the baroreceptors, which are triggered by the fall in blood pressure. This stimulates an increase in heart rate and peripheral vasoconstriction to increase the flow of blood back to the heart (the venous return). It also promotes an increase in cardiac contractility, whereby each heart beat is stronger and thus more effective at ejecting the volume of blood with each beat (stroke volume) and maintaining an adequate output from the heart.[192] This improves the blood flow from the right side of the heart to the lungs, then to the left side of the heart and hence the cardiac output is increased. The increase in heart rate and stroke volume increase the volume and pressure of blood ejected into the arterial system. The increase in peripheral vasoconstriction reduces the volume of the arterial space, thus increasing the overall blood pressure.

3.30 The pressure at the level of the heart and throughout the arterial circulation falls during the first 6-12 seconds of maintained high G exposure until the reflex mediated by the baroreceptors comes into effect.

3.31 This mechanism has evolved to restore the pressure in the aortic arch and carotid sinus back towards normal in the face of a reduced blood supply to the brain. The baroreceptor response acts to ensure that the blood pressure in the cerebral circulation is maintained at an adequate level to supply the brain. The same mechanism comes into play when there is a G force challenge.

3.32 Venous return, which is essential for the maintenance of cardiac output, is generally sustained under +Gz acceleration but arterial supply above the heart is subject to the enhanced hydrostatic effects of the force applied.

3.33 The baroreceptor responses are slower to take effect than the cerebral hypoxia reserve time.[99] Thus a rapid and sustained applied +Gz force that reduces substantially the hydrostatic pressure within the arterial blood supply to the brain can interrupt the supply of oxygenated blood before any physiological compensatory mechanisms can counteract it.

3.34 At levels over +4 Gz the heart rate starts to rise and venous return (and hence cardiac output) starts to increase after 10 seconds which, if high G is maintained, progressively continues to increase until about 40 seconds. By this time the mean pre-exposure arterial pressure at the level of the heart is restored.[113]

Respiratory Effects of +Gz Acceleration

3.35 The respiratory system is also subject to the effects of increased Gz. The influence of the increased hydrostatic gradient associated with exposure to an increase in +Gz leads to a redistribution of blood within the pulmonary circulation and increased perfusion to the bases of the lungs, at the expense of the upper regions. In contrast, the alveolar spaces at the top of the lungs are expanded but those at the lower regions are compressed, leading some to collapse. The overall effect of these changes is to increase the degree of mismatch between respiratory ventilation and perfusion with an associated reduction in respiratory exchange which leads to increased quantities of deoxygenated blood leaving the lungs.[88]

Signs and Symptoms of +Gz Exposure

3.36 The symptoms (experienced by aircrew) and signs (observed in aircrew by others) induced by exposure to +Gz are several and may differ substantially from one individual to another.

Physical Effects

3.37 All those exposed to +Gz will experience a perception of heaviness (especially of the arms) which increases linearly with the level of +Gz and visible sagging of the facial tissues. There can be distension of the orbit and an effect on eye muscle movements.

Visual Effects

3.38 The pressure in the eye (intra-ocular pressure) is usually 15-20 mmHg.[18] If, on exposure to high G, the pressure in the blood vessel supplying the back of the eye (the central retinal artery which is an end artery) falls below the level of intra-ocular pressure, blood flow ceases in the artery. As there is no alternative blood supply, once the local oxygen reserves are used up the retina ceases to function and there is visual loss.

3.39 The loss affects the periphery of the retina first leading to a perception of darkening or dimming of the outer visual fields. This is known as ‘grey out’ and is usually recorded in studies as ‘peripheral light loss’. There can be impairment of visual function at relatively low levels of acceleration, typically in the +3 to +4 Gz range.[192] In a US centrifuge study in the 1950s, loss of peripheral vision was seen at +4.1 Gz (+/- 0.7 Gz).[48] There is also loss of contrast acuity.

3.40 Experienced aircrew learn to use grey out as a signal of risk of impending G-LOC and alter the flight dynamics accordingly to avoid further visual loss or loss of consciousness.

3.41 Loss of vision is a function of the peak level of G achieved and the G onset rate. With higher G the peripheral light loss progressively increases until finally central vision is also lost; this is known as ‘blackout’. ‘Blackout’ is a specific term in this context meaning loss of vision and does not imply loss of consciousness. Blackout tends to occur at +4 to +4.5 Gz.[192] A US centrifuge study with 1,000 subjects showed blackout occurring at +4.7 Gz (+/- 0.8 Gz) in individuals with no anti-G protection.[48] Provided the G onset rate is gradual and the level of acceleration does not increase further there is preserved consciousness in this situation. Blackout has not historically been associated with impairment of cortical function.[263] Other senses, such as hearing and touch, are preserved during blackout. However, it is important to note that visual symptoms may not occur at all prior to loss of consciousness if the G level and onset rate is high.

3.42 Both grey out and blackout can be precursors to loss of consciousness if the G level increases by just under 1 Gz beyond the point at which visual symptoms occur.[48]

Almost - Loss of Consciousness and G - Loss of Consciousness

3.43 A-LOC refers to a number of symptoms that can be experienced by aircrew who are exposed to a short duration pulse of high G acceleration. It was first recognised a century ago and is characterised by a range of physiological, emotional and cognitive signs and symptoms. [10,39,48,174,185,221,223,248,250,288]

3.44 G-LOC is the loss of consciousness due to G forces that occurs when, on exposure to high levels of G, the blood pressure becomes insufficient for blood flow through the brain.[39] If blood flow ceases, 4-6 seconds later, once the local oxygen reserves have been depleted, unconsciousness results.

3.45 G-LOC has been recognised since the early days of flight and became a focus of research during the Second World War.[263] Much attention was diverted towards the topic in the mid-1980s following a series of G-LOC-related fatal F-16 accidents that affected the United States Air Force (USAF).[47,165,246,296] These included a number of surveys to assess prevalence.[9,58,113,185,214,216,227,253,255,311]

Cerebral Oxygenation

3.46 Ischaemia is a term used to describe an inadequate blood supply to a part of the body. Both A-LOC and G-LOC are believed to be associated with transient cerebral ischaemia. The difference between them may be a matter of degree in terms of the G level and duration of the exposure that causes a reduction in cerebral blood flow.

3.47 Insofar as the cerebral arterial blood flow is impeded, giving rise to ischaemia, the consequence is a form of hypoxia in cerebral tissues arising not from a reduction in the partial pressure of oxygen in the blood (as associated with altitude exposure) but a failure to deliver that oxygenated blood to metabolically active tissues. This therefore can be considered a form of ischaemic or circulatory hypoxia of acute onset.

3.48 Examination by Near-Infrared Spectroscopy (NIRS) of the regional cerebral oxygen saturation (rSO_2) under +Gz exposures has shown that saturation falls under +Gz, whether that be during short duration pulses or more sustained plateau centrifuge exposures.[235,236,270] A fall in saturation to a certain level induced G-LOC, irrespective of the +Gz level itself or its duration. Tripp also reported in 2010 that some degree of incapacitation persisted even after the rSO_2 had returned to pre-exposure levels.[270]

3.49 Studies of total and regional cerebral blood flow have shown that G-LOC is preceded by the virtual cessation of cerebral blood flow.[282] A slow onset of G has been seen in centrifuge studies to allow some modifying influences to be exerted which may alter cerebral blood flow compared with the overall reduction in head level blood pressure.[203] However in real-time flight such slow onset rates may be unrepresentative.

3.50 There is an important differentiation to be made between the ischaemic hypoxia seen with high +Gz loads and the hypobaric hypoxia seen with altitude exposure. In the G environment, there is a pressure problem, in that the blood is less able or unable to travel to and through the cerebral circulation. This leads to a significant problem maintaining adequate cerebral circulation. In the altitude setting there is an oxygen supply issue; blood still flows through the cerebral circulation but the oxygen content is insufficient to maintain cerebral function. The effects of moderate altitude hypoxia develop in tens of seconds to many minutes; even following a rapid decompression at 40,000 feet, with severe hypoxia likely to develop if breathing air, there is one circulation time's worth of adequately oxygenated blood in the system i.e. 12-15 seconds before useful consciousness is lost.[88,99] The time frames of the effects of the two scenarios are commonly different.

3.51 There is in-flight evidence that the cerebral oxygen status, as measured by NIRS, declines in dynamic flight.[148] Interestingly Kobayashi and colleagues noted that this effect was less marked in experienced pilots and speculated that this might be because such individuals are better at performing an Anti-G Straining Manoeuvre (AGSM). It may also represent a degree of cardiovascular adaptation to frequent +Gz exposure.

3.52 Low levels of +Gz, below that which produce peripheral light loss and that are therefore associated with persisting perfusion of blood to the cerebral tissue, do not lead to either A-LOC or G-LOC. These are illustrated by the +Gz levels (indicated on the y axis) relating to the area under the line in **Figure A** (see below).

UK Military Accident Experiences

3.53 The Service Inquiry into the crash of a RAF Aerobatic Team (RAFAT) Hawk at Bournemouth in 2011 investigated prior incidents and accidents that had been caused by, or at least partially attributed to, alteration of consciousness.[181] They found no other accidents and only three incidents, one reported in 2005 as a probable G-LOC and two that were previously unreported. One of the unreported incidents was a probable in-flight A-LOC in 2005 and another, involving a similar manoeuvre to the one flown by the RAFAT Hawk in 2011, was a probable G-LOC. An accident report following a Hawk 200 display accident in 1999 recommended that all display manoeuvres should be considered for G-LOC potential though this appears to have been on the basis of best practice rather than pertaining specifically to that accident.[184]

3.54 The Service Inquiry led to the determination that 'pilot incapacitation resulting from G-induced impairment was a possible cause of the accident'. In the last manoeuvre the pilot was exposed to just over +6 Gz, with a total time over +3 Gz of 8.75 seconds. The Inquiry report discusses the features of A-LOC and G-LOC and notes 'the demarcation between A-LOC and G-LOC may often be somewhat indistinct, and G-induced impairment may be regarded as a spectrum with differing degrees of cognitive function'. The Inquiry Panel 'concluded that the most likely causal factor of the accident … was A-LOC, leading to the reduced cognitive ability of the pilot'. The pilot appeared to have responded to aural stimuli and taken recovery action but had insufficient time to avoid flight into terrain and reduced cognitive ability may have hampered an ejection decision.

3.55 The military accidents would have been reported through the military Air Safety Information Management System and would not be retrieved through the European Co-ordination Centre Accident and Incident Reporting System (ECCAIRS) database.

3.56 G-LOC is characterised by loss of consciousness that may or may not be preceded by loss of vision. Confusion, the 'point of unconsciousness' and a central fixation of eyes were sometimes used as physiological end points in centrifuge experiments evaluating G-LOC indicating loss of some cognitive function in the period immediately prior to loss of consciousness.[20,69,264]

3.57 The exact point at which consciousness is lost is difficult to accurately determine in practice.[291,293] Studies of videotaped episodes of G-LOC on the centrifuge revealed an observation of a significant reduction in performance that preceded G-LOC.[47] The symptoms associated with a disturbance of neurological function due to high G forces have been termed the 'G-LOC syndrome'.[293]

3.58 It can be difficult to distinguish between an episode of A-LOC and G-LOC as both are associated with a period of unresponsiveness.[215]

3.59 Cammarota undertook a series of experiments where subjects were taken as far as the brink of unconsciousness or beyond and also studied the effects of a short, high G pulse.[52,53,54] These experiments demonstrated cognitive symptoms known to be associated with A-LOC occurring at these high G levels.

3.60 There is typically a period of confusion and reduced psychomotor performance on recovering from unconsciousness for 30-60 seconds and convulsions can occur as the blood supply to the brain is restored.[93,94,291,298] During this period mental processes are impaired and co-ordinated action impossible.[263]

3.61 If the acceleration is rapid onset and offset, recovery tends to be faster but it is not influenced by an individual's G tolerance.[131] For a period averaging 28 seconds (but with quite a wide range) a pilot would not be able to control their aircraft's flight path accurately after an episode of G-LOC.[295,304]

3.62 Complete amnesia for the fact that G-LOC occurred may affect recognition of the event though this can be accompanied by the psychological defences of denial and suppression of the loss of self control.[300]

G Tolerance

3.63 G tolerance is the amount of G force that can be tolerated by an individual. It is defined by the G level and duration at which specific physiological systems are significantly altered.[43] Tolerance can vary depending on the amount or level of acceleration achieved, the duration of exposure to the acceleration and the rate of onset of acceleration and is further influenced by a wide range of factors.

3.64 Relaxed G tolerance is the G tolerance for an individual with no anti-G protective measures; for tolerance to +Gz it is a function of eye to heart vertical distance.[38] It is influenced by the other physiological protection effects. It is usually measured as the G level at which some loss of vision first occurs; the point at which grey out occurs is the usual end point for research studies.[285]

3.65 There is a large variation in G tolerance between individuals. An individual who is exposed to high G for the first time will be unaware of their own personal G tolerance level. Some will naturally strain which will increase their tolerance.

3.66 From experimental flying studies von Diringshofen first reported that ‘the tolerance of the upright seated pilot is between 4.5 and 5.5 G’ in the early 1930s.[280] Cochran presented the results of a study of 1,000 aircrew in 1954 that showed blackout occurred at +4.8 (+/- 0.8) G, with a range of 2.2 to 7.1 G and G-LOC at 5.4 (+/- 0.9) G.[48,113] Hrebien found the mean relaxed G tolerance whilst sitting upright was +3.13 (+/- 0.1) Gz; this was measured to a loss of peripheral visual field (grey out) rather than blackout.[134]

3.67 Relaxed G tolerance can vary from day to day for an individual though the amount of personal variation is less than between individuals.[103,131] Ludwig reported that 75% of the total observed variation was due to difference between individuals, 16% due to day-to-day variation in one individual and 10% could be attributed to measurement error.[164] He found that it was only possible to measure an individual’s G tolerance to +/- 0.5 G with 95% confidence if measured on a single day and this could be improved to +/- 0.3 G if measured on several days, with no other variable factors.

3.68 Stoll set out the variability in G tolerance and the importance of G onset rates in her seminal paper on ‘Human tolerance to positive G’ in 1956.[264]

3.69 Prolonged duration of exposure has been studied but less than other aspects of tolerance as low levels of G are generally well tolerated for quite long periods. It is notable that in a 1958 experiment all 11 subjects were able to withstand +3 Gz for an hour demonstrating that this level of G rarely gives rise to adverse effects.[182]

Acceleration Onset Rate

3.70 The loss of consciousness associated with +Gz exposure is also related to both the level of +Gz force exerted upon the body and its duration. The time for G-LOC to occur varies with the rate of onset of the acceleration and the maximum level of acceleration reached. The ‘G onset rate’ is the rate of change of acceleration, expressed in G/second. The onset rate is of relevance as the physiological responses to mitigate its effects take time to become effective.

3.71 The relationship between +Gz levels and loss of consciousness has been examined extensively. Stoll reported the effects of G loads on grey out, blackout and loss of consciousness and her findings have been recreated by Whinnery et al.[264,297] In all such studies there has been found to be a short interval of a few seconds, irrespective of the magnitude of the G level, after the application of increased +Gz before adverse consequences are experienced. When a high level of G is applied rapidly, however, the onset of loss of vision or consciousness may be so rapid as to give little opportunity for the pilot to modify the amount of G being applied. Where the onset is slower visual symptoms can indicate the need to reduce the G load to avoid loss of consciousness. There is some increase in G tolerance after around 10 seconds which is understood to be related to the physiological reflexes described above coming into effect. This is illustrated in the Stoll G tolerance curve at **Figure A**.

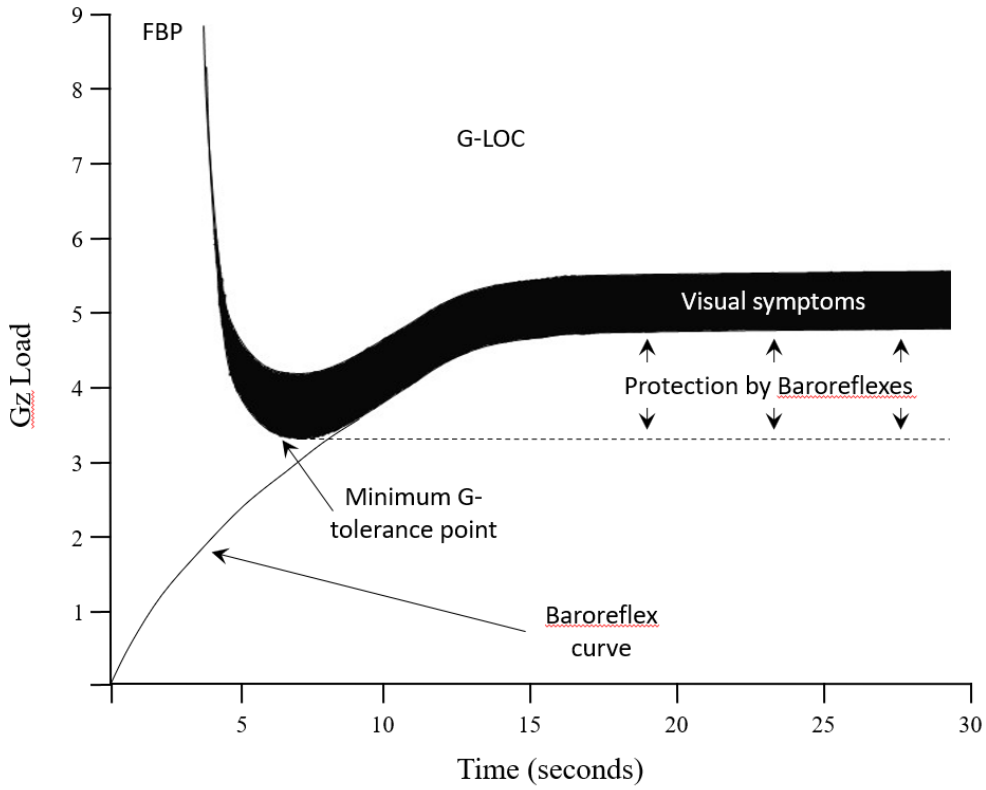

Figure A
G Tolerance curve
taken from Newman 2015[192] (after Stoll 1956[264]) and describes the inter-relationship between the three parameters, +Gz level, +Gz onset rate and time of exposure to +Gz force that define when symptoms will occur
FBP = functional buffer period

3.72 A gradual onset rate of acceleration is classically associated with visual symptoms. As previously described, these tend to progress from a dimming of vision known as grey out and/or a loss of peripheral vision, to a blackout, a complete loss of vision, as the acceleration increases. If acceleration continues to increase and areas of the brain responsible for supporting conscious function are depleted of their blood supply, loss of consciousness will then occur. With gradual onset rates, where there is time for the baroreceptor reflex to become effective, the duration of exposure becomes an important factor for G tolerance.

3.73 Rapid onset rates of acceleration of more than approximately 2 G/s, particularly if sustained for more than 5-6 seconds, can lead to loss of consciousness without prior visual warning symptoms as the blood flow in the central retinal artery and the blood flow to the brain ceases simultaneously.[47,192] In this situation it is solely the oxygen reserve in the tissue that maintains consciousness for a few seconds. The only way for consciousness to be maintained in this scenario, if there are no anti-G protective measures employed, is for the acceleration to be rapidly offset within the 4-6 second time period. As can be seen from the Stoll curve (**Figure A**), if the G level was imposed and removed very quickly (in less than about 5 seconds) then there would be no apparent loss of cerebral function. Such a very short pulse can occur in some modern fighter aircraft and even advanced competition civilian aerobatic aircraft, where rapid G onset rates and peak +Gz levels beyond +10 Gz are seen.[158]

3.74 The US Navy demonstrated that on rapid exposure to very high G levels (8 to 15 G), the time to produce G-LOC was a consistent 4.2 seconds and that the final G level reached did not influence the result.[20] The very rapid onset rate did not lead to loss of consciousness if the G was not sustained beyond a few seconds. The minimum time to G-LOC from any acceleration exposure on a centrifuge was stated by Whinnery to be 5 seconds.[297] The difference is likely to be related to the G onset rate of the centrifuges used in the studies.

3.75 At very rapid onset rates everyone will have a finite tolerance related to their brain tissue oxygen reserves. For the majority of people that tolerance point is broadly similar and G-LOC will ensue unless the acceleration is reduced or discontinued.

3.76 Tolerance is measured subjectively by the self-reporting of symptoms. These include the recognition of grey out or their personal fatigue limit being reached. Due to their subjective nature, the reliability of these symptoms of tolerance as a valid end point in studies can be problematic.

3.77 Many papers reviewed describe the results of exposure to G force in experimental conditions on the centrifuge and it is widely acknowledged that tolerance levels in flight are greater.[145]

3.78 Prior to the 1990s the USAF re-screened applicant pilots for likely tolerance to G force using physiological factors such as age, weight, blood pressure and height. Following studies that demonstrated the variability of effect of these factors on G tolerance this pre-screening was discontinued.[166]

Other Factors Influencing G Tolerance

3.79 It is known that there are many factors other than individual variability that may influence G tolerance.

3.80 As early as 1938, Armstrong described G tolerance as being adversely affected by respiratory infections, loss of sleep, fatigue, ‘emotional upsets’ and ‘fear of the tests’ (referring to the centrifuge experiments).[10]

3.81 **Primary factors** known to affect tolerance to G force in the head to foot direction are:

- Rate of onset of G
- Magnitude of the level of G reached
- Duration of G force exposure, both overall length and time at peak G

3.82 **Secondary factors** affecting tolerance include:

- Fatigue
- Availability and use of anti-G protective measures (see section on ‘G Protection’ below)
- Medication
  - Medications that affect the vascular system may impair G tolerance. Some specific classes of high blood pressure medication are likely to reduce G tolerance.[48] There is a single case report of a reduction in G tolerance related to a nutritional supplement, Coenzyme Q, attributed to its vasodilatory effect reducing systemic vascular resistance.[16]
- Illness including infection and pre-existing arrhythmias
  - Illness can adversely affect G tolerance. This may be directly attributable to an effect on the vascular system and being recumbent for a long time may affect the baroreceptor response. A pilot who has a history of an unusual heart rhythm (arrhythmia), in particular ventricular ectopy, may need to be cautious about exposure to high G as a change in heart rate is part of the physiological response.[290] High G force can precipitate arrhythmias such as premature ventricular contractions, bigeminy, trigeminy and supraventricular tachycardia.[285,312] Pilots with advanced cardiac disease and Parkinson’s disease with autonomic dysfunction are likely to have reduced G tolerance.[183] Dehydration may also be an adverse factor.

- Alcohol
  - Alcohol causes dilation of blood vessels and a reduction in G tolerance; depression of central responses and dehydration may also be factors with alcohol.
- High level of aerobic fitness training
  - Pilots who undergo marked endurance physical fitness training and have a high resting vagal tone may be predisposed to rate and rhythm irregularities and G-LOC.[303] A survey of US Navy aircrew found that those who ran regularly were more likely to experience G-LOC than those who trained using weights.[137] A recent centrifuge study of pilots of the Republic of Korea Air Force found no difference in physical condition between those who experienced G-LOC with 15 seconds of +9 Gz exposure and those who did not.[207]
- Temperature
  - A rise in body temperature causes dilation of small blood vessels in the skin and can lead to a reduction in G tolerance.
- Blood sugar
  - Low blood sugar or missing a meal prior to flying may be a factor that affects tolerance. Conversely having a large meal immediately prior to flying may lead to blood pooling in the abdomen and an AGS may cause abdominal discomfort.
- Anxiety
  - Anxiety may lead to hyperventilation and a reduction in the amount of carbon dioxide in the blood. This can increase cerebral vascular resistance, reduce blood flow through the brain and markedly reduce G tolerance. Motion sickness may reduce tolerance through a similar mechanism.
- Hypobaric hypoxia
  - Hypoxia associated with altitude can reduce tolerance to +Gz via a reduction in the oxygen stores in the brain.[132] In one study, exposure to hypoxia was seen to reduce the heart rate response to a G-related stress.[226]
- Push-Pull effect
  - Moving straight from negative to positive G force: the so-called push-pull effect.[13,14,15,61,112]

- Anthropometry
  - A pilot who is tall with a long neck that extends the heart to head distance may have lower tolerance to G force.[285] Duration G tolerance is more affected than the level of G.[207]

Factors Beneficial for G Tolerance

- Flying a preparatory G 'warm-up' manoeuvre
  - Flying a 'warm-up' manoeuvre to a moderate level of +Gz force prior to undertaking high G manoeuvring induces and carries over some of the compensatory responses including vasoconstriction and a reset of baroreceptors to help G tolerance. This effect is known as 'priming of the baroreceptors' and, although short lived, it has been confirmed to be beneficial. It increases protection against subsequent high G manoeuvres and is widely practised by pilots. The preparatory warm up has to be done immediately in advance of the high G manoeuvre to achieve this effect.
  - In a series of high G exposures it was demonstrated that the nadir of tolerance is greater after the first exposure.[155] The same study showed that the significant protective effect of a warm-up manoeuvre was greatest in the 15 seconds after the warm up. The duration and level of G force exposure did not alter the improvement in G tolerance for subsequent manoeuvres. Meyer found that a second G exposure after 30 seconds of rest from a previous G exposure gave a 10% increase in G tolerance.[179]
  - The classic way to undertake a G warm-up manoeuvre is to maintain between +3 and +5 Gz with no AGSM for at least 10 seconds. The benefits have been demonstrated to last for several minutes.[74,275]
- Age
  - Older age may be associated with a minor improvement in G tolerance as baroreceptor sensitivity may reduce and arterial walls become less distensible with age. Pilots with high blood pressure may also have slightly better tolerance.[285]
- Anaerobic exercise
  - Anaerobic strength and training with weights may be helpful due to increasing the contractile force of which muscles are capable which facilitates the performance of a more effective AGSM.[104]

- Training and currency in high G manoeuvres
  - Training in, or recent practice of, flying high G manoeuvres often improves G tolerance, possibly due to a 'resetting' of the baroreceptors. This is discussed more fully in the later section on Adaptation. Alternatively, this could be an enhancement of the AGSM (see below) through regular practice honing technique. For this reason pilots are advised, after an absence of more than a few days without flying, to first undertake a series of low G prior to high G manoeuvres.

G Protection

3.83 The development of aircraft capable of high Gz led to the potential for high Gz exposure of aircrew and the need to mitigate those effects by training and the introduction of specialised equipment. G protection thus typically includes the AGSM and the use of anti-G trousers (the AGS) as well as regular exposure and avoidance of factors known to reduce G tolerance. Positive pressure breathing is also used as a mitigation factor by the military but is not used in UK civilian aviation.

3.84 Anti-G protective measures increase both G level and G duration tolerances.[41] G-duration tolerance of sustained high G is not as relevant as G-level tolerance for this review.

3.85 Anti-G protective measures are designed to maintain as close as possible a +1 Gz cardiovascular environment. They attempt to return blood pressure and flow to the brain to the usual levels. If cerebral perfusion is maintained, cognitive impairments would not be expected. Of note pushing on the rudder pedals gives around +2 Gz protection due to the pump action of the lower leg muscles.

3.86 G-level tolerance is based primarily on the brain/eye level arterial pressure which is dependent on the baroreceptor reflex and the effectiveness of skeletal muscle contractions in the limbs and abdomen as utilised in the AGSM.

Anti-G Straining Manoeuvre

3.87 A variety of voluntary straining and breathing manoeuvres have been used to enhance G tolerance. A description of the various techniques can be found in Burton's review of 'Man at High Sustained +Gz'.[44] They are all essentially versions on a theme. General isometric muscular contractions combined with a short, forced expiration (the 'strain') improves head-level blood pressure.[33,307]

3.88 No significant correlation between relaxed and straining G tolerances for an individual subject has been found.[45]

3.89 The AGSM can increase G tolerance by +3 to +4 Gz if performed effectively.[90]

3.90 Issues with the performance of an effective AGSM include breathing too fast or too slowly, not straining sufficiently in advance of the high G onset, straining too long (leading to poor venous return from the lower limbs to the chest), taking too long to inhale in between strains and talking during G exposure.[168]

3.91 An unsatisfactory AGSM is thought to have been responsible for a number of in-flight pilot incapacitations.[222]

Anti-G Suit

3.92 An anti-G Suit (AGS) is a tightly worn inelastic garment consisting of a number of bladders (usually 5) positioned over the abdomen and legs that fill with compressed air through a G-sensitive valve, on exposure to G force over a certain level, usually around +2 Gz. The bladders compress those parts of the body over which the bladders are located. The leg bladders stop blood pooling in the legs and create a shift of blood towards the head. The abdominal bladder mechanically stops the diaphragm and also the heart and other organs in the chest from descending which would otherwise exacerbate the hydrostatic consequences arising from an increased vertical distance between the heart and the brain. Wearing the suit provides extra protection of up to +1 Gz when pressurised and +0.5 Gz even if uninflated, due to the fabric being non-distensible.[104]

3.93 The effectiveness of the bladders depends on them rapidly inflating on exposure to G forces and the efficacy of the anti-G valve is important. An AGS is quite uncomfortable to wear when fully inflated. There is thus a balance to be achieved between reducing discomfort and optimising G protection depending on the potential G exposure risk.

Gradual Onset of G

3.94 A gradual onset of G force will allow the baroreceptor reflex to come into effect and provide additional support to the cerebral circulation. It will also induce the visual symptoms that act as a warning of impending alteration of consciousness.

Body Positioning

3.95 Leg elevation has been used to increase G tolerance.

3.96 Crouching forwards has been used to reduce the effects of G force by minimising the vertical distance between the heart (aortic valve) and the brain (eye).[117]

Reclined Seat Angle

3.97 Reclining the angle of the pilot's seat is the only measure, other than Pressure Breathing for G (PBG), to offer anti-G protection from high, sustained G forces.[44,45] An angle of 55-65 degrees is needed to provide effective protection. Historically some aircraft seats were designed to flip backwards above a certain level of G force; no current aircraft utilise this feature.[107]

3.98 Only a reclined or a pronated seat that results in the pilot's heart and eye being at the same height will prevent any reduction in cerebral perfusion pressure with G forces and thus eliminate the risk of impairment of consciousness. In civil aviation this would create issues due to G forces being experienced in a different plane (Gx), such as impaired breathing and visual limitations. Such a seating position would be impractical and although used occasionally in the past, mainly in experimental types, is not in current use.

Anthropometry

3.99 Pilots with shorter necks have more natural tolerance to G forces than pilots with longer necks.

Positive Pressure Breathing for G

3.100 PBG may be needed to improve aircrew performance on exposure to very high accelerations. It is used by military pilots of very high-performance aircraft to increase G tolerance at forces of up to +9 Gz.[38,43] The pressurised gas being breathed effectively does the straining work associated with the AGSM, such that this manoeuvre is not required in the same way when pressure breathing. As such, PBG increases G tolerance without the fatigue penalty often associated with performance of the AGSM.[36,247,251,267] It is not used in civil aviation.

Training

3.101 Training is key to mitigating the risks associated with exposure to acceleration during flight. Military organisations have had particular concern about the exposure of aircrew to high G forces because of the association of high capability, modern military aircraft with fatal accidents from G-LOC. For example, the Eurofighter Typhoon has a peak G onset rate of around 15 G/s.

3.102 It was recognised as early as 1945 that after a period of exposure to high G, on reducing to 2 G, a pilot sometimes failed to recognise that the G level was greater than gravity.[263] This has implications for the training of today's pilots. Training should include awareness that after high G exposure a pilot may feel as though the normal gravity-only state has been resumed even if the acceleration has only been reduced to +2 Gz.

3.103 Alvim recommended periodic centrifuge training for any pilot performing aerobatics, not just those operating high-performance aircraft, for recognition of what he described as the 'consciousness endpoint'.[9] It is most useful if the centrifuge experience can be tailored to the aircraft and type of operations that the pilot intends to fly.

3.104 The UK RAF discontinued centrifuge training in 1996 when a +4.9 Gz limitation (due to airframe fatigue life considerations) was imposed on the Hawk aircraft.[114] It was reinstituted following the 2006 survey for all fast jet streamed aircrew early in their career and for those later in their career converting to high-performance aircraft.[255]

3.105 In the 2006 UK RAF survey 50.6% of the respondents did not consider 'pulling G' to be a problem.[114] Lack of awareness of the potential risks associated with G force exposure is important to counter.

3.106 A US study of F-16 student pilots identified no predictive risk factors for G-LOC, other than inexperience.[100]

Adaptation

3.107 There is substantial anecdotal information that pilots who fly regularly in the high +Gz environment tolerate it better. It is not uncommon for a front-seat student pilot to lose consciousness while the more experienced and adapted rear-seat instructor pilot maintains consciousness. There is quite a body of literature that shows distinct physiological adaptation in pilots regularly exposed to +Gz. This tends to lift the threshold at which they would suffer +Gz-related issues such as G-LOC.

3.108 Adaptation to +Gz has been seen from the early days of high +Gz flight. Armstrong recognised that tolerance was increased by serial exposure on successive days.[10] Regular centrifuge exposure to high G has also been shown to increase G tolerance.[44,104] Whinnery reported that pilots who underwent a centrifuge training program were able to increase their +Gz tolerance by at least an additional +2 Gz with regular exposure.[287] These findings were supported by those of other researchers.[85,86,98]

3.109 According to Gillingham, the frequency of exposure seems to have an influence on the resultant level of +Gz tolerance.[104] He reported that centrifuge subjects and fighter pilots have a greater +Gz tolerance if exposed to +Gz three times per week than if exposed only once per week and speculated that altered baroreflex sensitivity might explain this.[104] Some authors have claimed that at least one weekly exposure to high +Gz is sufficient to maintain maximum G tolerance.[48]

3.110 Scientific evidence of the increased tolerance of +Gz seen with repetitive exposure has only been documented relatively recently.[21,22,73,140,193,194,195,196,240,244,262] It appears that the basis of the increased tolerance to +Gz is due to adaptation of the cardiovascular system. Specifically, the evidence suggests that the compensatory baroreflexes become both more effective and more efficient at dealing with dynamic +Gz-induced blood pressure changes.[73,193,195,196] The baroreflex system develops an increased sensitivity to changes in arterial pressure. The adapted baroreflex is able to generate an augmented dynamic cardiovascular response to applied high +Gz loads. Convertino compared cardiovascular data from the final 10 heart beats of squatting with that of the initial 10 beats of standing.[73] He documented significant changes in baroreflex function (manifested by higher stroke volume and cardiac output) due to repeated exposure to high +Gz forces.

3.111 A cross-sectional study comparing the cardiovascular responses to an orthostatic challenge (head-up tilting) between a group of actively flying fighter pilots and a matched group of non-pilots demonstrated a clear and fundamental difference in the cardiovascular responses of fighter pilots, attributed to the pilots' frequent and repetitive occupational exposure to the high +Gz environment.[195,196]

3.112 A longitudinal study compared the cardiovascular response to head-up tilting of fighter pilots before and after a period of high +Gz exposure.[193] The pilots developed a greater heart rate response with the second test, which was significantly greater than that of their first test. This suggests an enhanced baroreflex sensitivity in the fighter pilots after they had returned to high +Gz flying, a finding that is consistent with earlier studies.[195,196]

3.113 A study by Schlegel et al examined the effect of a single bout of prolonged +Gz exposure (to +3 Gz for up to 30 minutes) on cardiovascular function, and found that baroreflex responsiveness had been enhanced.[240] These findings are consistent with those of earlier studies suggesting baroreflex adaptation due to chronic and repetitive +Gz exposure.[195,196] More recent studies have also confirmed the alteration and enhanced performance of the cardiovascular system as a result of chronic and repetitive +Gz exposure.[244,262]

3.114 This +Gz-induced cardiovascular adaptation is an advantageous protective mechanism, which increases the pilot's tolerance of applied +Gz loads.

Clinical Aeromedical Issues from Exposure to G Forces

3.115 The G forces encountered whilst flying aerobatics pose specific demands on the cardiovascular and cerebrovascular systems. Valvular heart disease is particularly important as stenotic disorders restrict the cardiac output and regurgitant valves may not be able to increase the stroke volume and restrictions on aerobatic flying may be required.[77] With valvular heart disease there is a reduced ability to counter the effects of G force and with valvular disease or after valve surgery there is an increased risk of arrhythmia. Pilots with a history of arrhythmias are likely to also be at increased risk due to a propensity for these to be provoked by G loading.

3.116 An increase in G force with disease of the thoracic aorta can increase the mechanical stress on the aorta and the potential for aortic dissection.[77]

3.117 Medication for high blood pressure, heart conditions (particularly negative inotropes that alter the contractility of the heart) and abnormal heart rhythms may affect G tolerance. Medications that affect the central nervous system or disease that affects nerve conduction may also affect an individual’s response to high G exposure though many pilots with these types of disorder would be likely to be denied medical certification because of their underlying disease.

3.118 The UK does not have a standard medical restriction limiting pilots with these conditions from undertaking aerobatics but an individual restriction can be imposed, for example prohibiting all or specific aerobatic manoeuvres. This is only applicable to flying which requires medical certification as there is no medical oversight of pilots flying using a self-declaration of fitness.

Chapter 4

Acceleration and Cognitive Performance

Cognitive Performance

4.1 Cognition is underpinned by neural structures although it is not in itself a physiological state. It is not synonymous with performance degradation as, even when cognition is impaired, performance level can be maintained if there is sufficient remaining capacity.

4.2 Information can be acquired externally or from memory and forms the basis for judging, deciding and choosing subsequent actions.

4.3 There is considerable day-to-day variation in individual cognitive performance and even greater inter-subject variability.[218,260]

Cognitive Performance and Acceleration

4.4 There is relatively little information available about the effects of G forces on higher mental functions. These functions include complex cognitive activities such as reasoning, judgement and use of memory and language.[211] In part this is due to the difficulty of accurately measuring these functions in a positive or negative Gz environment, and to the varied methodologies and levels of Gz employed in studies to date.

4.5 Subjective reports of cognitive performance changes with G forces by pilots are unreliable as, if cognition is affected, memory processes including recall may be impaired. For example, there is a 1927 description of exposure to acceleration by Doolittle who states that in a 'sustained 4G condition' he 'retained all faculties except sight'.[89] Whilst this may be true, such subjective statements cannot be relied upon.

4.6 Physiological and methodological issues with measurement of cognitive performance are encountered with high and increasing Gz. Most studies have been undertaken in a simulated environment, most often a centrifuge.

4.7 The rate of onset of Gz and the duration of Gz exposure have varied between studies and further complicate the impact on cognitive performance and its relationship to the real-world environment of piloting an aircraft.

4.8 McCloskey re-produced a table adapted from one originally published by von Gierke in 1991 which provides an overview of the research into cognitive impacts of Gz forces.[172] For this review the table has been modified and further updated, to include a range of studies reviewed by the authors of this report (**Table A**). It is important to note that the methodologies between studies are often not comparable, however, a tabular summary is a useful way to gain an overview of the diverse research in this area. The range of studies included is limited to those available to the authors of this review.

4.9 The references highlighted in grey were cited in the original McCloskey article and were not read directly by the Review Team.

Category	+Gz level at which decrement observed	Type of Decrement (or +Gz level where aspects tested without decrement as annotated)	References
Vision	+2 Gz	Spatial orientation (when head position offset)	Albery (1990)[7]
	+3 Gz	Visual tracking more difficult	Cheung & Hofer (1999)[62]
	+3 Gz	Decrement of 16% of visual acuity	Frankenhaeuser (1958)[96]
	+3 Gz	Contrast sensitivity decreased after 5-12 minutes post acceleration.	Chou et al (2003)[63]
	+3.5 Gz	Sharpness of vision (post +Gz exposure)	Randjelović et al (2013) [Abstr][220]
	+3 to 4 Gz	Detection thresholds increased for foveal and peripheral vision	White (1960) White & Monty (1965)
	+3 to 5 Gz	Increased errors in dial reading	Warrick & Lund (1946)
	+4 to 5 Gz	Visual dimming, blackout	Kerr & Russell (1944) Hallenbeck (1946)
	+4 to 5 Gz	Decreased contrast sensitivity	White (1958) Braunstein & White (1962)
	+4 to 5 Gz	Increased reaction times to visual discrimination	Canfield, Comrey, Wilson (1949)[55]
	+5 Gz	Visual-motor co-ordination (gunsight tracking)	McKinley et al (2008)[177]
	+5 Gz	Peripheral visual Information processing	McKinley et al (2008)[177]

Category	+Gz level at which decrement observed	Type of Decrement (or +Gz level where aspects tested without decrement as annotated)	References
	+7 Gz	Visual monitoring (dial reading)	McKinley et al (2008)[177]
	+7 to 9 Gz	Gradual colour perception	Balldin et al (2003)[12]
	Unknown	Spatial orientation	Nesthus et al (1993) [Abstr][190]
Memory and Central Processing	+2 Gz	Choice reaction time no decrement	McCloskey et al (1992)[172]
	+3 Gz	Increased reaction times to a multiplication task	Frankenhaeuser (1958)[96]
	+3 Gz	Slower responses to tracking task and competing verbal processes for novice subjects	Dalecki, Bock, Guardiera (2010)[76]
	+3 to 7 Gz	Short-term memory decrement	McKinley et al (2008)[177]
	+4 Gz	Impairment of short-term memory	Levin, Andersson, Karlsson (2007)[162]
	+4 Gz	Perceptual-speed tasks slower, some adaptation possible	Comrey et al (1951)[72]
	+4 Gz	No significant memory decrement in offensive or defensive fast jet sorties	Hormeño-Holgado & Clemente-Suárez (2019)[130]
	+5 to 6 Gz	Increased subjective ratings of workload	Albery et al (1985)
	+6 to 7 Gz	Increased errors in a memory task	Chambers (1961; 1963) Chambers & Hitchcock (1963)
	+6.9 Gz	Attention switching improved, but memory performance and simple reaction times declined	Biernacki et al (2013)[25]
	+7 Gz	Short-term memory	McKinley et al (2008)[177]
Manual Control	+2 Gz	Keypad entry no decrement, and reach task decrements across trials	McCloskey et al (1992)[172]

Category	+Gz level at which decrement observed	Type of Decrement (or +Gz level where aspects tested without decrement as annotated)	References
	+2 Gz	Increased errors with motor performance, some adaptation with practice	Cohen (1970)[70]
	+3 Gz	Exaggerated control forces produced on joystick	Guardiera et al (2007a)[118] Guardiera, Dalecki, Bock (2010)[120]
	+3 Gz	Flight path control	Dalecki, Bock, Guardiera (2010)[76] Guardiera, Dalecki, Bock, (2010)[120]
	+3 Gz	Force production	Göbel et al (2006)[110] Guardiera et al (2007b)[119]
	+3 Gz	50% decrement in tracking accuracy	Guardiera et al (2008)[121]
	+3 Gz	Reaching for controls	Canfield, Comrey, Wilson(1953)[56]
	+4 Gz	Increased tracking error with lightly damped control characteristics	Creer (1962)
	+4.5 Gz	Simple reaction times increased	Truszczynski et al (2013)[274]
	+5 Gz	Increased tracking error	Burton & Jaggars (1974) Little et al (1968) Piranian (1982) Loose et al (1976) Frazier et al (1982)[98]
	+5 Gz	Slower reaction times	Canfield, Comrey, Wilson (1949)[55]
	+5 Gz	Reaction time initially slower but no decrement with practice at +5Gz	Canfield et al (1950)[57]
	+5 to 10 Gz	Manual tracking	Deaton & Hitchcock (1991)[79] Repperger, Rogers & Hudson (1984)[225]
	+5 to 7 Gz	Pursuit tracking	McKinley et al (2004)[175]
	+6 Gz	Increased tracking error with heavily damped control characteristics	Creer (1962)

Category	+Gz level at which decrement observed	Type of Decrement (or +Gz level where aspects tested without decrement as annotated)	References
	+6 Gz	Simple reaction times did not change for experienced fast jet pilots	Truszczynski et al (2014)[272]
	+7 Gz	Relative motion	McKinley et al (2008)[177]
	+7 Gz	No difference in pitch roll capture, unusual altitude recovery and situation awareness	McKinley et al (2008)[177]
Time and mass estimation	+3 Gz	Time perception less accurate during centrifugation	Frankenhaeuser (1958)[96]
	+4 Gz	Increased error for weight estimation	Darwood et al (1990)
	+5 Gz	Time perception less accurate	Repperger et al (1990)[224]
	+5 Gz	Motion inference (estimation of time interval)	McKinley et al (2008)[177]
	+6 Gz	Time underestimated during long tasks	Frazier et al (1990) Popper et al (1990)
	+7 Gz	No decrement in perception of time and speed (precision timing)	McKinley et al (2008)[177]
Mood and Affect	+2 Gz	Electroencephaolography-indicated and self-reported mood decline	Dern et al (2014)[81]
	+3 Gz	Perceived physiological wellbeing decreased	Schneider et al (2008)[241]
	+3 Gz	Adrenaline and subjective stress	Frankenhaeuser, Sterky, Jaerpe (1962)[97]
	+3 Gz (increasing)	Enjoyment (mood) increased after centrifugation	Biernacki et al (2012)[23]

Table A: Acceleration and Human Performance Literature Review Summary (adapted from von Gierke, McCloskey and Albery, in Handbook of Military Psychology 1991 London: Wiley and Sons as published in McCloskey et al 1992 [172])

4.10 **Table A** above includes a range of categories as originally used by McCloskey.[172] A small range of studies which relate most directly to cognitive impairment (as opposed to more physiological or emotionally-related measurements) are explained in more detail in the section below.

4.11 Also of merit is the following table published in the paper by McKinley et al in 2008, as a simplistic but useful illustration of the cognitive decrements examined in research.[177] Each dependent measure, or measured variable, is shown as being performed at 100% at the +1 Gz level. Performance at higher +Gz levels are shown as a proportion of 100%. For example, with contrast sensitivity as measured by Chambers and Hitchcock at the +5 Gz level performance is only 34.04% of what was observed at the +1 Gz level.[60] The table oversimplifies the fact that methodologies between studies are often not directly comparable but nevertheless provides a useful visual summary of broad differences in performance as +Gz increases.

Reference	*Dependent Measure*	*1Gz*	*2Gz*	*3Gz*	*4Gz*	*5Gz*	*6Gz*	*7Gz*	*8Gz*	*9Gz*
Dial Reading (Instrument Reading)										
Warrick & Lund, 1946	Errors	100.00		64.27						
Choice Reaction Time (Simple Decision Making)										
McCloskey et al., 1992	Reaction Time (msec)	100.00	87.50							
Frankenhauser, 1958	Reaction Time (sec)	100.00		91.99						
Visual Acuity										
White. 1960	Absolute Threshold (Peripheral)	100.00	95.82	86.87	82.99					
	Absolute Threshold (Focal)	100.00	98.50	96.10	92.04					
Chambers & Hitchcock,1963	Contrast Sensitivity	100.00	84.04	77.66		34.04				
White, 1962	Contrast Sensitivity	100	100	80	74					
Frankenhauser, 1958	Percent Error of visual acuity	100		83.66						
Decision Making (Complex Decision Making)										
Cochran, 1953	Average Percent Accuracy	100.00	97.50	96.50	95.00	100.00	90.00			
	Average Reaction Time	100.00	94.00	87.50	73.50	75.00	76.50			
	Average Throughput	100	58.89	45.43	26.98	32.76	31.34			
Tracking										
Rogers et al., 1973	% Accuracy	100	97	90	85	80	65	50	23	
Motion Inference										
Repperger et al., 1990	Motion Inference, Slow Velocity	100		89.29		26.79				
	Motion Inference, Fast Velocity	100		114.29		80.95				
Spatial Orientation										
Albery, 1990	+30 Degree manipulation	100.00	55.00	35.00						
Nethus et al., 1993	Manikin Error rate, 14 FIO2 (%)	100.00				60.00				
Perceptual Speed										
Comrey et al., 1951	T-score equiv. for raw number correct	100.00	98.61		90.55					
Frankenhauser, 1958	Reaction Time (sec)	100.00		80.10						

Table B: Normalised Data from Literature across Cognitive Abilities
(Reproduced, with permission, from McKinley, Tripp, Loeffelholz, Esken & Fullerton (2008)[177])

Acceleration Levels in General Aviation and Cognitive Performance

4.12 McKinley and colleagues (2008)[177] conducted a subject matter expert consultation to identify eleven skills which were considered important for military pilots required to perform effectively in a +Gz environment. They tested these skills with a range of military personnel across eleven tasks using a rolling +Gz profile which changed from +1 Gz through +3 Gz and +5 Gz to +7 Gz. The eleven skills included: Gunsight Tracking (visual motor perception), Precision Timing, Motion Inference, Relative Motion, Peripheral Information Processing, Pitch-Roll Capture, Unusual Attitude Recovery and Situational Awareness, Rapid Decision Making, Visual Monitoring and Short-Term Memory. Of note, for the context of +Gz in this review, the only task that showed a decrement at the +3 Gz level was Short-Term Memory. The other tasks did not show a statistical decrement until either +5 Gz or +7 Gz which is above the level likely to be experienced in general aviation. This suggests that there are a number of cognitive functions that are resilient to lower levels of acceleration up to +3 Gz which may not be problematic in the general aviation environment.

4.13 Dern and colleagues (2014)[81] reported neurophysiological changes with a psychological effect from exposure to +2 Gz. However, this was based on 30 minutes of continuous increased +Gz force and is not representative of performance aircraft aerobatic manoeuvres, although it may be relevant for some spacecraft flight profiles. Other studies as outlined below, while varied in their details, are broadly associated with levels of Gz above +2 Gz.

4.14 Tripp (2001)[268] deliberately took subjects to G-LOC in a centrifuge study and demonstrated that they stopped performing a maths task (addition and subtraction) 7.44 seconds prior to losing consciousness, whereas they continued a tracking activity until 3.2 seconds in advance of G-LOC. The mean +Gz level to induce G-LOC was relatively high at approximately +6.55 Gz.

4.15 The following papers, discussed in chronological order, considered levels of +Gz which general aviation pilots are more likely to experience, between +2 and +5.5 Gz. They have been selected for their study of cognitive performance as opposed to simple vision or physiological performance. Studies where not enough methodological detail was available to determine the applicability of results are not included.

4.16 The methodological and physiological challenges noted above for high G research are present in these studies, including that it is difficult to extrapolate results from the centrifuge into a general aviation environment.

4.17 **1951**. Comrey et al investigated the effect of up to +4 Gz on perceptual speed ability.[72] They used black and white test items; images of five simple and similar figures with one image in the centre and one above, below and to each side of the central image. One of the peripheral images was the same as the central image, and participants had to select the matching image to successfully complete the task.

4.17.1 Twelve test cards each with fifteen items were used and were mounted on cardboard so that participants worked through the items from the top left to the bottom right. The card was installed so that it was only illuminated during the test sequence and was not visible to participants at other times. A separate study involving 40 participants had established the difficulty level of the twelve test cards in advance.

4.17.2 Each trial with the cards was for 15 seconds, with participants articulating which figure was identical to the central one in each option. For this experiment the 14 male participants *did* wear G-protection suits. It was not reported whether any of the participants had any flying experience. The 14 subjects were divided into two groups, and every participant completed six experimental runs on each of three different test days. On the test days participants completed a trial +3 Gz run with no figure matching and then two runs each at +1 Gz, +2.5 Gz and +4 Gz (in varying order) with the matching task. There was a two-minute break between trials in each set, which the researchers felt was not quite enough time to have recovered from the physiological effects of the +Gz.

4.17.3 Performance in the last three trials of all days combined was significantly better than the first three trials of all days combined, so results were reported in two halves. Both practice and adjustment effects were evident, with participants achieving significantly lower perceptual-speed scores for the +4 Gz trial during the early experimental trials, but not significantly lower during later trials. The researchers noted that although performance was initially worse in the +4 Gz condition, participants were able to adapt as trials progressed. They attributed the initially poorer performance to distraction by the +Gz forces. Their overall conclusion was that ‘limited exposure to the effects of increased positive radial acceleration, up to the level of +4 Gz, may distract subjects in the performance of perceptual-speed tasks, but adaptation to such distractions readily takes place’.

4.17.4 While a sophisticated experimental design was used to assess the effects of +Gz on perceptual speed, this research cannot clearly indicate the novel effects of a pilot experiencing these +Gz forces during a flight. It is useful to know that adaptation is possible to +4 Gz (with the use of an AGS), but this particular study does not provide insight into briefer novel exposures to +Gz.

4.18 **1958**. Frankenhaeuser conducted research using a human centrifuge, with subjects seated in a closed cabin.[96] Specifically, she was interested in longer exposures of between two and ten minutes, under the influence of +3 Gz. Participants were male volunteer medical students (not pilots) ranging in age from 18 to 36 years, who did not wear AGS or conduct self-protection measures such as an AGSM. All participants had at least one trial run at +3 Gz to ascertain that their vision would remain intact at this level, (that is, no dimming of vision noticed by participants).

4.18.1 There were eight experiments with results as follows:

I: *Visual choice reaction time*. Seven participants responded to a combination of red, green or white lights using two signal switches (one in each hand). Light combinations were presented in random order and separated by an interval of irregular length (an average of two seconds). Each participant received ten minutes of training time. The experimental condition had four phases of two minutes each with an interval of approximately 45 seconds, including two minutes without centrifugation, two minutes during centrifugation, a further two minutes during centrifugation and a final two minutes after centrifugation. Frankenhaeuser found that participants' performance during the first two minutes at +3 Gz was significantly inferior (slower response times, mean reaction time of 0.782 seconds) to performance before centrifugation (mean reaction time of 0.724 seconds), and that the two centrifugation periods compared with the two non-centrifugation periods were significantly different. The effect was more pronounced in the first two minutes than the last two minutes of centrifugation. However, with such a small actual time difference (0.058 seconds) this is likely to be of negligible operational effect.

II: *Visual Acuity*. A copy of one of Boström's test figures (a modification of a clinical vision test) was reduced to 0.7 x 0.7 millimetres and presented one metre away from the participant. The figure was rotated, with subjects reporting verbally the position of the gap (left, right, up or down). The position of the gap varied in a pre-determined random order. The same centrifugation test intervals were used, with participants articulating differences in the figures at their own pace. Thirteen participants completed this experiment. The percentage of errors in the visual acuity test was significantly larger during exposure to +3 Gz than under non-centrifugation conditions. The decrement in performance corresponded to a loss of 16% of acuity.

III: *Accuracy of Movement*. Six participants followed the movement of a pointer by operating a second pointer (a pursuit-meter) with their forearm. This experiment used only three phases; pre-centrifugation for one minute, during centrifugation for two minutes, and post-centrifugation for one minute. Each participant completed two experimental sessions. Results indicated that accuracy of movement in a pursuit task decreased significantly during exposure to +3 Gz, although operational significance may be negligible.

IV: *Perceptual Speed*. A modified Thurstone Identical Forms Test was used (a matching test). Participants needed to identify which of five test figures was identical to the stimulus figure. The procedure involved 60 items on cards of 10 items each. The experimental protocol involved 20 items before centrifugation, 40 items during, and 20 items after centrifugation. Time taken to answer and errors were recorded for each of the six participants. It was concluded that exposure to +3 Gz did not affect perceptual speed.

V: *The Stroop Test*. The Stroop test assessed reading speed and colour naming which can be competing processes. Three cards were used; Card A had names of colours (red, blue, yellow and green) all printed in white, Card B had coloured circles in the four colours with no words, and Card C had the words from Card A printed in the colours of Card B (e.g. the word yellow may have been coloured red). Participants had to name the word, ignoring the colour in which it was printed. Each card had 100 items arranged in 10 rows. The experimental procedure was to present the first 50 items on cards A, B and C before centrifugation, all 100 items on cards A, B and C during centrifugation, and the last 50 items on cards A, B and C after centrifugation. Each of the six participants averaged around 5.5 minutes at +3 Gz and participated in two experimental sessions. Time to complete each card and the number of errors were recorded. The results indicated that reading speed (Card A) and colour naming were significantly slower at +3 Gz than under normal conditions, whereas when a verbal distractor was introduced (Card C) performance was not significantly inferior during acceleration.

VI: *100-3 Test*. Participants were asked to count backwards from 100 as quickly as possible by subtracting three each time. Each participant took the test once before the experiment, followed by a three-part protocol with 45 seconds in between to minimise the effects of practice. One test was undertaken before centrifugation, one test during centrifugation and one test after centrifugation. Tasks were varied by using a different starting point each time (98, 99, 101 and 102) and errors were recorded. Each of the six participants completed two experimental sessions. The time taken to perform the 100-3 test increased significantly during exposure to +3 Gz.

VII: *Multiplication*. Participants were presented with one 1-digit and one 2-digit number that were to be multiplied. Items were presented on printed sheets and subjects responded verbally, with item difficulty increasing during each test. There were again three phases in the experiment; a two-minute test before centrifugation, a four minute test during centrifugation, and a two-minute test after centrifugation. Six participants took part in two experimental sessions each. Performance was slightly better after centrifugation than before, and considerably worse during centrifugation than before or after centrifugation, but the only statistical difference was that performance during centrifugation was significantly inferior to that under normal conditions.

VIII: *Time Perception.* Auditory signals of 1 to 20 seconds were presented in random order to participants through earphones. Each participant was instructed to either reproduce the entire duration or half the duration of the stimulus signal by pressing a button which gave a signal in the earphones. Participants underestimated the time interval when responding to the signal during +3 Gz acceleration compared with under normal conditions i.e. they subjectively thought time moved more quickly under +3 Gz.

4.18.2 Overall Frankenhaeuser's work suggests that there is a significant performance decrement across a range of parameters at +3 Gz if sustained for a few minutes at a time. Many of the manoeuvres conducted in general aviation would induce +Gz higher than +3 Gz for only a few seconds rather than minutes, and consequently it is unclear whether the performance decrement would be as obvious in a real-world context when compared with these research scenarios. These findings may be important for general aviation pilots completing a prolonged series of manoeuvres without additional G protection; it is acknowledged that it would be difficult to separate +Gz induced effects on performance from fatigue in this situation.

4.19 **1990.** Albery conducted centrifuge research on five participants.[7] The study was in three parts with nine subjects initially being tested on their perception of the 'down' direction at 1 Gz while the centrifuge cab was randomly placed at several different angles off vertical. Subjects used an arrow on a television monitor with an attached control dial to position the arrow in the direction they perceived as 'down' relative to their position. Five subjects who had the most consistent results at 1 Gz subsequently performed trials at +2, +2.5 and +3 Gz during part two of the study. During part three the same subjects repeated the experiment but performed the task with the seat at an offset angle to simulate flying head/acceleration configuration. They found that, at +2 Gz and above, subjects whose head was offset demonstrated greater error in estimating the direction of the 'down' arrow. Of note, no specific statistical calculations were reported in this paper.

4.20 **1992.** McCloskey, Albery, Zehner, Bolia, Hundt, Martin & Blackwell investigated three tasks at sustained +2 Gz for five eight-minute trials (a total of 40 minutes) to simulate astronaut re-entry after spaceflight.[172] The first was a choice reaction time task where participants were presented with four circles, up to three of which could be illuminated at once. They had to press a key (or keys) to indicate the number of illuminated circles using two fingers of each hand, one finger per button for each circle. The second task was a keypad entry task which involved entering a six-digit number displayed on a visual display by using a numerical keyboard. The third task was a multifunction display task where participants had to press a bezel button on one of five multifunction displays (from a resting position of their hand being on the flight stick). The participant had to pull a trigger located on the flight stick at the onset of light, and then as quickly as possible reach out to press the bezel button located on that multifunction display. There were no performance decrements in the choice reaction task across trials. In contrast keypad entry task results were significantly slower across trials. The multifunction display task results also showed significant decrement in early trials but recovered to reach baseline levels by the last trials. Although the authors were primarily concerned with the ergonomic design of controls for spacecraft, the cognitive results suggest a level of resilience with these cognitive skills in a sustained +2 Gz environment.

4.21 **2007.** Levin, Andersson & Karlsson explored memory performance during +Gz exposure using a Swedish word recognition task.[162] Eighteen male participants with a range of flying experience participated in Dynamic Flight simulator trials. The research used a Continuous Recognition Task (CRT) where a series of words were shown and repeated, with participants recognising and identifying repeated words as the +Gz load gradually changed from +1 Gz up to a maximum of +4.8 Gz. A control condition without +Gz exposure was also used for comparison. The experimental runs were approximately 3-4 minutes long.

4.21.1 The CRT was based on four- to eight-letter Swedish nouns presented in black on a white computer screen. Participants used a two-button computer mouse to indicate an ‘old’ (i.e. repeated) word (left button) or ‘new’ word (right button). There was a total of six different word lists so that they could be rotated for the three phases of the experiment, ensuring that participants had an opportunity to encode some new words in each part of the trial, and recognise old words. Words appeared on the screen for three seconds each before the next word appeared.

4.21.2 Each participant had their own individual ‘G-Plateau’ determined by finding their G-limit (the point where they experienced visual symptoms of grey out) while maintaining a relaxed seated posture and not engaging in any anti-Gz manoeuvres or wearing an AGS. Their plateau was then calculated to be 70% of this +Gz level, an hour before their test run. The average +Gz level was +3.7 Gz +/- 0.54, with a minimum of +2.8 Gz and maximum of +4.8 Gz. Response accuracy and time were collected alongside a range of physiological measures.

4.21.3 The authors noted that there were no statistical effects observed relating to the set of words used, time of day, pilot versus non-pilot participant, or level of +Gz used, on any of the variables measured. Results indicated that there was approximately a 10% reduction in ‘hit’ rate (correctly identifying an old word) for the G-exposure condition compared with the control. The ability to recognise words memorised at 1 Gz and repeated during G exposure did not seem to be affected, but the ability to recognise ‘old’ words that had been presented for the first time (i.e. were ‘new’ words) during G exposure was impaired. The authors suggested that this might be the result of a deteriorated encoding process at increased +Gz levels.

4.21.4 Response time results showed one main effect for ‘answer’ (correct versus false) in that the mean response time for an incorrect answer was significantly longer than for correct answers. On balance, the results suggested that memory encoding, but not retrieval, was affected negatively when exposed to substantial and sustained +Gz load.

4.22 **2010.** Dalecki, Bock & Guardiera investigated simulated flight path control of fighter pilots and novice subjects at +3 Gz in a human centrifuge.[76] The researchers used 24 male right-handed participants; ten had extensive experience flying the Eurofighter aircraft with the German Air Force (age 36.8 +/- 3.91 years), and the remaining 14 were novices who had passed a basic medical check (age range 24.5 +/- 1.5 years). Participants *did* wear an AGS, and completed the study in a high-fidelity Eurofighter simulator. Participants completed a tracking task, moving the simulator's control stick to track continuous altitude changes in a target aircraft for five minutes, ranging between 250-5,000 feet differences and starting from 11,000 feet. The +Gz level in these manoeuvres varied but did not exceed +3.5 Gz. Participants had completed the same tracking task in a stationary centrifuge beforehand (no additional +Gz). During the tracking task, participants also completed a modified auditory Stroop test. The Stroop test used only two words; "laut" and "leise", respectively "loud" and "faint" in German, which were spoken in either a loud or faint voice. Participants were asked to report the loudness of the spoken word but not the semantic content as quickly as possible, and during the testing phase 60 words were spoken in about five minutes and 35 words in about three minutes. The experimental protocol was to run the simulator without centrifuge for 15 minutes, then with the centrifuge for three blocks; firstly with the pursuit tasks for five minutes at +1Gz, then the Stroop test for three minutes, and then the pursuit task and Stroop test together for five minutes (the final two blocks varied between +1 Gz and +3 Gz to minimise serial order effects).

4.22.1 Results indicated that for the tracking task only, novice subjects were significantly less accurate in the first minute of the trial in both the +1 Gz and +3 Gz conditions compared with experienced pilots but did improve across the time period of the trial. There was no significant difference in the tracking task between trials for the experienced pilots. For the Stroop test only condition the pilots had significantly shorter reaction times compared with novice participants and this difference was more pronounced in the +3 Gz condition. There were no significant effects found for any of the groups in the dual task condition.

4.23 **2019**. Hormeño-Holgado and Clemente-Suárez investigated the effect of different combat jet manoeuvres on the psychophysiological response of professional pilots.[130] Twenty-nine experienced pilots aged 28.3 +/- 7.4 years from the Air Fighting School of Spanish Air Forces participated in the research. They wore AGS as part of their normal flying kit and most had live combat flying experience. Two air combat sorties, offensive and defensive, were flown by each pilot in an F5 combat aircraft (not a simulator) and various physiological and cognitive/psychological measures were collected two hours prior to and 30 minutes after each flight. The maximum Gz experienced was recorded as +5.5 Gz. It is not stated in the paper, but can be inferred from the analysis of results, that each sortie was a separate flight. In particular, a short-term memory task was measured: a three-digit number was presented to participants for one second. After a five second interval they were asked to recall the number and say it backwards. There were no significant differences in response to this memory task after either the offensive or defensive sortie.

Chapter 5

Information Received from National and International Organisations

Civilian Organisations

International Aviation Authorities

5.1 Of the 38 international aviation organisations contacted (as described in the Methodology Chapter), to ask about their experience of cognitive impairment with low G force exposure, 17 provided comments.

5.2 Two responded and also forwarded the enquiry to, or put the Review Team in touch with, their national transport or aviation accident investigation body. Some others consulted with colleagues or referred the question to their acceleration expert.

5.3 A few suggested references for the Review Team to consider.

5.4 The following comments were received:

‘We … have no experience or records of this phenomenon’

‘not aware of such a phenomenon as a risk to civil aviation safety’ and ‘not undertaken any specific activities in this domain.’

‘we do not have any relevant cases’

‘there have not been any cases of such as causes of A-LOC or G-LOC in general or commercial aviation’ in ‘more than 25 years’ [of experience].

‘don’t know of any research or statistical data’

‘not in my experience’

‘not aware of any civil cases’

‘not aware of such a case’

‘I do not know of any accident due to GLOC’. This respondent emphasised the value of training especially in the AGSM which was ‘Very useful when pulling G’s especially over 4G… So also very useful for pilot that fly aerobatics’.

‘I am not aware of any documented relationship between aviation sub-LOC G exposure and cognitive impairment, acute or longer term. I am similarly unaware of any anecdotal relationship along those same lines.’

‘I have no knowledge or awareness of this phenomena you have under review.

‘Head of Centrifuge … said, he had 2 pilots who lost his conciousness on 4,5G. After training their G tollerance increased. … I am in favor of introducing the obligation of such training for aerobatic pilots... I think, that we should at least assess G tolerance of pilots before they start fly aerobatics, especially with older ones, on antihypertensive medications which are usually disaster when it comes to G tolerance.’

‘no similar cases’

‘I´m not sure if research has been done on basic cognitive functions during sustained high G-loads. In connection with hypoxia (OBOGS [On Board Oxygen Generating System] problems) research has shown shorter times to GLOC. This is not a typical civilian situation, and aerobatics with military jet aircraft often mean longer exposure, which is also both physically and mentally more tiring than the second-long peak exposures experienced in light propeller planes. If we think of a scenario with older pilots who may have conditions for small-vessel disease in the brain (i.e. hypertension), it is not at all unlikely that there may be a cognitive reduction even at g-loads lower than GLOC, at GLOC the perfusion has ceased completely and the actual limit is different depending on individual factors and G onset rate. With slow G onset rate, most people can do more, but there are people who reach GLOC already at 4.5 G (or lower). I have no personal experience regarding reduced cognitive performance at high G but theoretically it seems possible. However, stress alone can reduce cognitive performance significantly. ... My conclusion is that the likelihood of cognitive influence depends on the individual's status and other conditions together (G-onset rate, G-protection, recent high-G exposure, efficient anti-G maneuver, fitness to fly etc.). In modern military planes with good G protection and elevated fraction of oxygen, the risk should be very small, significantly higher in the accident scenario described. The increased risk of sudden incapacitation with age should also be considered.’

Only one respondent considered that cognitive impairment could occur prior to A-LOC: ‘the definition of A-loc is a little wide and a cognitive impairment can occur even in phase before reciving A-loc.’

5.5 One National Aviation Authority with a neurosurgeon on staff provided the following response:

‘There is a general consensus that there is a correlation between cognitive function and relevant regional cerebral blood flow (rCBF), and as Gz forces affect the cerebral perfusion pressure (CPP) I believe there is also a general understanding that G forces may affect cognition.

The simplified explanation and common understanding is that –Gz causes stagnation hypoxia and that +Gz leads to anemic hypoxia. This may affect neurological function. However, in reality it is likely to be much more complicated due to a high number of variables that will affect this equation, i.e.:

- The hypobaric environment is associated with hypoxia (that induce cerebral vasodilatation) and hypocarbia (that induce cerebral vasocontriction)
- G-forces may also alter the intracranial pressure and compliance due to CSF [Cerebro-Spinal Fluid] displacement (which will also affect CBF)
- Both G onset rate, G amplitude and duration of G forces affect the individual tolerances
- Individual anatomical differences in intracranial circulation
- Disturbances of Windkessel mechanism [elastic recoil of the major arteries leading from the heart smooths out the blood flow from pulses to a steadier stream].
- Previous G exposure, hydration, clothing, anti-G maneuver, comorbidities, medications etc may affect the individual G tolerance
- Blood distribution to other areas of the brain
- The cerebral autoregulation is associated with a certain delay (seconds), but will then usually maintain a stable CBF if the MAP is between 60 and 150 mmHg (more or less).
- All other factors affecting the neural reflexes (e.g. arterial baroreflexes)
- Alternating +Gz and –Gz forces (e.g. –Gz causes cerebral vasoconstriction and bradycardia, and due to the delay in reflexes the person is more susceptible to +Gz immediately after –Gz exposure – the push-pull effect).
- The pulsating nature of the brain complicates the equation further (the widely used CBF = CPP/CVR [Cerebro-Vascular Resistance] is an oversimplification as the intracranial compliance or impedance will also affect the blood perfusion).
- …etc

Most of our knowledge is based on subjects in clinical studies without G force exposure (some with comorbidities and some without). It may be challenging to conduct high quality studies on the level of impairment of cognitive function during G exposure due to the many variables and confounders as well as practical/methodological details (e.g. lack of validated method of rCBF measurement during significant G maneuvers)'.

Accident Investigation Bodies

5.6 The Review Team was given examples of accidents where G-LOC had occurred but not where cognitive impairment with G force was considered to have been a factor.

5.7 One organisation conducted a search of their database of aviation occurrences (over 30 years of data) and stated ‘we find no occurrences that have involved GLOC or ALOC. Similarly, we find no occurrences involving cognitive impairment in pilots who experience lower levels of g forces’. They also commented that having asked colleagues for their experience ‘no one reports having encountered ALOC or GLOC previously in … investigations or safety studies’.

Summary

5.8 Of the responses received from all civilian sources there were no cases described that fitted the criteria of acceleration-induced cognitive impairment at relatively low G force.

UK Military

5.9 On 24 June 2019 RAF CAM informed the review that following consultation with international colleagues and experts ‘no consulted expert or organization recognises the existence of a “low-G impairment syndrome”. ’ RAF CAM opinion was that UK high-G operations’ risk levels, with existing mitigations, remained as low as reasonably practicable and tolerable.

5.10 RAF CAM noted that expert medical opinion was unanimously in support of its position statement: ‘the historical and current evidence base and experience does not support the existence of a low-G impairment syndrome. No nation either trains to mitigate “low G impairment” or modifies air operations to avoid that putative condition.’

5.11 It concluded that ‘Existing research has not attempted to identify cognitive effects over short duration G exposures typical of fast jet flight. The conduct of such research is problematic, as there are significant technical difficulties due to the short exposure times. Furthermore, a negative finding may not necessarily offer sufficient “proof of a negative” in the scientific context. Therefore, RAF CAM does not recommend further research in this area.’

5.12 The Review Team asked for further detail of the responses received from organisations which had been asked to provide an opinion for RAF CAM’s consultation with international colleagues and experts.

5.13 In December 2019 RAF CAM informed the review that they had consulted a number of authorities on whether they recognised a syndrome of cognitive impairment during routine flight activity that could affect critical decision making during exposure to G levels below those causing A-LOC or G-LOC. The following responses were obtained:

1. Aviation Medicine Working Group of the European Air Group (an interoperability forum of Air Forces from Belgium, France, Germany, Italy, Netherlands, Spain and the UK):

   ‘The existence of a low-G syndrome was not recognised by any representative’.

2. Human Factors and Medicine Panel of the North Atlantic Treaty Organisation:

   ‘did not support the existence of a low-G syndrome’.

3. Air Force Interoperability Council. This group were presented with the scenario of an exposure to between +2.5 and +3.5Gz for 15.5 seconds whilst wearing a G suit but without A-LOC or G-LOC:

   Canada ‘does not recognise such a syndrome of cognitive impairment when exposed to low G, such as 2-3G (outside of potential A-LOC due to push-pull or other predisposing condition at “low” G levels). There would be significant implications if, say, 3G for a pilot wearing a G suit (with appropriate inflation algorithm) causes cognitive impairment.’

   Australia ‘Not recognised as a medical or scientific syndrome.’

   New Zealand ‘No, we do not.’

   USAF ‘No, the USAF does not recognize any cognitive impairment during routine flight at those G-levels that affects critical decision making, that I’m aware of or even seen discussed. Just based on the information provided, I would think that a medically cleared and acrobatic (sic) trained pilot would be able to sustain those Gs fairly easily, especially with a functioning G suit for additional protection. With the Gs having been sustained for 15.5 seconds, that makes me think there wasn’t an issue with a rapid onset that could explain a temporary/mild A-LOC, or any kind of mechanical failure of the G inflation system. But I’m also not familiar with the Hunter’s life support system, nor its G performance capability.’

   US Navy ‘Not recognised.’

US Army 'SMEs [Subject Matter Experts] have never heard of this, nor are we aware of any reputable aerospace medicine doctors that endorse it with respect to high-performance aircraft. In fact, pilots regularly operate within this G profile with intact cognitive abilities, decision making, and psychomotor function during ACMs [Air combat manoeuvres].'

4. Aerospace Medical Association International Acceleration Interest Group 'the unanimous opinion was that such a syndrome was not recognised.'
5. Qinetiq 'confirmed that the company … did not recognise the existence of a low-G syndrome.'

5.14 The information provided to the review concluded with the following statement:

'CAM accepts that… expert opinion does not completely rule out the existence of a hitherto unrecognised low-G impairment syndrome. However, the total unanimity and unambiguous nature of expert opinion and long-term international experience offers significant reassurance. This is also congruent with the conclusions of the AAIB main report and supplementary findings. Therefore, with plausible and significantly more likely alternative explanations it remains our opinion that the probability of such a syndrome existing is so low as to render further research unnecessary.'

5.15 Following the publication of the AAIB's Supplementary Report published in December 2019 RAF CAM noted the AAIB's conclusion that 'the findings of the AAIB investigation published in Aircraft Accident Report 1/2017 remain valid', and 'The g experienced by the pilot during the manoeuvre was probably not a factor in the accident' and confirmed they would be making no further recommendations to the Service operating community.

Chapter 6

G Forces in Civil Aviation

Professional Pilots

6.1 In civilian commercial flying operations, pilot exposure to excessive G force is not encountered during normal flight and therefore the exposure to any greater than normal physiological effects is limited. Exposure is operationally limited due to two main factors:

1. The nature of the flight and factors such as take off, climb to height, flight from A to B, descent and landing; and
2. The aircraft design; it is the design of the airframe itself that determines the amount of G force that it is capable of achieving or can be applied to it without threatening its structural integrity.

6.2 Conversely, military fast jet pilots are exposed to significant physiological effects and are trained accordingly. They are trained to counter high levels of G force as it is common for them to experience sustained G force levels of over +5 Gz for a minute or longer, short durations of +7 Gz to +9 Gz for up to 10 seconds and rapid G onset rates of greater than 10 G/s, for example when undertaking air combat manoeuvring or basic fighter manoeuvres. There are also some circumstances in which pilots of military high-performance helicopters will experience high G force but this is uncommon as most helicopters cannot sustain high G.[248] Of those who can tolerate high G loads this would only be for short periods when undertaking fighter affiliation type evasive manoeuvres.

Fixed Wing Commercial Operations

6.3 G levels in commercial airline operations tend to be relatively constant around a narrow range centred on +1 Gz and very rarely exceed +2 Gz. The highest levels would be encountered as a consequence of a firm or hard landing. The G loading could also increase from an occasional over-positive control input in manual flight such as resulting from a Traffic Collision Avoidance System Resolution Advisory manoeuvre which can result in anything up to approximately +2 Gz.

6.4 Some G loading may be experienced in moderate or severe turbulence but it is normally very short lived, lasting for less than 0.5 seconds.

6.5 For the purpose of this review several commercial aircraft operators were asked for data on the G loading (maximum average and peak maximum) for their fleets during 2019 to understand the normal range of G expected in airline operations.

6.6 The total sample covered a wide range of Airbus and Boeing types and the data was sourced over a significant number of flights.

6.7 **Figure B** illustrates the average(s) of the maximum +Gz recorded for all sectors flown in 2019 and is representative of the dataset of a large/medium sized fixed wing UK operator.

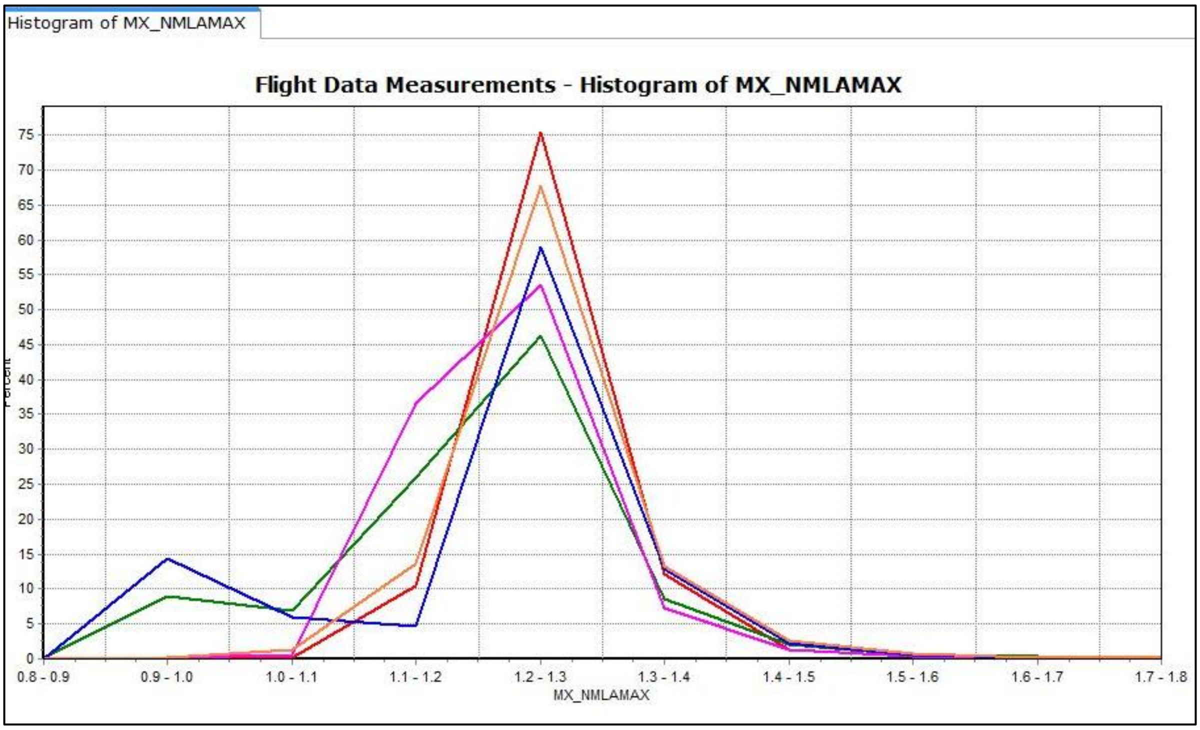

Figure B

Flight Data Monitoring analysis of vertical acceleration during flight Jan-Dec 2019: Fixed Wing operations

6.8 A +Gz level of greater than +1.75 Gz was recorded in only 0.000045% of the sectors with an exceptional peak recorded of +2.7 Gz.

6.9 A typical single sector would see an average of +1 Gz, with occasional brief deviations from +0.8 Gz to +1.3 Gz.

6.10 Data from a large/medium sized UK operator recorded a maximum of +2.3 Gz in 2019 with the average maximum ranging from +1.16 to +1.23 Gz.

6.11 For some large aircraft, flight manoeuvring load acceleration limits are published which tend to all be very similar and broadly fall in the range of -1 Gz to +2.5 Gz. Limits on Airbus types are functions of the fly-by-wire system and restrict how much input the pilot can have on the aircraft's control stick. There is no comparable restriction on Boeing types and there is no readout of G level in the flight deck.

Rotary Commercial Operations

6.12 An early National Advisory Committee for Aeronautics helicopter study indicates that the most significant load factors seen in helicopter operations can be +2.68 Gz on powered recovery from intentional autorotation (simulating engine failure and consequent loss of lift power from the rotors) using full available power in a combined cyclic-pitch and collective-pitch pull-up.[122] In normal flight, -0.5 to +1.5 Gz is typical and the upper level is rarely exceeded even with tight radius turns in police or survey aircraft. As with fixed wing aircraft the helicopters themselves can be certified from an airworthiness perspective to much higher G loads.

6.13 **Figure C** gives the data for G loading in 2019 from a typical rotary wing operator; the values have a relatively narrow range and none were recorded over +1.5 Gz.

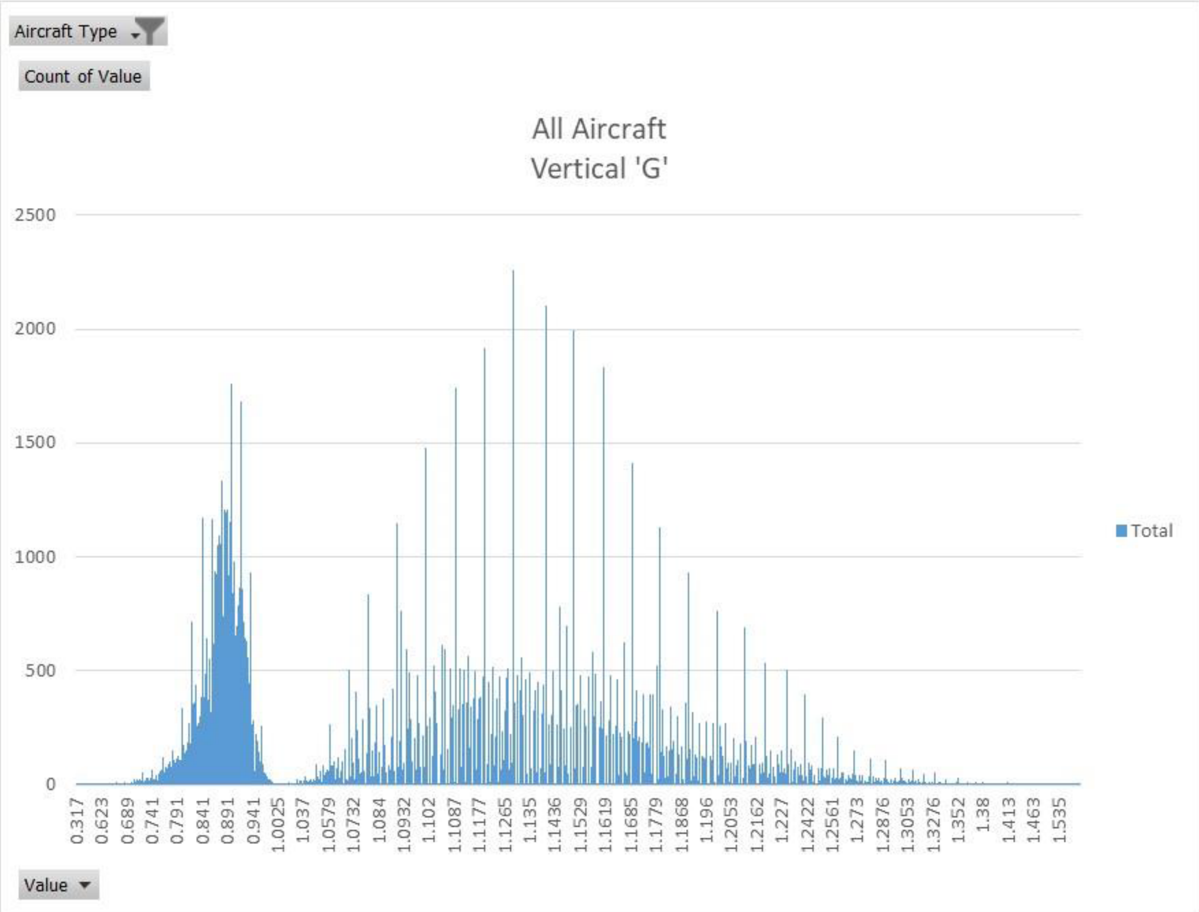

Figure C

Flight Data Monitoring analysis of vertical acceleration during flight Jan-Dec 2019: Rotary operator

General Aviation

6.14 Exposure to G forces for recreational, private pilots varies widely according to the type of flying being undertaken and aircraft being flown. Most student pilots will be instructed on how to recover from a spin and pull up out of a dive where they will experience some increase in G. Many will also be taught basic aerobatics including how to undertake an inside loop, however most will not be exposed to increased G force on a routine basis.

6.15 It is more common for private pilots to be exposed to the physiological effects of positive Gz than negative Gz which at an early stage of flying training would only normally be experienced in turbulence. Negative Gz causes considerable discomfort and it is usually this that causes pilots who progress to undertake aerobatics to limit their exposure.

Training for Increased G Exposure

6.16 For UK pilots to perform solo aerobatics they need to undertake a recognised training syllabus which includes both a theoretical and practical element. The current basic theoretical knowledge syllabus for a European Union Aviation Safety Agency (EASA) Aerobatic Rating is set out in European Union (EU) legislation[71] and includes:

> AMC 1 [Acceptable Means of Compliance] Flight Crew Licensing (FCL).800 Theoretical knowledge
>
> The theoretical knowledge syllabus should cover the revision or explanation of:
>
> (1) human factors and body limitation:
>
> (i) spatial disorientation;
>
> (ii) airsickness;
>
> (iii) body stress and G forces, positive and negative;
>
> (iv) effects of grey- and blackouts.

6.17 In addition to pilots training for the EASA Aerobatic Rating this syllabus is also followed by both the Aircraft Owners and Pilots Association and British Aerobatic Association.

6.18 Training is key to ensuring safe flight when aerobatic manoeuvres are being performed. Instruction in the risks associated with flying specific aircraft in certain operational environments is essential and should be covered in basic training prior to the pilot experiencing G forces.

6.19 Aerobatic pilots need to have undergone training to understand the potential effects of G forces and to understand that their individual tolerance may vary. They also need to know that G forces can have substantial physiological effects that have the potential to adversely affect flight safety even if the level reached is not very high and not sustained for a long period. The risk of alteration of consciousness events is a particular issue for pilots who have low hours on type.

Display Flying

6.20 Once qualified a private pilot may progress to more complex aerobatics and then may choose to enter aerobatic competitions or undertake display flying. In the UK a pilot may train to and perform aerobatics at flying displays to six skill levels: limited level, standard, intermediate, advanced, advanced plus and unlimited. There are no defined maximum +Gz levels for standard, intermediate or advanced level aerobatic display manoeuvres. Of note, intermediate level display pilots may undertake a Cuban 8 which is one of the more physiologically demanding manoeuvres.

6.21 Under Article 86(8) of the Air Navigation Order (ANO) for a pilot to undertake display flying at public events, the CAA must issue them a Display Authorisation (DA) provided it is satisfied that the applicant is a fit person to hold the authorisation and has the requisite knowledge, experience, competence, skill and physical and mental fitness to fly as a display pilot.[6] The CAA appoints Display Authorisation Evaluators (DAEs) to assess pilot performance and recommend the granting of DAs to pilots. The CAA has published Civil Aviation Publication (CAP) 1724 which contains guidance for DAEs so that they can provide recommendations to the CAA for the grant of DAs.[67] It sets out the required standards and provides guidance on best practice to ensure that pilots participating in flying displays can demonstrate the correct attitudes and behaviours, acquire the necessary knowledge and skills and continue to maintain such attitudes and skills over time. CAP 1724 also contains guidance for display pilots in areas such as preparation, standardisation and evaluations.

6.22 As part of the display pilot assessment process all applicants have to undergo an oral examination with a DAE to establish that they have an understanding of the operation and limitations of the aircraft to be flown along with an assessment of their attitude and motivation. One aspect that the DAE is required to cover is G load restrictions of the aircraft. The DAE is also required to 'discuss human performance and its limitations relating to display flying, including stressors such as anxiety, pressure or physiological limitations, cognitive biases, cumulative fatigue, mental attitude and personal limitations. Include in the discussion common causes of Flying Display accidents and Flying Display related human factor considerations / lessons learnt. Cover the importance of being suitably "fit to fly on the day" (i.e. physically and mentally rested and in the right frame of mind)'.

6.23 The CAA does not hold records of the total number of hours of display flying in the UK. It usually issues over 200 permissions annually for displays which can range in duration from 10 minutes up to 7 hours, with a wide variety of aircraft flown. The number of display permissions issued from 2017 to 2019 is shown in **Table C.**

	2017	**2018**	**2019**
Number of ANO Article 86 permissions	144	139	152
Number of SERA flying display permissions	51	62	51

Table C
Volume of flying display permissions issued for display seasons 2017-2019
SERA = Standardised European Rules of the Air

6.24 An ANO Article 86 event is one that is open and advertised to the public where some or all of the aircraft could be undertaking aerobatics. Flypasts in front of the public are also included in this category.

6.25 A Standardised European Rules of the Air (SERA) display permission is issued for a private flying display (for a private event such as a wedding) where some or all of the aircraft could be flying aerobatics. Some displays may consist of only a flypast.

6.26 Whilst CAP 1724 requires holders of DAs to individually record all DA renewals, upgrades and displays, both actual and practice in their log books, no information is collated centrally on the number of hours flown practising for displays, in aerobatic competitions, practising for competitions, or conducting recreational aerobatics.

6.27 Civilian pilots who undertake aerobatics choose to take part in this activity and have a wide range of previous flying experience. They are not generally exposed to high Gz levels on a regular basis. In contrast, their military counterparts have been through a highly selective process, have undertaken extensive training and, for fast jet pilots, are exposed to high Gz on a regular basis. Therefore the tolerance range to high Gz of civilian pilots is likely to be quite broad and potentially considerably less than military fast jet pilots.

Aerobatic Aircraft and G Exposure

Recreational Aerobatics

6.28 Aerobatic aircraft usually have a ‘G meter’ that records the maximum and minimum G levels during flight. The meter will record absolute levels of G but gives no indication of the G onset rate, nor the duration of maximum or minimum G exposure. It gives a highest and lowest reading which is valid for the time period since last reset as well as showing the G level being experienced in real time. During aerobatic manoeuvres the G meter can be used by the pilot to check G levels at entry, throughout and at the exit of manoeuvres, however this can become challenging if conducting complicated or advanced manoeuvres.

6.29 Levels of G force experienced in standard aerobatic manoeuvres are reported in a number of papers.[145,183] Typical examples include a fifteen second loop during which there are two exposures of one second to 3.5 G and a six second aileron roll with a maximum G experienced of +2.5 Gz.

6.30 Extended aerobatic sequences present more of a potential issue. An example is the ‘vertical 8’ manoeuvre that takes 35 seconds in total and involves varying levels of G up to +4.5 Gz and usually includes an outside loop that exposes the pilot to negative G force prior to positive G, with a resulting immediately reduced G tolerance.

6.31 Inexperienced pilots may be more prone to errors in their flying that can increase G loading in level and/or duration unexpectedly.

6.32 A lower number of accidents occur in practice flights compared with actual displays.[204] A pilot practising a display for an air show is less likely to need to please the crowd, be under peer pressure to perform to the edges of their ability or their aircraft’s performance and will be able to postpone the practice when the weather is unfavourable. Importantly, they are also unlikely to practise at a low altitude.

Ex-Military Aircraft

6.33 Certain high-performance ex-military aircraft flying in the UK on the civilian register must be operated under CAP 632 and the associated Organisational Control Manual.[66] Where these ex-military aircraft had an AGS fitted for operational flight that AGS should be operational. Paragraph 6.16 of CAP 632 states ‘Pilots who have little or no military jet or high-performance piston-engine experience will invariably be required by the Chief Pilot to undergo rigorous and detailed conversion training including, where appropriate, specific aviation medicine training’.

Display and Competition Flying

6.34 Pilots undertaking aerobatics as part of a public display or competition will be under pressure to perform to their own and their peer group's exacting standards.[204] There are significant human factors that come into play during a public event and a pilot will want to please the crowd when displaying.

6.35 Many aircraft commonly flown in aerobatic displays and competitions are capable of imposing significant G forces on the pilot. Modern examples include the Extra 200/300 which are capable of up to +10 Gz. Older aircraft can also reach significant levels of G; e.g. Yak 50/54/55 +9 Gz (and -6 Gz).

6.36 A display pilot will be reluctant to alter the routine they have planned and correction of minor errors can inadvertently lead to unexpectedly high G loading.[204]

+Gz Capability of Aircraft on the UK General Aviation Civil Aircraft Register

6.37 A review of all aircraft types on the UK General Aviation Civil Aircraft Register ('the Aircraft Register') was undertaken to establish the amount of +Gz of which each is capable. G onset rates were not considered as, whilst high-performance aircraft can generate significant onset rates, the calculation of specific onset rates are outside the scope of this review. Hence the use of the aircraft's +Gz capability, combined with its likely operating environment, was used to determine an overall Gz-related risk that could be posed to the pilot if flying that aircraft in that environment.

6.38 A list of aerobatic fixed wing powered aircraft was derived from the Aircraft Register and the likely operating environments researched for all aircraft types. Pilot Operating Handbooks, Aircraft Flight Test Schedules, Aircraft Handling Test Reports, EASA Type Certificate Data Sheets, aircraft specific Aircrew manuals, Aircraft Release to Service, Flight Reference Cards, Aircraft Operators and Pilots Association and Light Aircraft Association data were utilised.

6.39 For the purposes of this work, the Normal Operating G (Gno) limit was used as it is more readily available and is the limit to which pilots routinely operate, rather than the G Never Exceed, the force at which an aircraft may suffer catastrophic structural failure. As Gno may vary for the same aircraft flown at different altitudes, speeds and fuel weights, all calculations and comparisons were undertaken assuming a Velocity Never Exceed (Vne) in Knots Indicated Airspeed (KIAS) (the speed the pilot will see in the cockpit on the Airspeed Indicator) and a Gno envelope (where applicable) at sea level.

6.40 All general aviation aircraft listed in the Aircraft Register were divided into aircraft groups and categories based on the table in Chapter 9, page 63 of CAP 1724: Flying Display Standards Document as set out in Table D.[67]

Group	Category	Description
Single Engine Piston (SEP)	A	Engine Horsepower (HP) < 200
	B	201 HP to < 600 HP
	C	> 600 HP
Multi Engine Piston (MEP)	D	< 300 HP total
	E	301 - < 600 HP
	F	> 600 HP, Single Pilot
	Z	> 600 HP, Multi-pilot/Crew
Jet Powered Aeroplanes (JPA)	G1	Straight Wing, single engine jet aircraft
	G2	Swept Wing, single engine jet aircraft
	H	Multi engine jet aircraft
Turbo Prop Aircraft (TPA)	I1	Single Engine turboprop aircraft < 600 Shaft Horse Power (SHP)
	I2	Single Engine turboprop aircraft > 600 SHP
	J	Multi engine turboprop aircraft
Helicopters and Gyroplanes (H&G)	L	Helicopters
	M	Gyroplanes
Gliders, Hang Gliders and Paragliders (GLI)	N	Gliders
	O	Hang Gliders
	P	Paragliders
Microlight Aeroplanes (MLA)	T	Microlights with weight shift control
	U	Microlights with three-axis control
	V	Microlights with hybrid control
Powered Parachutes, Powered Paragliders, Powered Hang Gliders (LPA)	W1	All types of trike unit powered parachutes
	W2	All types of foot launched powered paragliders
	W3	All types of foot launched powered hang gliders

Table D

Aircraft Groups and Categories as defined in CAP 1724

6.41 +Gz onset rate was not calculated for each aircraft type as this would have required aerodynamic calculations outside the scope of this review including wing properties, thrust, weight, elevator areas and elevator to wing moment arm calculations. It is acknowledged however that an aircraft designed for aerobatics such as an Edge 540, that has a Gno limit of +12 Gz, would be able to achieve a considerably greater +Gz onset rate than a training aircraft such as a Bulldog which, whilst capable of performing aerobatics up to a Gno limit of +4.75 Gz, was designed as a training aircraft rather than a competition aerobatic aircraft.

6.42 The effect of sustained +Gz was considered out of scope of this review. Some aircraft, if they are light enough and produce enough thrust, can sustain high levels of +Gz for long periods of time whilst others may only be able to maintain their Gno limit in a dive due to their weight or lack of thrust. Routine flying does not require sustained levels of high Gz and even in competition aerobatics and air displays the duration of sustained Gz is limited.

6.43 A theoretical calculation of the maximum Gz that an aircraft can achieve can be undertaken using the aircraft design characteristics, specifically maximum wing performance, and the speed which, if exceeded, may result in structural damage to the aircraft, known as the Vne. However, this would usually give a theoretical level of Gz that would exceed the structural limitations of the aircraft. Therefore, for this review, if the Gno limit for an aircraft was not available, its risk category was allocated based on the type of aircraft, taking into account its design and Vne, and the environment it was likely to be operating in.

Exclusions

6.44 **Table E** lists aircraft types that were then excluded from the dataset. The aircraft in these categories were considered unable to achieve high levels of Gz either due to their design (e.g. helicopter, microlight) or because of their limited speed and/or thrust envelope (i.e. the aircraft does not fly fast enough) or a combination of all three. There are rare exceptions where aircraft such as helicopters do achieve high Gz whilst performing in an air display (e.g. Royal Navy Lynx display), however these aircraft are not on the civil register.

Exclusions	
L	Helicopters
M	Gyroplanes
N	Gliders
O	Hang Gliders
P	Paragliders
T	Microlights with weight shift control
U	Microlights with three-axis control
V	Microlights with hybrid control
W1	All types of trike unit powered parachutes
W2	All types of foot launched powered paragliders
W3	All types of foot launched powered hang gliders

Table E
Excluded aircraft

General Aviation Gz-Related Operational Risk

Aircraft Risk

6.45 For each aircraft group and category, analysis was conducted into the capabilities of the aircraft, specifically Vne and Gno and these parameters were used to subsequently categorise the aircraft into the three Aircraft Risk categories shown in **Table F**.

Description	Aircraft Risk
Aircraft has **limited ability** to subject the pilot to high levels of Gz	Low
Aircraft has **some ability** to subject the pilot to high levels of Gz	Medium
Aircraft has **significant ability** to subject the pilot to high levels of Gz	High

Table F
Aircraft risk categories

Environmental Risk

6.46 The environment that the aircraft is most likely to be operated in was also categorised as displayed in **Table G**.

Description	Environmental Risk
Aircraft operated in a **benign environment** (e.g. touring or transit flying)	Low
Aircraft operated in a **moderately dynamic** environment e.g. aerobatic flying training or low energy aerobatic manoeuvres at air displays)	Medium
Aircraft operated in **highly dynamic** environment (e.g. competition aerobatics or performing high energy aerobatics at air displays)	High

Table G
Environmental risk categories

Overall Risk

6.47 An overall Gz-related risk posed to a pilot flying the aircraft in a specific environment was then determined taking into account the aircraft type and likely operating environment of each type as shown in **Table H**.

		Environmental Risk		
		Benign	Moderately Dynamic	Highly Dynamic
Aircraft Risk	Limited Gz Capability	Low	Low	Medium
	Some Gz Capability	Low	Medium	High
	Significant Gz Capability	Medium	High	High

Table H
Overall Risk Matrix

6.48 The risk categories are defined as follows:

- Low. Based on limited aircraft capability and a benign or moderately dynamic operating environment or some capability in a benign environment, the overall G-related risk to the pilot is considered to be low.
- Medium. Based on combinations of aircraft capability and operating environments in between the low and high risk categories, the overall G-related risk to the pilot is considered to be medium.
- High. Based on some aircraft capability in a highly dynamic operating environment or significant capability in either a moderately or highly dynamic operating environment, the overall G-related risk to the pilot is considered to be high.

6.49 An aerobatic aircraft that can achieve a high level of Gz, operating in a competition aerobatic environment, is considered to pose a greater risk than an aircraft that can only achieve a low level of Gz and is predominantly operating in a more benign environment.

6.50 Many of the aircraft in the dataset can achieve a high level of Gz without operating in a challenging environment.

6.51 It was considered that pilots flying high Gz-capable aircraft are less likely to be subject to high Gz unless either operating in a competition or display environment or practising aerobatics prior to a competition or displaying at an air show.

6.52 There were 175 General Aviation fixed wing powered aircraft types on the UK Aircraft Register in April 2020. **Table I** shows the Gz-related risk levels following analysis of their Gz capabilities and operational environments.

Risk Grouping	Criteria	Number of Aircraft Types	Percentage
Overall Risk	Overall risk level of Low	38	41
	Overall risk level of Medium	33	36
	Overall risk level of High	**21**	**23**
SEP Group	Low risk aircraft types	34	41
	Medium risk aircraft types	31	38
	High risk aircraft types	**17**	**21**
Category A	Low risk aircraft types	31	67
	Medium risk aircraft types	12	26
	High risk aircraft types	**3**	**7**
Category B	Low risk aircraft types	3	13
	Medium risk aircraft types	7	29
	High risk aircraft types	**14**	**58**
Category C	Low risk aircraft types	0	0
	Medium risk aircraft types	12	100
	High risk aircraft types	0	0
Jet Powered Aircraft Group	Low risk aircraft types	0	0
	Medium risk aircraft types	2	33
	High risk aircraft types	**4**	**67**
Category G1	Low risk aircraft types	0	0
	Medium risk aircraft types	2	50
	High risk aircraft types	**2**	**50**
Category G2	Low risk aircraft types	0	0
	Medium risk aircraft types	0	0
	High risk aircraft types	**2**	**100**

Table I
Gz-related risk of aircraft on the UK Aircraft Register

6.53 The following can be highlighted from the data in **Table I**:

- 23% (21 aircraft types) of the 92 aerobatic aircraft types considered on the UK General Aviation Civil Aircraft Register were categorised as High Risk. When considered against all 175 General Aviation fixed wing powered aircraft types this reduces to 12%.
- 21% (17 aircraft types) of the SEP Group are categorised as High Risk. These are mainly competition aerobatic aircraft.

- Within the SEP Group, Category B aircraft types pose the greatest risk with 58% (14 aircraft types) categorised as High Risk compared with 7% (3 aircraft types) in Category A and zero in Category C.
- 67% (4 out of 6 aircraft types) of the Jet Powered Aircraft Group were categorised as high risk, 50% in Category G1 and 100% of Category G2.

6.54 It is important to note that it is the combination of aircraft capability and operating environment that poses the risk.

6.55 The 21 aircraft on the Aircraft Register that are categorised as High Risk due to their Gz capabilities and operating environment are displayed in **Table J**.

6.56 The full categorisation of risk for the 92 aerobatic aircraft types considered on the Aircraft Register is given in the Aircraft Categorised Risk Data table in **Appendix F**.

Group	Aircraft	Hp	Category	Max Indicated Air Speed (Vne) (kts)	Gz Limit (Gno)	Environment	Overall Risk Categorisation
SEP	RYAN ST3KR	125	A	130	10	Highly Dynamic	High
SEP	CHRISTEN EAGLE	200	A	185	9	Moderately Dynamic	High
SEP	EXTRA 200	200	A	200	10	Moderately Dynamic	High
SEP	CAP 232	300	B	219	10	Highly Dynamic	High
SEP	EDGE 540	310	B	230	12	Highly Dynamic	High
SEP	EXTRA 230	230	B	220	10	Moderately Dynamic	High
SEP	EXTRA 300	300	B	220	10	Moderately Dynamic	High
SEP	EXTRA 330LX	315	B	219	10	Moderately Dynamic	High
SEP	GB1 GAMEBIRD	315	B	234	10	Moderately Dynamic	High
SEP	MXS-R	320	B	240	14	Highly Dynamic	High
SEP	SUKHOI SU-26M	360	B	240	12	Highly Dynamic	High
SEP	XA42	315	B	215	10	Highly Dynamic	High
SEP	YAK 50	451	B	220	9	Highly Dynamic	High
SEP	YAK 54	360	B	243	9	Highly Dynamic	High
SEP	YAK 55	360	B	240	9	Highly Dynamic	High
SEP	ZLIN 50	260	B	158	9	Highly Dynamic	High
SEP	ZLIN Z 526	208	B	170	6	Highly Dynamic	High
JET	AERO L-39C ALBATROS	Jet	G1	400	8	Highly Dynamic	High
JET	GALEB G-2A	Jet	G1	380	8	Highly Dynamic	High
JET	GNAT	Jet	G2	525	7	Highly Dynamic	High
JET	HUNTER	Jet	G2	620	7	Highly Dynamic	High

Table J

Aircraft categorised as having High Gz-related risk

Chapter 7

Hypoxia

Human Physiological Systems

7.1 While a fully comprehensive review of all the potential physiological effects of flight is beyond the scope and remit of this review it is appropriate to set out some background about systems of the human body that are influenced by the effects of flight.

7.2 In flight, some of the most prominent physiological mechanisms affected by perturbations of their environment are the inter-related respiratory and the cardiovascular systems.

7.3 Internal biological processes are largely dependent on a process known as 'aerobic respiration'. This refers to the way in which food substrates are utilised, with oxygen (chemical symbol O_2), to meet metabolic requirements. Almost all human tissues require a supply of oxygen and some are very intolerant of anything more than a very brief interruption to that supply.

7.4 Respiration can be considered as having 'external' and 'internal' components. External respiration refers to the process of bringing oxygen into the body and its passage through the respiratory membranes of the lungs as well as the elimination of carbon dioxide (chemical symbol CO_2). Internal respiration refers to the distribution of oxygen through the circulation and into the cells of the body that need it for metabolism and the transfer away from the cells of carbon dioxide. In this way the human cardiovascular and respiratory systems work in concert to deliver the required oxygen from the external air environment to living cells and to remove carbon dioxide, a by-product of metabolic processes. The output of oxygenated blood from the lungs via the left ventricle of the heart should contain sufficient oxygen to meet all the body's requirements and the carbon dioxide in the venous blood returning though the right side of the heart should be eliminated by the lungs.

7.5 The amount of oxygen carried in a volume of blood is critically dependent on the role of haemoglobin (Hb) which is a substance contained in the red blood cells that circulate in the blood. Haemoglobin binds reversibly with oxygen so that it can carry the oxygen from the lungs to the body tissues where it is required. The very small amount of oxygen that can be carried dissolved in the fluid within the blood is insufficient to service the needs of the body tissues on its own. Oxygen is released when the blood arrives in tissues with a low oxygen tension and so provides the essential support for the energy-generating metabolic processes of those tissues. This is demonstrated in the oxygen dissociation curve (**Figure D**).

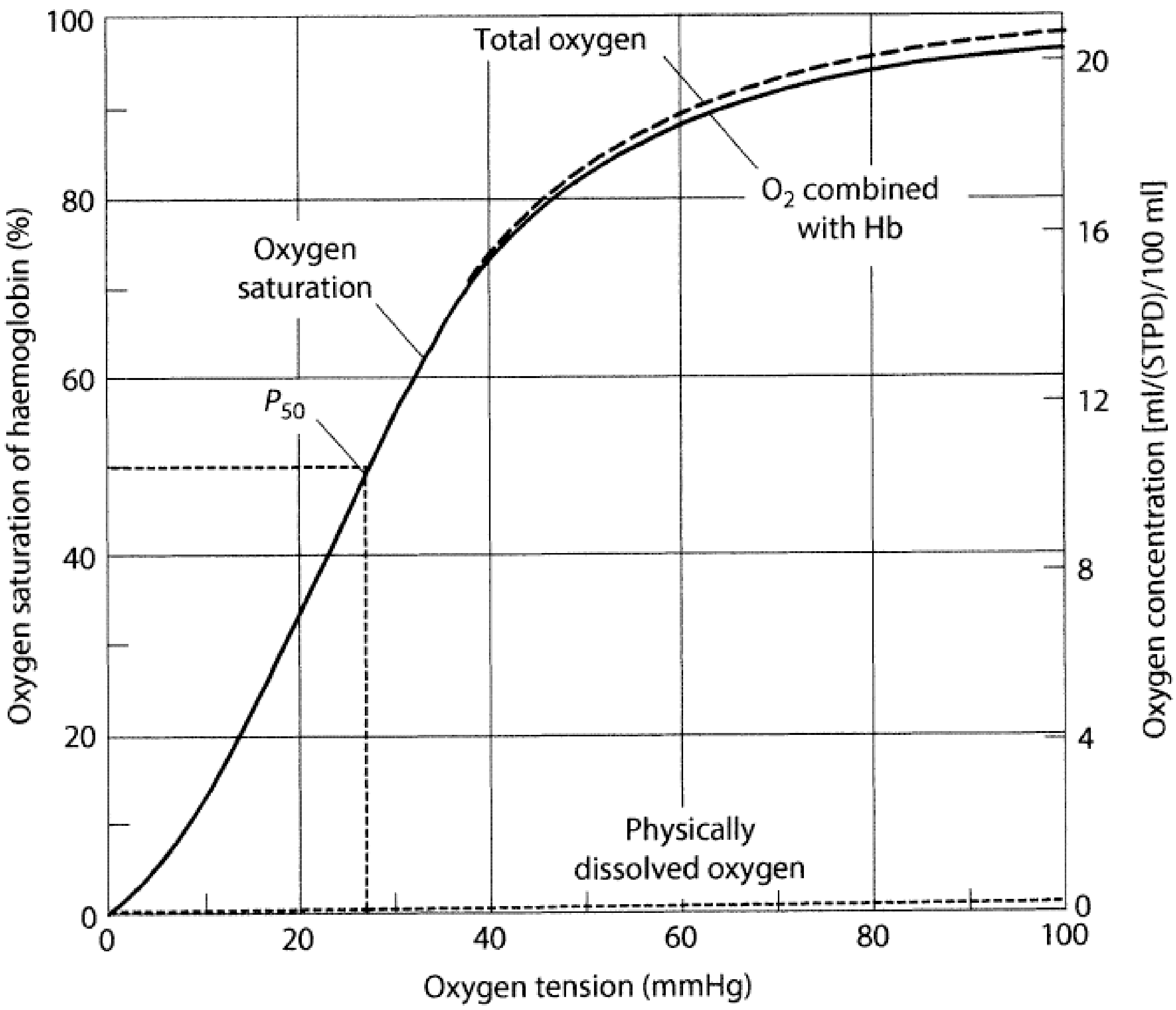

Figure D. Oxyhaemoglobin dissociation curve of blood.
Reproduced from Ernsting's textbook of Aviation & Space Medicine with kind permission of Taylor & Francis.[88]

The relationship for normal (Hb concentration, pH, pCO_2 and temperature) blood between oxygen tension and oxygen concentration (dashed line) and oxygen saturation (solid line). The flatter part of the curve, to the right, shows the relatively modest reduction of saturation with oxygen tensions between 70 and 100 mmHg and is of relevance for the tolerance in health of ascent to low altitudes without substantial falls in oxygen saturation.

7.6 After its passage through the tissues the haemoglobin returns in the blood to the heart via the venous system, to circulate once more through the lungs and be recharged with oxygen.

7.7 The output of the heart is measured as the product of the volume of blood ejected with each beat of the heart, that is the stroke volume, and the frequency of that action, the heart rate. Changes in either will influence the volume of blood expelled from the heart in unit time, the cardiac output, usually expressed in litres per minute.

7.8 When the body is at rest the cardiac output is relatively constant. A steady heart rate (also known as pulse rate) normally delivers sufficient cardiac output to fulfil the requirements of the regional circulations of the body provided the arterial driving pressure (or blood pressure) is adequate to deliver it.

7.9 In normal life the steady state will be influenced by many factors. These can vary from the need to increase the blood flow to the gastro-intestinal tract to assist in the digestion of food and the distribution of its products around the body, to the additional supply of oxygenated blood to skeletal muscles when undertaking exercise. Even rising from the recumbent to the upright position will have effects on pulse and blood pressure. The reflexes that control respiration and the cardiovascular system can be adjusted by inputs from the nervous system and the release of hormones such as adrenaline and can provide rapid changes to meet immediate physical demands such as exercise.

7.10 Similarly, to increase the volume of inspired air available for respiratory exchange in the lungs, that is the ‘minute volume’, the breathing rate must increase and/or the volume of gas moved into and out of the lungs with each breath, the ‘tidal volume’, raised. In the absence of significant hypoxia (the condition when tissues have inadequate oxygen to conduct metabolism) the respiratory rate is closely linked to the amount of carbon dioxide present in the circulation, which is important for the maintenance of a balance between the acids and alkalis (bases) in the body. This ‘acid-base balance’ influences greatly the body’s metabolic processes.

7.11 When specific organs need more energy (i.e. the metabolic demands increase) a number of changes occur to meet that demand. For example, to meet the metabolic requirements of exercising muscles there is an increase in respiratory exchange in the lungs and an increase in blood flow through the muscles to both provide additional oxygen and remove the carbon dioxide produced within them.

7.12 The circulation of blood flow around the body is one continuous system within which are two major functional areas. These are the systemic (carrying blood with oxygen from the heart to the body’s organs) and the pulmonary (carrying blood which has had much of the oxygen removed to the lungs to be recharged) with blood traversing each in turn, that is, in series. The various systemic regional circulations, supplying different organs, operate in parallel and blood flow is varied through each circulation according to need. In this way the flow is finely tuned to deliver oxygenated blood to meet the requirements of specific organs.

7.13 Local blood flow to a specific region is controlled by both pulse rate and the degree of dilatation or constriction of blood vessels supplying that region. If one region demands an increased flow it can be facilitated by dilatation of the arteries supplying that region and, if it is necessary to divert blood flow away from another area to meet the demand, constriction in that other region's arterial supply will reduce the flow there for a time. Through these mechanisms the body is able to direct oxygenated blood to the most critically important areas and the relative distribution to differing regional circulations is responsive to specific requirements on a moment by moment basis.

7.14 Brain (cerebral) tissue is relatively intolerant of hypoxia and blood flow has less variability than some regions although there are local changes in perfusion association with increases in cerebral activity.[124] Cerebral blood flow rises sharply when local arterial hypoxia occurs, and is almost doubled where oxygen tension falls to 30 mmHg.[124] Cerebral blood flow does fall slightly on moving from lying or sitting to standing up but is generally adequate for cerebral perfusion unless arterial pressure falls substantially. There are four main arteries that supply the head and brain and the preservation of the blood supply to the brain is assisted by the existence in the brain of an anatomical arrangement of branches of the main arteries joining as a circle (the circle of Willis). This serves to preserve cerebral blood flow to meet the demands of the brain under normal physiological circumstances even if one or more of the main supply arteries is compromised.

7.15 The pulmonary circulation is in series with the systemic circulation. Blood is pumped into it from the right ventricle of the heart and passes through the small blood vessels surrounding the air sacs in the lungs, the alveolar capillaries. It is brought into such close proximity with the alveolar air sacs, situated at the ends of the airways, that exchange of oxygen and carbon dioxide can take place rapidly. After passage through the lungs, blood now replenished with oxygen returns to the heart to be pumped into the systemic arterial system again. Within the pulmonary circulation there can be regional variations to facilitate good blood flow through well-ventilated parts of the lungs and less blood flow through poorly-ventilated zones thus optimising the exchange of respiratory gases.

The Need for Oxygen

7.16 The maintenance of a normal oxygen level (known as the partial pressure of oxygen or oxygen tension) in the tissues by the continuous supply of adequate oxygen molecules to meet metabolic requirements is essential for life. This state of 'normoxia' can be subject to a range of factors that could prevent adequate oxygen being supplied to active tissues. These hypoxic conditions (when tissues do not have adequate oxygen for normal metabolism) can be classified in a number of ways.

- Hypoxic hypoxia
  - when there is an inadequate supply of oxygen getting into the pulmonary capillaries. Causes of this include some lung conditions, heart failure and exposure to environments in which the partial pressure of oxygen in the inspired air is too low, such as can occur at high altitude. The last situation is referred to as 'hypobaric hypoxia'.
- Anaemic hypoxia
  - when there is insufficient oxygen carrying capacity in the blood. Causes include blood diseases and lack of iron in the diet.
- Ischaemic (circulatory) hypoxia
  - when the flow of oxygenated blood is insufficient to meet tissue demand. Causes include obstructions to blood flow and sudden, major blood loss.
- Histotoxic hypoxia
  - when there is a fault in the metabolic processes such as might occur owing to the presence of a poison such as cyanide or vitamin deficiencies that interrupt the utilisation of oxygen at a cellular level.

7.17 Each of these forms of hypoxia can occur in aviation, alone or in combination, but the hypoxic hypoxia arising from ascent to altitude (hypobaric hypoxia) is the form most commonly associated with flight.[88]

7.18 The majority of human habitation is at a relatively low height above sea level. The barometric pressure at which air is breathed at these altitudes, although subject to meteorological variation, is more than adequate in a healthy person to provide an appropriate partial pressure of oxygen within the lungs to meet the body's needs. Some physiological modifications, such as increasing the number of red blood cells carrying haemoglobin to adapt to living at higher altitudes, occur in highland populations and as the result of terrestrial acclimatisation in lowlanders ascending slowly in mountainous regions. In aviation, ascent to hazardous altitudes occurs far too rapidly for any acclimatisation to occur and have a beneficial effect.

7.19 There are a number of immediate effects of sudden exposure to a low oxygen pressure at altitude. The central nervous system (including the brain) is considered to be the organ that is most sensitive to oxygen insufficiency and the first one to suffer under these conditions. Oxygen consumption by the brain is relatively high and alters little in response to activity such as exercise.[99] Subtle neurological signs, often unnoticed by the subject, are associated with degrees of cerebral hypoxia.

Hypobaric Hypoxia

7.20 Flying involves ascending to altitude. The barometric pressure of the atmosphere falls in an exponential manner on ascending from sea level and breathing the ambient air will result in a fall in the partial pressure of oxygen in the lungs. Above specific altitudes the effects of this can induce impairment in mental and physical function of the human body. In health, exposure to quite modest altitudes can be tolerated without substantial adverse and clinically detectable changes. However, extended exposure to greater altitudes or even brief exposures to more extreme altitudes can have serious effects and can lead ultimately to death from severe hypoxia.[102]

7.21 The principal causes of hypobaric hypoxia in flight are:

1. ascent to altitude without supplemental oxygen or
2. a failure of a personal oxygen system to supply adequate oxygen to meet respiratory requirements or
3. a failure of an aircraft's pressurisation system so that the occupants are exposed to a much higher altitude than expected.

7.22 Hypobaric hypoxia has a range of physiological effects, irrespective of the cause, although the severity of adverse manifestations and the rapidity with which they occur may be influenced by the manner in which they arise.

7.23 Sudden exposure to an altitude of 50,000 feet is expected to lead to unconsciousness within approximately 15 seconds and death to occur within a few minutes unless adequate oxygen is provided immediately. In contrast, exposure to an altitude of about 10,000 feet is unlikely to cause immediate or noticeable symptoms in a healthy adult at rest. Exercising at 10,000 feet may bring about more noticeable effects including greater breathlessness than that degree of exercise would induce at sea level and exercising at higher altitudes is likely to lead progressively to more marked signs and symptoms. Sustained exposure of several minutes to an altitude of 15,000 feet commonly causes generalised headache and a reduction in physical work capacity and may have noticeable effects on higher mental functions. After a few minutes between 15,000 and 20,000 feet the resting individual is likely to notice some influence on neuromuscular control so that adjusting switches or small controls may be more difficult and on higher mental functions. There may be a loss of appropriate self-assessment and lack of awareness of deterioration in performance. At these altitudes the degree of hypoxia experienced will stimulate a respiratory response with increased ventilation, leading to hyperventilation (breathing at a rate and volume in excess of the body's requirement to remove carbon dioxide) and its associated hypocapnia (a resultant reduction in carbon dioxide in the lungs and circulation) which can cause its own signs and symptoms. Any physical exertion will aggravate this state still further.

7.24 On sudden exposure to altitudes above 20,000 feet, even at rest, a subject breathing ambient air would show declining functionality in mental and physical performance leading ultimately to loss of consciousness and eventually death. The time course of this deterioration varies according to the specific altitude and there is variation in the signs and symptoms exhibited. There is also variation in the interval before the individual becomes unable to take action themselves to address the challenge but, importantly, the lack of awareness of the need to act can occur at a very early stage. This so called 'Time of Useful Consciousness' (TUC) or 'Effective Performance Time' is the interval between loss of adequate inspired oxygen and the loss of functional capacity although frank unconsciousness may not have yet occurred. TUC can be on average 3-5 minutes at 25,000 feet and just 15-20 seconds at 40,000 feet but with wide inter-personal variation.[88]

7.25 That the effects of hypoxia are insidious has been known for very many years and is the reason that many military aircrew undergo specific training to allow them to experience how hypoxia affects them personally. This is in the expectation that prior training will help them to recognise the effects of hypoxia should it occur in flight, arising from any one of the three scenarios listed above. A wide range of symptoms and signs may occur although it is considered that individuals may experience similar symptoms whenever they become hypoxic, even if the threshold varies.[138]

Hypoxia and Neurological Effects

7.26 Effects of hypoxia on the nervous system can manifest themselves by impairing nervous function and mental performance. Both are clearly of great significance in aviation.

7.27 While severe neurological effects associated with high altitudes are readily recognised, the more subtle psychological and physiological manifestations associated with lower altitudes have been the source of research and debate. Results from McFarland in 1938 quoted in Gillies textbook of aviation physiology report dizziness, light headedness and inability to think clearly after 20 minutes at the equivalent of 14,000 feet.[102]

7.28 The explanation for the importance of the altitudes between 8,000-12,000 feet as the region at which adverse effects may start to appear is related to the way in which oxygen is bound to, and becomes dissociated from, haemoglobin in the circulation. This varies according to the oxygen tension of the tissues through which the blood is circulating and is of great significance in the uptake and delivery of oxygen between the lungs and the respiring tissue.[88,99] In health, when breathing air at sea level, a high proportion of haemoglobin will be carrying oxygen. This proportion is known as the oxygen saturation, commonly up to about 98%. However, owing to the strong binding characteristics of haemoglobin that saturation falls only modestly initially on ascent from sea level to about 8,000 - 10,000ft.

7.29 There has been extensive debate on the extent of neurological effects from exposure to altitudes below 10,000 feet. Denison et al investigated the deleterious effect of hypoxia on higher mental function at quite modest altitudes.[80] He reported that exposure to an altitude of 8,000 feet had a detrimental effect on mental function, specifically on learning. This followed a previous observation by Ernsting that subjects exposed to 8,000 feet breathing air prior to a decompression had already suffered a reduction in higher mental functions.[87]

7.30 Since Denison's work many other studies have investigated the influence of mild hypoxia on mental function with somewhat variable results. Kelman et al in 1969 decided that their results did not support a suggestion that at 8,000 feet general psychological performance is adversely affected but that Denison's findings might be on specific specialised functions.[143] Green and Morgan in 1985 reported results on experiments at three altitudes and, commenting critically on previously published studies, concluded no significant effects of modest altitude on performance were seen.[115] However their exposures were of less than 10 minutes' duration and any marked effects may not have been revealed in that short time at such a moderate altitude.

Hypoxia and Hyperventilation

7.31 There is great individual variability in response to hypoxia partly related to the associated degree of hyperventilation that it stimulates. Van Dorp et al reported in 2007 the results of studies in which the effects of adding carbon dioxide to inspired gas had a beneficial effect on the performance of complex tasks under conditions of hypoxia, in contrast to a poorer performance when hypocapnia (low carbon dioxide concentration) was allowed to occur.[277]

7.32 Gibson determined that hyperventilation on its own can induce a range of symptoms difficult to distinguish from those of hypobaric hypoxia.[101] However he concluded that, although hyperventilation had effects on motor function, there was little or no evidence of a reduction in psychomotor function associated with the fall in carbon dioxide by itself. This is despite cerebral blood flow being sensitive to changes in arterial carbon dioxide tension.[124] Significant hyperventilation in the absence of hypoxia can produce symptoms or even syncope (fainting) although there appears to be at least a sustained level of cerebral blood flow irrespective of further reductions in arterial carbon dioxide below 20 mmHg.

7.33 Hyperventilation is common and can induce signs and symptoms similar to those induced by hypoxia but, as it does not appear to affect psychomotor function, any effect on higher mental function is likely to be limited.

Hypoxia in Low Altitude Flight

7.34 Military fast jet aircraft are equipped with low differential cockpit pressurisation systems and personal oxygen systems for use throughout flight. Thus, provided all this equipment is functioning normally, the aircrew would be protected against hypoxia at any operational altitude. Even in the event of loss of cabin pressurisation at high altitude the personal oxygen system would respond automatically such that the crew would be fully protected against hypoxia. At low altitudes, such as might be associated with display flying, hypobaric hypoxia in aircrew operating military fast jets with fully functioning life support systems is unlikely.

7.35 The vast majority of light aircraft and helicopters involved in displays are unpressurised. The cabin altitude in unpressurised aircraft is essentially the same as the environment at that altitude.

7.36 A large jet, commercial or transport aircraft, flown for the purposes of displaying to those on the ground, would be flown at considerably less than its normal cruise altitude and as a consequence its cabin altitude would be very much lower than the maximum permitted. Unpressurised aircraft will also be flown, for the purposes of display, at much lower altitudes than their normal operational limits.

7.37 Although there has been research and debate about potential subtle effects of modest altitude exposure on intellectual functions, the learning of new tasks and the particular sensitivity of night vision to hypoxia, day time flying of well-practised procedures at very modest altitudes has not been reported in the literature reviewed to pose specific hypobaric hypoxic challenges.

Ventilation/Perfusion Inequalities in the Lungs

7.38 The very many alveoli present in the lung are not ventilated equally at +1 Gz, nor are they all perfused with blood equally. Several possible functional conditions thus exist in different parts of the lung; well-ventilated alveoli, well perfused with blood: poorly-ventilated alveoli well perfused with blood: well-ventilated alveoli poorly perfused with blood: and finally, poorly-ventilated and poorly-perfused alveoli. The overall efficiency of respiratory gas exchange is a function of the overall proportion of these groups.[186]

7.39 Thus, some deoxygenated blood passes through the lung without undertaking full respiratory exchange, returns to the heart and is then pumped into the systemic circulation. This is termed a right to left shunt and if the shunting is substantial it can induce a degree of hypoxaemia (low blood oxygen).[111]

Hypoxia with +Gz

7.40 When a pilot is exposed to +Gz the small ventilation/perfusion inequality that exists in the lungs in the resting state will increase. A right to left shunt can occur, which leads to a generalised reduction in the oxygenation of blood leaving the lungs to be distributed to the rest of the body. The degree of shunting increases under +Gz because of the influences on both ventilation and perfusion of the greater forces applied above and below the level of the heart.[106] The reduction in oxygen carriage (desaturation) of the arterial blood becomes apparent at around +3 Gz with a sustained exposure to +5 Gz (for 1 minute) leading experimentally to a fall in arterial oxygen saturation value of 85%, compared with the normal level at +1 Gz of 98%.[106,113] Centrifuge experiments have shown that the right to left shunt can be equivalent to 50% of cardiac output at +5 Gz.[106]

7.41 The inflation of anti-G trousers may increase this effect and the performance of an AGSM can also influence regional pulmonary blood flow.

7.42 Cerebral arterioles are known to dilate with hypotension, hypercapnia and hypoxia.[124] The second of those is not likely under acceleration but the other two could be factors to a greater or lesser extent. This autoregulation of cerebral blood flow with +Gz serves to preserve the oxygen supply to the brain and protect cerebral function.

Comparison of G-Induced Hypoxia with Altitude-Related Hypoxia

7.43 Studies carried out by Stevenson, and published in his Doctor of Philosophy (PhD) thesis, included results showing the effect of various degrees of hypoxia.[261] In this case breathing gas with a partial pressure of oxygen appropriate to a degree of hypobaric (altitude-induced) hypoxia was supplied to the experimental subjects so as to induce a simulation of hypobaric hypoxia but at normal (approximately sea level) barometric pressures, hence normobaric hypoxia. In these studies physiological measurements at various levels of normobaric hypoxia (with and without modification of the inspired carbon dioxide, which itself influences cerebral blood flow) and centrifuge-induced exposure to +Gz were reported.

7.44 It is reported in the thesis that +Gz exposures have some physiological equivalence to unprotected exposures to altitudes of between 12,000 and 18,000 feet but the time course in which the influence of such levels is exerted may be rather different. While there is comment within the thesis to an effect of changes to cerebral oxygen saturation, arising from the most significant level of hypoxia used (equivalent to approximately 16,000 feet), on cognitive performance, specific demonstrations of such effects were not reported.

Cognitive Performance and Hypoxia

7.45 Hypoxic hypoxia may occur across a range of activities which involve altitude, including flying and mountaineering. A hypoxic state may be induced for the purposes of research, but not all results will be applicable for aviation environments where hypoxia may be experienced and there are several methodological challenges with hypoxia research.

7.46 The literature on hypoxia was sampled to understand whether there were substantial differences in cognitive effects between the methodologies used for hypoxia associated with altitude and with acceleration.

7.47 As with the effects of acceleration, the effects of hypoxia on cognitive performance have been measured in a variety of different ways. This makes drawing general conclusions from the results of varied studies difficult. Some of the methodological differences which make comparison challenging include:

- The way that hypoxic conditions are reported varies; for example, between a standard altitude and percentage blood oxygen saturation. In some studies CO_2 levels (e.g. alveolar CO_2 tension) or blood O_2 saturation levels are maintained at normal values despite a hyperventilatory stimulus, induced by the degree of hypoxia experienced.
- Altitudes and the induction of hypoxic conditions used in research vary.

- Exposure times and previous experience with hypoxia (or activities where hypoxia may be expected such as flying or mountaineering) vary. The distinction is important because flying causes an ascent much too rapid to allow acclimatisation, such as may occur with mountaineering.
- Mostly male subjects have been used, consequently there are potential differences in the way that female participants might respond to hypoxic conditions that remain unclear.
- Some studies used supplementary oxygen or other ameliorating devices, others did not.

7.48 As with the acceleration psychology literature, an attempt has been made to group similar research together to create a visual summary, as represented in **Table K** below:

Category	**Oxygen Saturation level (SaO_2) or altitude**	**Type of Decrement**	**References**
Vigilance	8,000 feet	Hypoxic subjects performed better than control group on an easy vigilance test, but opposite results found on a harder test.	Kelman & Crow (1969)[142]
	11,500 feet	Four-hour exposure had no effect on a simple vigilance test.	Fiorica, Burr, Moses (1971)[91]
Memory and central processing	8,000 feet	Learning was improved with oxygen than without.	Billings (1974)[26]
	8,000 feet (equivalent)	Once tasks were learned, did not produce a performance decrement.	Denison, Ledwith, Poulton (1966)[80]
	8,000 feet	No psychomotor task decrement (tried to replicate Denison et al 1966).	Kelman, Crow, Bursill (1969)[143] Paul & Frazer (1994)[209]
	12,500 feet	Pilot operational tasks and command errors increased with hypoxia.	Peacock (2012)[210]

Category	Oxygen Saturation level (SaO_2) or altitude	Type of Decrement	References
	31,000 feet	Working memory strongly impaired.	Malle et al (2013)[170]
Stimulus response and Psychomotor tasks	65% SaO_2	Response times to an auditory stimulus were slower.	Beach & Fowler (1998)[19] Fowler, Prlic, Brabant (1994)[95]
	High CO_2 levels 8,000 feet	Performance on five different psychomotor tests declined at higher CO_2 levels.	Gibson (1978)[101]
	up to 3,660 feet	Rate of learning did not change between altitude groups, but overall performance decreased at highest altitude.	Green & Morgan (1985)[115]
	O_2 12%	Exposure to 12% O_2 degrades performance on a psychomotor task during heavy exercise.	Knight et al (1991)[146]
	Up to 12,500 feet	Procedural errors increased during hypoxia.	Nesthus, Rush, Wreggit (1997)[189]
	12,467 – 14,763 feet	Arterial desaturation attenuates cognitive improvements during exercise under hypoxia.	Komiyama et al (2017)[149]
	16,568 feet	Reaction time, attention switching rapid visual processing showed no significant changes to hypoxic conditions.	Pun et al (2018)[217]
	18,000 feet	Performance on a range of simple cognitive tasks all degraded at this altitude with no supplementary oxygen.	Scow, Krasno, Ivy (1950)[245]

Category	Oxygen Saturation level (SaO_2) or altitude	Type of Decrement	References
	Up to 22,965 feet	Performance on a choice reaction task was stable in hypoxia after an acclimation protocol. Note: This study was in mountaineering scenarios, not aviation.	Leifflen et al (1997)[160]
Mood and Affect	8,000 feet	Mood declined (although complex cognition did not).	Legg et al (2016)[Abstr][159]
	14,379 feet	Hypoxia degraded mood and cognitive function.	Bonnon, Noel-Jorand, Therme (1995)[28]
	Up to 24,700 feet	No changes in a range of physiological and self-reported measures after normobaric hypoxia training.	Bustamante-Sánchez et al (2018)[49]

Table K

Hypoxia and cognitive performance literature review summary.

7.49 A self-reported survey of general aviation pilots in the US suggests that around 15% of the pilots surveyed (in a sample of 200) may have experienced a hypoxic event during a non-commercial flight.[129] However it is acknowledged that such surveys are unreliable due to the insidious and silent nature of the symptoms of hypoxia which are often subtle and not subjectively apparent. The survey does highlight however that there is a variation in mandatory reporting rules for hypoxia; 28/30 pilots who claimed to have experienced a hypoxic event did not submit a safety report.

7.50 Further evidence about the effects of hypoxia and acceleration may be available by investigating the experience of general aviation pilots. This is not an area currently covered by the UK's Mandatory Occurrence Reporting Scheme (MORS).

Chapter 8

Discussion

Introduction

8.1 The physiological and psychological effects of acceleration on pilots have been recognised since shortly after flight became possible. Investigation of the effects was expedited immediately prior to and during World War 2 and gained further impetus during the space exploration era in the 1950s and 1960s when Gx was often the main focus of attention.[157,163,280]

8.2 A pilot flying an aircraft needs expert decision-making abilities, memory and other cognitive processes to maintain safe flight, especially when also exposed to the physiological stresses of an increase in +Gz.[259] From a civilian perspective many of the studies relevant to the potential cognitive effects of G forces were written 50-70 years ago. Over the past few decades aircraft have become increasingly powerful, more manoeuvrable and capable of, and able to withstand, higher levels of G and G onset rates.

8.3 Many of the older studies proved more informative than recent ones as their aim was to study the lower levels of +Gz which was the focus of this review. More recent research has tended to concentrate on the mitigation of the effects of high G onset rates and very high sustained acceleration levels to enable pilots to fly and fully operate the increasingly high-performance aircraft being developed. Although research on tolerance to sustained high G, as required for air combat manoeuvres performed by military pilots, is not directly relevant to this review some ex-military aircraft are used in civil air displays and it is therefore important to consider their capabilities and potential G exposure to the pilots flying them.

8.4 There were a few studies identified which were published in the 21st century that gave information about cognitive performance with lower levels of acceleration.

8.5 From the review of the studies it is apparent that the only type of civilian flying where a significant amount of G, above +2 Gz, is regularly experienced is display flying and aerobatic, particularly competition aerobatic, flying.

Cognitive Effects

Cognitive Performance at Low +Gz

8.6 The concept of a spectrum of effects on cognition with increasing G may be considered in the same way as the spectrum of effects demonstrated on the level of consciousness. Cognition will certainly be affected by conscious level. Research interest has been directed towards whether cognition is affected at high G levels and studies of cognitive performance with acceleration have tended to emphasise effects on cognition at high levels of G, above + 7Gz, as this is the area of greatest interest for the military.

8.7 Cognitive effects at low levels of G have not been investigated extensively since the available research tends to favour military applications with sustained +Gz of a few minutes or more. This does not mimic the likely brief conditions that general aviation pilots may experience (for example a few seconds of +Gz at a time).

8.8 Although some general aviation pilots who conduct +Gz manoeuvres may have a military background, there is considerable variation in experience, prior training and mitigating equipment used, such as AGS. These factors alongside a variety of methodological differences make it difficult to determine trends in cognitive decrement as exposure to +Gz increases that relate in a meaningful way to general aviation. Individual differences and variation in G tolerance also contribute to a wide variation in the effects demonstrated at any given +Gz level.

8.9 The majority of studies ran very small numbers of participants and would have consequently lacked statistical power to detect any real differences. In many studies, the information needed to assess the significance of any findings, such as means and standard deviations, was not reported. Relatively small sample sizes (typically 3-10 subjects) reduce the power of any statistical analyses. Even where statistically significant differences in performance are found, the practical, *operational* significance of the performance decrement may be limited.

8.10 The seven studies which investigated lower +Gz levels (between +2 to +5.5 Gz), described earlier in this review (see paragraph 4.15), used a range of methodologies and this lack of consistency makes them difficult to compare however, the following basic results can be summarised:

- Comrey et al (1951)[72]; Participants with unknown flying experience using AGS showed some distraction in the performance of perceptual-speed tasks in a centrifuge up to the level of +4 Gz, but adaptation was observed.
- Frankenhaeuser (1958)[96]; Non-pilot participants with no AGS showed significant performance decrement across a range of cognitive parameters if +3 Gz was sustained in a centrifuge for between 2 and 10 minutes at a time.

- Albery (1990)[7]; Five male non-pilot participants performed a spatial orientation task at +2 Gz to +3 Gz while their head was offset from a normal seated angle. Participants whose head was offset demonstrated greater error in estimating the direction of the 'down' arrow accurately (no statistical calculations were reported).
- McCloskey et al (1992)[172]; Eight non-pilot participants (three female) were studied conducting three tasks performed at +2 Gz over a 40-minute period. The choice reaction time showed no performance decrement, the keypad entry task was significantly slower across trials and the multifunction display task showed significant decrement in early trials but recovered to baseline levels by the last of the five trials.
- Levin et al (2007)[162]; Participants with a range of flying experience but no G protection in a dynamic flight simulator (including a centrifuge) showed decrements in memory encoding, but not retrieval, when exposed to a +Gz load of up to +4.8 Gz for 3-4 minutes at a time.
- Dalecki et al (2010)[76]; With a mix of novice and pilot participants wearing AGS in a centrifuge, novice subjects were significantly less accurate in the first minute of a tracking task in both +1 Gz and +3 Gz conditions compared with experienced pilots but did improve across the time period of the trial.
- Hormeño-Holgado and Clemente-Suárez (2019)[130]; Experienced fast jet pilots with G protection showed no short-term memory decrement after real-life exposure of up to +5.5 Gz. Although the overall sortie was 20-35 minutes, the time spent at high Gz appeared to be only a few minutes at a time.

8.11 An eighth series of studies led by McKinley (2008)[177] investigated eleven tasks considered important for military pilots who would be exposed to +Gz. The eleven skills included: Gunsight Tracking (visual motor perception), Precision Timing, Motion Inference, Relative Motion, Peripheral Information Processing, Pitch-Roll Capture, Unusual Attitude Recovery and Situational Awareness, Rapid Decision Making, Visual Monitoring and Short-Term Memory. Of note, of the eleven tasks, only one, Short-Term Memory, showed any decrement at the +3 Gz level. This suggests that a range of other cognitive tasks show some resilience at levels up to +5 Gz.

8.12 On balance the results suggest that cognition may be affected at levels even below +3 Gz when the G force is sustained for more than 3 minutes, but exactly how performance may be degraded, and after what period of time, is not easily identified in the research.

8.13 In prolonged exposure to G forces it may be difficult to differentiate between impairment of performance due to +Gz and fatigue. The effects of G forces on attention are perhaps even more important. Being distracted or preoccupied with G forces could have significant effects on the resources available for all cognitive processes from perception, to memory and motor control. These are important factors that general aviation pilots should be aware of as they could subtly impair performance in a prolonged aerobatic sequence.

8.14 It is the prolonged nature of these experiments, with exposure to sustained acceleration, that is the key point and means that it may not be valid to translate the results of these studies to G force exposure that is much shorter in duration. Studies where G profiles are representative of aerobatic flight are so brief in +Gz duration that it is very difficult to determine the nature and extent of any effect on performance.

8.15 Dalecki's research, demonstrating that novice subjects have slower responses to tracking tasks and competing verbal processes (the Stroop test) has interesting implications for pilots as it suggests that experience has some mitigating effects on performance degradation.[76] However, the pilots used in these studies were experienced military pilots who were accustomed to flying the jet simulated in the research and had received training in managing the +Gz environment.

8.16 In order to make stronger predictions about the impact of +Gz on the cognitive performance of pilots undertaking general aviation manoeuvres, research more specifically addressing these criteria would be needed. Although research is more easily controlled in a centrifuge setting, further in-flight research would provide a richer contextual understanding of the impact of performance decrement as +Gz increases. It is acknowledged that this would be difficult to achieve as collecting data on a multiplicity of cognitive functions in flight whilst executing a realistic flight profile would be very challenging. Also the number of participants would be very small limiting the power of the studies to find effects.

8.17 Performance measurements such as errors made during a tracking task, hit and miss scores on a target, visual field size and complex choice reaction time take a long time to elicit and record. The duration of G exposure representative of a real-world scenario is generally too short to enable a quantitative measurement of cognitive function.

8.18 Limitations acknowledged, technological solutions to this type of measurement are being developed, (e.g. remote eye tracking, pupillometry) and it may be possible to gain more accurate measurements in the future. These techniques may also have limitations as there is no direct objective measure of cognitive processing and even if the eye is looking in a particular direction this cannot necessarily be interpreted as indicative of central processing of information.

8.19 Centrifuges provide the best compromise between control and realism. The wider the range of participants and the more representative the acceleration profiles, the better the results will generalise. The studies done by McKinley involved 1 G/s onsets, 15 seconds exposure to +3, +5 or +7 Gz, and 1 G/s offset.[177] A more complex profile with multiple peaks up to +7 Gz was also flown.

8.20 However even on the centrifuge it is not considered currently possible to obtain performance measures during ‘short’ duration +Gz exposures of up to 2 seconds. Even up to and around 20 second exposures there are severe restrictions on what can be measured.

8.21 An alternative approach may be to develop computational models from the extant data that could also provide predictions about likely performance decrements.

8.22 There are three separate issues to be considered:

1. What is the effect of a single period of exposure?
2. What is the effect of several consecutive periods of exposure?
3. What are the effects after a period or periods of exposure?

8.23 Most studies have looked at the first question but the second and third may be equally important, especially if part of the ‘effect’ of +Gz exposure is mediated by attention reduction or fatigue/stress effects and there is minimal data available on these latter two scenarios.

8.24 Whilst a performance decrement is demonstrated in some of the studies described in this review, because of the differences between them in choice and experience of participants, individual differences between participants, type of acceleration exposure, study design and methods used, it is difficult to draw any overarching conclusions about cognitive performance under acceleration conditions of up to +5.5 Gz. Almost every study has just one, or sometimes two, measured variables. This paradigm might underestimate the potential attentional effects of +Gz in a much more complex environment requiring attention to multiple, ongoing activities.

8.25 These studies demonstrate that whilst it may be easier to standardise and replicate centrifuge studies this may not be representative of the continuously changing G levels experienced in the flight environment.

8.26 The technology to capture both physiological and cognitive responses is developing, and it is likely that in time a more advanced measurement of these capabilities will be possible. In particular, there are several areas of direct portable physiological measurement such as electroencephalography as well as evoked response potentials and magnetoencephalography that could potentially be used to obtain real-time data in flight or in centrifuge studies. These bypass the limitations of indirect performance-based measurements but have their own limitations.[205]

8.27 It may be possible to monitor pilot performance under +Gz in a dual pilot aircraft with one pilot using G protective measures and the other not. There is a need to develop more nuanced measurements of cognitive function which are more closely related to aviation tasks in flight.

8.28 The choice of task is important and would need to be relevant to the nature of the flight operation under consideration. This may prove challenging for flights involving aerobatic manoeuvres and it is acknowledged that translating such research results into a practical application may not be straightforward.

8.29 Whilst it would be interesting to undertake an in-flight study of mathematical and tracking task performance during G exposures of short duration as may be experienced by display/aerobatic pilots, as noted in paragraphs 8.16-8.20 this is not considered to be currently viable.

Cognitive Performance at High +Gz

Slow Onset

8.30 When considering whether there is evidence of loss of cognitive function at low levels of G some relevant information can be elicited from studies involving high levels of G.

8.31 In studies of cognitive function prior to G-LOC there is sequential loss of function towards the point of loss of consciousness if the G force is of relatively slow onset and continually increasing. This is compatible with decreasing oxygen supply to the brain tissue affecting the higher parts of the brain, those that are most distant from the heart, first.

8.32 Tripp found that simple arithmetic is affected prior to a tracking task and both cease to become possible a distinct period of time before the point of unconsciousness is reached which is important in appreciating the build-up of effects of G forces on cognition.[271] However, although the subjects in this study were members of an acceleration test subject panel, and therefore experienced with G, none of them appeared to have been pilots, which means their ability to do a pilot-related tracking task is not a truly valid representation of how pilots would act. Also, the study was an intentional G-LOC study and the results are fundamentally based on progression to frank unconsciousness. If the study had not involved progression to unconsciousness, the tracking deficiencies and mathematics results may have been different.

8.33 It is considered that the mathematical tasks used in many of the papers reviewed do not readily replicate the mental tasks involved in high +Gz manoeuvring.

8.34 The deficits seen in tracking tasks may have been due to problems controlling isometric force in the limbs due to increased limb weight at elevated G levels, rather than a purely cognitive impairment.[105,238]

8.35 In view of these confounding factors it cannot be determined that cognition may be affected prior to vision loss. It is known that visual loss can be anticipated at the levels of +Gz as shown in Figure A in the relaxed state with no mitigation in the form of anti-G protective measures.

8.36 From an operational perspective the standard entry level +Gz into a simple loop manoeuvre is around +4 Gz which to a trained, experienced pilot poses no issue. During typical air display manoeuvres the pilot does not perform a pursuit tracking task either alone or in combination with a mathematics task. Many of the studies on the effects of acceleration have attempted to mimic the motor and cognitive tasks performed by military, fast jet pilots during highly dynamic air combat manoeuvring, rather than those undertaken in civilian air displays with modest G levels and standardised, pre-planned manoeuvres.

8.37 A study of a 45-second target tracking and acquisition task demonstrated the percentage reduction in performance as a function of acceleration and compared it with previous studies.[43] The primary aim of the study was to investigate the effect on performance of different blood alcohol concentrations but the baseline figures in the absence of alcohol are of interest. Although some deterioration in performance occurred at lower levels of acceleration the reduction became much more marked after +4.5 to +5 Gz. Again, this was a tracking task and any effect on cognition cannot readily be differentiated from a physical impairment of limb motor function.

8.38 Cognitive function is clearly affected by an alteration of consciousness. Descriptions exist from the 1930s of aerial manoeuvres of '3-4Gs' leading to a disturbance of vision and a state of 'semiconsciousness'.[10] The understanding of what was described as a semiconscious state has not really progressed significantly since that time. The point at which loss of consciousness occurs is not always readily identifiable and the point at which there is some effect on consciousness even less so. There is no agreed definition of the +Gz level at which A-LOC begins, but it does appear to require exposure to a short duration high G spike of at least +6 Gz so is not relevant for low G exposure.[250]

The Contribution of Hypoxia to Cognitive Function with +Gz

Hypoxic Hypoxia and Cognitive Function

8.39 There have been many studies of performance under various degrees of hypoxic hypoxia and many elements of the resultant effects are cognitive in nature. Most such studies are either undertaken in hypobaric chambers or using breathing gases with reduced oxygen to replicate the reduction in oxygen pressure with altitude. Of note, the time frame is distinct from acceleration studies as hypoxia studies are conducted over minutes rather than seconds. Overall these studies suggest that exposure to sufficient altitude for sufficient time will induce a degree of hypoxia that will impact on the capacity to perform physical or mental tasks to a greater or lesser degree. However, there is inter-personal variation and, even in a single individual, performance may be influenced by other co-incident factors. The degree of impairment and the precise nature of that impairment of function has been studied but there is considerable variability within the nature and form of those studies, including differences in measurements and recording systems, such that direct comparisons can be difficult to make.[52] There appears to be consensus that the higher the altitude the more marked are the effects seen. What is less clear is the minimum altitude at which an effect may occur and how long an exposure to that altitude would be required before any detriment to performance would become manifest. The longer the duration of exposure to an altitude above that threshold the greater the effect that might be seen but establishing a threshold duration shows considerable variability. The nature of the task would also be a factor, with a common view that the more complex the task the more easily the effects of hypobaric hypoxia are seen.

8.40 The wide range of methodologies used in the studies of cognitive performance and hypoxia made it difficult to make many comparisons between the literature on acceleration and cognitive performance, and hypoxia (without acceleration) on cognitive performance.

8.41 Despite issues with consistency of study design, the body of research suggests that hypoxic conditions degrade performance across a range of cognitive tasks. Information from the papers reviewed indicate that this degradation is sometimes subtle and whether these subtle changes are of operational relevance is not necessarily determined; research participants were often able to adapt to a mild hypoxic state with only minor decrement. The potential for hypoxia to affect cognitive function below 12,500 feet is not clear cut and may affect some pilots more severely than others.

Oxygenation of Cerebral Tissue with +Gz

8.42 The oxygen available in the brain is a function of:

- Arterial oxygen saturation (the amount of oxygen in the blood)
- Cerebral metabolic rate for oxygen (how fast the cells are using up oxygen)
- Cerebral blood flow

8.43 Sustained G force influences the oxygenation of cerebral tissue by a combination of effects. One of these is the influence on the arterial blood pressure leading to a reduction or cessation of cerebral blood flow and another is to induce an increase in ventilation/perfusion inequality.

8.44 NIRS is an accepted research tool used to measure the oxygenation of the blood although it has limitations as it is only appropriate for cortical measures of cerebral oxygenation, rather than deeper internal brain areas.[53,148]

8.45 The fall in oxygen saturation to 85% that has been demonstrated with sustained exposure to +5 Gz is the same level of saturation that occurs in pilots, crew and passengers in a pressurised commercial jet aircraft at a cabin altitude of 8,000 feet.[106] No significant cognitive impairments have been demonstrated in that environment, which can have exposure times of well over 12 hours in long-haul airline operations.

8.46 The relative influence on cerebral tissue oxygenation of the effects on cerebral perfusion pressure and on ventilation/perfusion in the lungs due to increased G forces is difficult to differentiate and to quantify from the material studied. However, such differentiation is perhaps less important than the overall effect of exposure to +Gz and any associated deterioration in cognitive performance.

8.47 The long duration of studies of cognitive performance at less than +5 Gz are not representative of the fluctuating G levels experienced during aerobatic manoeuvres. Also, it may be that the long duration is itself causing any effect demonstrated on cognition by way of fatigue or other factors.

8.48 There are few studies other than the ones reported as part of a PhD thesis that have sought to compare hypoxic hypoxia of the type induced by ascent to altitude with cerebral hypoxia that may be induced by G forces.[261] The comparison between a specific level of Gz, experienced for a very limited time interval, and a specific degree of hypobaric hypoxia experienced for a much greater time period is complex. Moreover, the degree of physiological effects and possible cognitive consequences may be challenging to translate to the operational environment. Further studies may assist in elucidating any cognitive comparison of abrupt G exposures with modest degrees of hypoxia experienced for quite limited time periods in flight but the confounding variables would be multiple and complex.

8.49 The findings for hypobaric hypoxia effects on cognition in a +1 Gz state are no more consistent than those using higher levels of +Gz and the impact of hypoxia at low levels of +Gz on cognitive performance is not clearly defined.

8.50 The loss of cerebral perfusion and resultant loss of consciousness with high +Gz loads occurs much faster than the cerebral impairment and loss of consciousness due to altitude-related hypoxia.

8.51 The time difference and manner in which exposures to hypobaric hypoxia due to altitude and ischaemic hypoxia due to acceleration occur may explain a difference in the cognitive (and other) effects that result. With hypoxic hypoxia there is generally a slow exposure leading to a global effect on cerebral tissue with the regions of the brain that are most sensitive to hypoxia being affected first, over a time period of many seconds to minutes or longer. With ischaemic hypoxia there is a progressive effect with the brain tissue most vertically distant from the heart and/or without a good collateral blood supply being affected first. In the latter case, the duration of manoeuvres likely to be encountered in aerobatic flying, is generally so short that all cerebral tissue will be affected rapidly if the G level is sufficiently high and is not offloaded.

8.52 In hypoxic hypoxia blood flow is not compromised, rather there is a systemic reduction in the oxygen partial pressure in the arteries supplying blood to the brain. The oxygen supply reduces as a function of distance along the arterial branches meaning that the areas most remote from the heart and those with no collateral supply are at greatest risk when the oxygen partial pressure falls.[52] In hypoxia due to G forces it is the blood flow that reduces or ceases; at the low altitudes at which air displays are undertaken there is little direct effect on the partial pressure of oxygen.

8.53 At a cellular level these two different scenarios may lead to comparable cellular mechanisms, irrespective of the underlying cause. The model used by Cammarota predicts that the mechanism for unconsciousness is likely to be similar for all metabolic threats, including G forces and acute (meaning severe and sudden) hypoxia.[52]

Aerobatic Accidents Due to Pilot Incapacitation

8.54 It is difficult to determine whether pilot incapacitation has been a causal or contributory factor in fatal aerobatic accidents. Similarly, it is difficult to attribute causal factors in accidents due to spatial disorientation or any state in which there is altered awareness of surroundings or spatial position.

8.55 Pilot incapacitation is often a 'diagnosis of exclusion' when all other potential causes of fatal accidents have been eliminated. Although pathological examination may sometimes be informative, pathological information is often not available and some of the pathological processes that cause incapacity are too transient to show up at post-mortem examination. In particular A-LOC and G-LOC would not give rise to any bodily changes that would be detectable at post-mortem or via toxicology. In such circumstances, if all other potential causes have been ruled out, and the pilot had been exposed to high G, an episode of alteration of consciousness leading to pilot loss of control and subsequent impact with the ground could not be positively discounted.

Recommendation 1

The CAA should consider undertaking an analysis of UK aerobatic accidents and incidents to review the likely G exposure and potential causes of any errors and poor decisions. Such analysis could include comparison of pilot performance in flights involving exposure to different levels of +Gz (eg up to +2 Gz, up to +5 Gz or greater than +5 Gz) to facilitate recognition of patterns of association.

Study Conditions

Study Environments

8.56 Many of the studies on acceleration exposure have been undertaken on centrifuges. Whilst this is a good proxy for in-flight exposure to levels of +Gz it may not always accurately reflect the pilot experience. In-flight performance tends to be better than in the centrifuge, possibly because of heightened attention to the task. Taking these considerations into account, the results of centrifuge studies, even though they may not be entirely representative of the flying environment, may provide an indication of potential performance issues.

8.57 Neither in-flight nor centrifuge environments are conducive to undertaking tests of performance on practical grounds. The short duration of most acceleration exposures make these tests very difficult to accomplish. Where centrifuge experiments have been carried out it is difficult to know whether the effects shown can be translated to the operational environment.

8.58 Most aerobatic sequences involve a series of short duration accelerations in succession and this is very difficult to simulate in circumstances where valid and reliable cognitive testing can be done.

Study Subjects

8.59 The majority of research studies have used young, healthy, predominantly male, military pilots as subjects and other studies have used non-pilots as subjects. This may or may not always be representative of the civilian pilot population.

8.60 Although some subjects were familiar with the centrifuge not all of them had been acclimatised to it. If the study's end point was a potential G-LOC they may have been stressed by the possibility of G-LOC being precipitated and this may have affected cognition either directly or via reduced attention to the tasks.

Measuring Cognitive Function

8.61 There are several physiological impediments to measuring cognitive function accurately when exposed to G forces either in the centrifuge or in flight including:

- Acceleration restricts a pilot's physical ability to move their limbs.
- Manual dexterity becomes affected as G increases and measurements of motor performance become difficult due to mechanical disturbance. This may affect hand-eye co-ordination and any movements that involve arm reach such as control inputs and tracking tasks.
- There is impairment of the forces that a pilot is capable of exerting.
- There may be an increase in the time required for neuromuscular co-ordination of motor response and the execution of motor tasks such as the manipulation of flight controls.
- Reaction times to visual or auditory stimuli may be affected by mechanical issues, sensory perception or response, or because of cognitive deficit.
- Speech becomes physically extremely difficult at high Gz levels and anti-G protective measures are tiring and can be distracting.
- Processing delays could be from perceptual, recognition, discrimination or comprehension issues.
- There are mechanical effects on visual acuity.

8.62 There are additional methodological issues with +Gz tolerance research which make it difficult to form general conclusions from the effects found in different studies. These include:

- The short duration of high +Gz exposure opportunities can hamper accurate performance capture and limits the range of tasks available for investigation.

- Testing effects on cognition during grey out or blackout is fraught with difficulty as most cognitive tests involve visual perception.
- The levels of +Gz and exposure intervals vary widely, with very limited evidence of long-term effects.
- Studies vary between using subjects with and without piloting and/or fast jet or acceleration experience or prior training.
- The position of subjects varies in combinations between lying prone and sitting upright.
- Whether subjects use protective equipment differs between studies.
- The age ranges of subjects vary widely.
- Most studies have used only male participants, which may have unforeseen physiological limitations.
- It may be difficult to distinguish errors in reading aircraft instruments from a mechanical effect on visual or auditory acuity, or sensory perception or response issue from an effect on cognition.

Measurement Tools

8.63 Currently available measurement tools for cognitive capability and performance are limited in both the centrifuge setting and in flight.[259] In addition to the measurement issues noted above, it is difficult to find tasks to measure cognitive capabilities accurately given the limited time exposures available. A number of more complex tasks that might be useful in determining performance parameters are too complicated, time consuming or need special equipment which is not possible in the environment of a live cockpit. Using tasks such as mathematical calculations, dual-attention tasks (e.g. the Stroop test) and tracking tasks may provide some insight but are not always representative of the tasks that a pilot will need to perform in flight. The development of cognitive performance measures, closely related to general aviation tasks, would facilitate more appropriate assessments of the cognitive effects of G force on pilots. While some research has used subject matter expert opinion to identify key skills required for military pilots, and to measure these in a centrifuge cockpit, it was not clear how the key skills were identified or whether they would transfer to the general aviation environment.[177] It is likely that, as the technology around data capture improves, more in-flight research will be able to be conducted that is able to better capture performance parameters for real in-flight activities rather than simulated cognitive activities.

Centrifuge Training

8.64 Centrifuge experience is useful to prepare pilots for exposure to G forces of +3 Gz and above though there are differences between the centrifuge and the operational environment. Pilots may suddenly pull more G than anticipated and non-flying co-pilots may not have time to prepare themselves for the sudden increase. Failures within an AGS or a slow inflation rate of the system may cause an unexpected issue. There is a particular element of caution with the use of a centrifuge as a training tool. Although it is a controlled and safe environment it could lead to a false perception of how likely an individual is to recognise the onset of high G forces.

8.65 UK research in the future may be aided as a result of RAF Cranwell now having a human centrifuge that can reach +9 Gz in 1 second. It is designed to simulate flight in a Typhoon, Hawk or F35 aircraft.[229]

G Tolerance

8.66 The factors affecting G tolerance will vary slightly from day to day for each pilot and more so from one individual pilot to another.

8.67 Most studies on G tolerance have been undertaken in experimental settings on a centrifuge. Pilots in control of an aircraft will not be in a relaxed state and are likely to have a high level of attention and awareness. In-flight studies have demonstrated that tolerance to G forces whilst flying is generally higher than in a centrifuge.

8.68 Importantly, there are no pilot characteristics that are specific for a propensity to A-LOC or G-LOC although pilots of a shorter and stockier build are on the whole better able to tolerate high Gz than tall, slim ones. Pilots of high-performance aircraft should be aware that tolerance can vary and past experience does not necessarily predict their own physiological reaction to G force exposure in the future.

8.69 Training is especially important for low hours, inexperienced pilots converting to flying a new aircraft type.[114,165,255,311] Pilots should be aware of their own G tolerance level and that symptoms other than light loss can precede G-LOC.[250] Some of the consistent features such as experiencing a void whilst not being able to take action or a floating sensation are very unusual and specific to this situation.

8.70 It is crucial that there is widespread awareness that G tolerance can vary and alteration of consciousness can affect any pilot undertaking aerobatic manoeuvres.

Recommendation 2

The CAA should ensure that the training of pilots in aerobatic manoeuvres should include an awareness of the basic physiological principles of exposure to G force and the effects of increased G, the factors that increase or decrease the risk of G-related impairment or incapacitation, that a pilot's G tolerance can vary and alteration of consciousness can affect any pilot undertaking aerobatic manoeuvres. There should be awareness of the anticipated levels of G associated with each manoeuvre the pilot is taught. Pilots should be made aware that visual or other premonitory symptoms may not necessarily occur with rapid onset high G and G-LOC may occur without warning. Pilots should keep a log of all G-related training.

Aerobatic Flying

8.71 Pilots who fly aerobatics, whether for recreation, sport, display or competition need to apply not only their basic flying skills but in addition manage to accurately fly the aerobatic routine and cope with the physical demands of G forces.

8.72 Many pilots who undertake display and competition aerobatic flying have a military background and/or significant high G experience. These pilots are usually accustomed to titrating G loading using visual symptoms to recognise when they need to reduce the level of G force. An awareness of the potential for G-LOC is essential.

8.73 It has been widely acknowledged since the very early days of aviation that if an individual exceeds their G tolerance their performance could be affected and flight safety could be compromised. Pilots intending to undertake aerobatic manoeuvres need to be aware of the possibility of altered consciousness due to G forces that can compromise motor and cognitive function, the scenarios when this is most likely and also other scenarios when it could occur, even if these are less likely.

8.74 There is potential for a degradation in flying performance when aerobatic manoeuvres are undertaken that expose the pilot to levels and/or duration of G forces that can have physiological effects if G protective measures are not employed.

8.75 An awareness of human factors issues is a pre-requisite for display pilots and forms part of the DAE/DA mentoring but acceleration physiology is not specifically mentioned in CAP 1724.

G Tolerance

8.76 An individual's relaxed (unprotected) G tolerance, before signs of adverse physiological impact occur, varies and is usually between +3 Gz and +4 Gz. The philosophy underpinning acceleration research is to understand and improve G tolerance.

8.77 Whenever manoeuvres involving a level of G force higher than the pilot's tolerance are undertaken there needs to be a level of planning and preparation commensurate with the intended schedule of flying, including the use of appropriate anti-G protective measures. Planning should also be undertaken to cater for unexpected scenarios.

8.78 Training and regular G exposure, as well as the use of appropriate personal protective equipment, along with the correct performance of the AGSM are the key to improving pilot tolerance of the high G environment.

8.79 An individual's G tolerance can vary from day to day and previous tolerance levels cannot be relied upon as a way of avoiding the effects of G forces. Various external and personal factors affect G tolerance and these all need to be taken into account.

Recommendation 3

The CAA should ensure that when applying for the issue, renewal or upgrade of an aerobatic DA the pilot should demonstrate an understanding of the factors that may influence their own G tolerance, knowledge of the symptoms of G-related impairment and incapacitation and how to respond to these symptoms if they occur during a display flight. They should also be able to demonstrate how they assess the aerobatic manoeuvres they intend to perform for their potential to alter consciousness and how the mitigating measures they have in place alter this assessment.

Aeromedical Aspects of Aerobatic Flying

8.80 If a pilot intends to fly an EASA aircraft they will require an aerobatic rating on their licence and will need to apply for a medical certificate. There is a space on the application forms for EU Class 1 (commercial), 2 (private and some instruction) and Light Aircraft Pilot's Licence (LAPL) (i.e. recreational) medical certificates for a pilot to indicate the type of flying they intend to undertake when they apply for their certificate, however it is rare for a pilot to specify aerobatic flying.

Recommendation 4

The CAA should consider adding a specific question on the medical certificate application form about whether the applicant intends to undertake aerobatics.

8.81 There is no dedicated medical certificate for pilots who wish to undertake aerobatics and no UK or EU medical regulatory criteria specified for aerobatic flying. Since 1 April 2016 all pilots holding a DA have been required to hold an EU medical certificate or an equivalent International Civil Aviation Organization medical certificate.[65,68]

Recommendation 5

The CAA should consider whether any aeromedical advice is required to be published for pilots intending to undertake aerobatics and for the doctors who may be involved in their medical assessments.

8.82 The Aeromedical Examiners (AMEs) who undertake Class 1, 2 and some of the LAPL assessments should all have been taught about aeromedical considerations for aerobatic flight in their basic aeromedical training. If a pilot informs their AME or indicates on the application form that they wish to undertake aerobatics, the AME will be able to take particular note of any relevant medical history and give appropriate advice.

Recommendation 6

The CAA should ensure that the medical oversight of AMEs and aviation medicine training providers should include confirmation that medical considerations for aerobatic flight is included in the AME training syllabus and Basic Certificate in Aviation Medicine course programme and that existing AMEs can demonstrate knowledge of the medical considerations of aerobatic flight.

Adaptation to Aerobatic Flying

8.83 It is currently unknown precisely how much exposure is enough to give or maintain adaptation to aerobatic flying. Work that has been done on active duty pilots who are regularly exposed to G forces shows adaptation with their normal flying operations if flying at least a couple of times a week. A display pilot who flies at least once a week and has a history of G exposure over time is more likely to be adapted than a novice pilot. The G environment of the display is an important point and it appears that a weekly exposure is enough to maintain maximum G tolerance.[48]

Safety Culture

8.84 On review of historical literature there are clear indications of a lack of willingness to report incidents of altered consciousness, presumably because of an actual or assumed adverse consequence this could have on flying training and potential implications for career progression. Many incidents were not reported formally contemporaneously.

8.85 There appeared to be an extremely small number of incidents of impairment due to G forces reported through the MORS/ECCAIRS system. This parallels the findings of the Military Aviation Authority (MAA) that peripheral effects on vision and grey out were often not reported whereas blackout and equipment failure were routinely flagged.[181]

8.86 It is possible that many pilots who undertake aerobatics may have held flying roles where they routinely experienced visual loss and other effects of G forces and expect to experience these effects when undertaking aerobatics in civilian flying and would not consider this unusual.

8.87 There may be evidence about the consequences of exposure to G forces which could be made available by investigating the experience of general aviation pilots; it would also be beneficial to include potential incidents related to the effects of hypoxia in the same investigation. This is not currently covered by the UK's MORS and there may be benefit in encouraging pilots to provide more information about these events.

Recommendation 7

The CAA should consider undertaking a survey of pilots with an aerobatic rating including DAs to determine whether incidents of G-related impairment are occurring that are normalised and are not being reported with a view to proposing changes to the UK's Mandatory Occurrence Reporting Scheme if appropriate.

Chapter 9

Conclusions

General Comments

9.1 All flying carries some degree of risk to the participants and to people on the ground in the vicinity of the flight. This is managed via a series of risk assessments, set procedures, mitigations, training and equipment often collectively known as a Safety Management System.

9.2 Good cognitive function is essential for piloting an aircraft in normal flight conditions. When a pilot is exposed to increased G forces additional physiological stresses may be encountered. Training and experience are required to maintain a high standard of flying and the necessary executive functions at all times.

9.3 Accidents that may have cognitive impairment as a contributory or causal factor are very difficult to determine due to the difficulty in distinguishing between an error or mis-judgement and cognitive impairment from a medical condition or physiological effect.

9.4 The AAIB reports of the accident to G-BXFI at Shoreham on 22 August 2015 estimate the levels and duration of G force affecting the pilot in the part of the flight immediately preceding the accident. Although G levels are estimated at different points in the flight it is accepted that in practice, throughout an aerobatic sequence, the level of G force will be continually changing.

9.5 This review has explored the possibility of cognition being adversely affected by exposure to G forces of +5 Gz or less, acknowledging that the rate of onset, duration and amplitude of the G force will all be relevant to potential effects.

Aerobatic Flight

9.6 In civil aviation G forces are rarely an issue as the vast majority of civil aviation flights do not invoke high levels of G force and operationally the physiological effects of exposure to high G are very unlikely to be encountered. In routine civilian operations a very small amount of G force may be experienced during turbulence or when in a gentle banking turn. In these scenarios the physiological effect of G force is negligible and highly unlikely to cause any adverse effect.

9.7 The exception is flights that include aerobatic manoeuvres. Such aerobatic manoeuvres are most commonly encountered in air displays, aerobatic competitions and air races, or when practising for any of these events. Display flying carries a degree of risk, not only for participants but also for spectators and bystanders. This inherent hazard is part of the attraction for the participants and spectators.

9.8 Aerobatic flying is a sport and pilots may put pressure on themselves to complete a manoeuvre because it is a personal challenge or they want to do well in a competitive event. There also may be peer pressure, wanting to do better than their contemporaries, a need to be emulated or self- or externally-imposed pressure to give a crowd the display that has been advertised and that they have attended to see. There is an element of thrill-seeking both for the pilot and the spectators who are looking to appreciate the skill of the pilot and the risks being taken. Display pilots have a responsibility to ensure those risks are adequately mitigated and risks are reduced to as low as reasonably practicable.

9.9 The overwhelming majority of aerobatic pilots repeatedly perform sequences involving high G without adverse effects either on themselves or others. Indeed, pilots use G physiology to their advantage as they can pull a very high G level for a few seconds enabling them to showcase their display whilst utilising the body’s oxygen reserve period. Very high G onset rates can be reached in either jet or propeller driven aircraft during certain manoeuvres including pulling sharply out of a dive and rapidly entering a steeply banked turn.

9.10 Although the total number of hours of aerobatics undertaken on an annual basis in the UK is not known it runs into many thousands of hours taking into account recreational aerobatics, instruction in aerobatics, practising for displays and competitions and display flying.

9.11 High G manoeuvres are physically and cognitively demanding and performing a series of high G manoeuvres is also fatiguing.

9.12 Aerobatic pilots need to be able to make decisions and solve problems rapidly whilst remaining alert to cues in their environment and executing effective actions immediately. Training and experience are the key pre-requisites for a pilot undertaking aerobatic manoeuvres.

9.13 Military pilots in combat roles are subject to higher and more sustained levels of G than their civilian counterparts. As well as maintaining control of the aircraft they have to be able to respond to aggressive manoeuvres by pilots of other aircraft in close proximity. They are a highly selected and trained group of pilots and those who cannot manage the concurrent activity required of military operations will be selected out during one of the multiple phases of flying training.

9.14 Civilian aerobatic pilots will also be subject to selection though to a lesser extent, notwithstanding that some will have military flying experience. Some of this will be self-selection as only a small proportion of pilots will choose to undertake aerobatics. Others may not have the requisite competence, attitude, application or financial support required to complete aerobatic training.

9.15 Aerobatics require a high degree of mental agility and concentration. An adequate supply of oxygen to the brain is needed to maintain orientation, neuromuscular actions, reflexes and consciousness.

Physiological Hazards of Increased G Exposure

9.16 There are physiological hazards associated with exposure to high sustained acceleration forces which can have adverse physiological effects.

9.17 During high G manoeuvres, if the blood flow supplying oxygen to the brain is interrupted, the brain only has its internal oxygen reserve to use. In the event of a cessation of cerebral blood supply the oxygen reserve will be used up within a few seconds and the level of consciousness will be altered with an immediate risk to safe flight.

9.18 Any manoeuvres which expose the pilot to more than +3 Gz for a sustained duration of longer than four seconds have a potential risk of adverse physiological effects.

9.19 There are a very small number of references to G tolerance below +3 Gz in the literature. These appear mainly to relate to novice subjects not previously exposed to high G and are likely not to be representative of the G tolerance of experienced pilots. Pilots are likely to choose to select themselves out of aerobatic training if they have a low G tolerance. Alternatively, if a student has insufficient G tolerance they will not be able to meet the competency standards for performing a given manoeuvre or set of manoeuvres and either their instructor will recommend that they discontinue the aerobatic rating or they will not pass the aerobatic flight test.

9.20 A pilot flying an aircraft capable of a high G onset rate has to be aware of the potential for alteration of consciousness without premonitory visual symptoms and, when flying with a rapid G onset rate, to keep strictly to flying bursts of a few seconds of high G with recovery time in between to ensure consciousness is maintained.

9.21 The risk of G-LOC is relatively low in civilian display flying which can be planned to ensure the G onset rate is kept at a level where warning signs of grey out give sufficient time to offload G and/or execute an escape manoeuvre where applicable. Planning of manoeuvres should have sufficient contingency to allow for offloading G if vision becomes impaired.

9.22 Manoeuvres that first expose a pilot to negative G and are then followed by a high positive G load (push-pull) pose a particular risk for alteration of consciousness. Moving rapidly from high positive to negative and then positive G again ('pull-push-pull') poses an even greater risk.

Cognitive Effects of Exposure to G Force

9.23 There is little scientific evidence of compromise of cognitive performance at the levels of G commonly encountered in civilian aviation.

9.24 At higher levels, or a more sustained duration of G force, it is difficult to uncouple any effects on cognitive performance due to G force from actions that may be impacted by fatigue, distraction or other causes. It is important to note that a decrement in performance does not necessarily imply a decrement in cognition. The reverse is also true as a decrement in cognition does not imply a decrement in performance if there is sufficient capacity in reserve.

9.25 A human experiencing increasing G forces is likely to be devoting some attention to the phenomenon itself or else to counteractive measures. There is extensive evidence on the negative effects of diverting attention away from core tasks (a common example is mobile phone use and inattentional blindness) and this may be an important secondary mechanism that could account for any acceleration related impairments.

9.26 In centrifuge studies performance may be degraded with as little as a few minutes at +2 to +4 Gz. Performance decrements that may be observed include increased reaction time on tracking tasks, more errors in visual perception, slower reaction to competing, concurrent tasks, a slowing of mental arithmetic that is more error prone and inaccurate time perception. Issues with the encoding of memory may also be observed.

9.27 However, there may be confounding factors with studies undertaken in a centrifuge including the experience itself as the participant is aware that there is not the possibility of death or injury that could be present in flight. Study participants may vary widely ranging from some being pilots with a varied number of flight hours and others being totally unfamiliar with either the flight or centrifuge environment.

9.28 The immediacy and decrement with which performance is degraded is likely to vary based on pilot experience, training, anti-G protection, previous exposure to acceleration and time spent at increased G and is not consistent. Some decrements noted in the studies reviewed are well within the range of normal diurnal variation and are unlikely to represent any meaningful decrement in operational performance. The research reviewed does not indicate a smooth decrement of function or a consistent protective aspect from training and equipment in the +Gz environment.

Impairment of Cognition

9.29 A complete failure of cerebral blood supply from G forces and resultant local tissue hypoxia will lead to a failure of cognition from loss of consciousness once the oxygen is used up and the brain cells have no energy available for normal function.

9.30 With a reduction in blood supply the time course of hypoxia will vary depending on the perfusion of the different regions of the brain which will vary according to the rate of onset of G, the level attained and the duration for which it is sustained as well as due to individual anatomical and physiological differences. With increasing Gz there may also be a reduction in effective oxygenation of the blood as some blood will pass from the right to the left side of the heart without being oxygenated (a 'right to left shunt'). Thus, the oxygen supply may be compromised if high Gz is sustained.

9.31 The number of variables involved makes it difficult to state with certainty specific circumstances when cognition may be affected though it can be stated that it is far more likely with higher and more prolonged G forces.

9.32 Many factors can affect cognition including task recency and familiarity, underlying aptitude and training experience, sleep deprivation, fatigue, illness, inattention and distraction. Other potential factors include:

- Environmental – e.g. heat/cold, noise and vibration;
- Task factors – e.g. time available, contingent rewards/punishments (e.g. performing for an audience);
- Biological – e.g. age, alcohol, drugs, blood sugar, time of day/circadian effects, stress hormones, state of health, anxiety;
- Psychological – e.g. individual differences in intelligence, working memory capacity, preoccupation.

9.33 Therefore, separating the effects on cognitive function with any consequent operational implications for display flying from the complex physiology involved in a physically dynamic situation is challenging.

9.34 The considerable day-to-day variation in individual cognitive performance and even greater inter-subject variability makes experimental comparisons of cognitive performance, both between individuals and for the same individual at different times, challenging.

9.35 The cerebral vascular supply will vary from one individual to another both in terms of anatomy and physiology and may influence the type of symptoms and signs associated with the reduction in perfusion of the brain seen with G forces.

9.36 Any pilot is susceptible to alteration of consciousness with exposure to G forces if their personal, physiological tolerance limit is exceeded. The likelihood of alteration of consciousness increases with increasing G. Where there is alteration of consciousness there will be effects on cognition. The term 'A-LOC' includes symptoms and signs that describe effects associated with impairment of cognition.

9.37 Impaired cognition could lead to misperception or non-optimal decision making and affect the execution of learned skills.

9.38 At high levels of G there are likely to be numerous other factors that could distract, reduce attention or otherwise interfere with normal cognitive processes and it is a reasonable assumption that cognitive performance will be affected prior to reaching physiological limits of tolerance i.e. G-LOC. Lower levels of G are much less likely to affect cognition.

Is there an Alteration of Cognition at Low Levels of G?

9.39 Cognitive impairments become evident in well-trained healthy participants at around +5 Gz with some changes setting in as low as +3 Gz albeit that these have only been demonstrated in studies with sustained G and are unlikely to be of practical importance.

9.40 Because of large inter-subject and intra-subject variation these figures cannot be taken too literally so a tired, older pilot might experience the same effects as a healthy, younger one at +1 to +2 Gz lower.

9.41 The relationship between signs/symptoms and the level of G is not linear.

9.42 The overwhelming weight of scientific evidence does not suggest any meaningful, practical or relevant cognitive alteration at low levels of G.

9.43 Cognitive function seems to be largely protected at low to moderate G levels, especially with low onset rates. Short duration high G spikes can lead to A-LOC with cognitive impairment and sustained high G, especially with high onset rates, leads to loss of consciousness. Notwithstanding the impairments that can occur with sustained exposure at lower levels, the average human can tolerate up to +4 Gz with little cognitive compromise.

Is there any Effect on Cognition Prior to Grey Out or Blackout?

9.44 There is no evidence to support the existence of cognitive effects prior to grey out or blackout. It is considered that, with gradual onset acceleration, the G levels prior to experiencing visual effects are too low. Visual symptoms depend on low onset rates, which trigger the baroreflex leading to boosted cardiovascular performance and maintenance of cerebral perfusion.

9.45 Cognitive effects can be experienced without grey out and blackout with a rapid onset, high G short duration spike as part of either A-LOC or G-LOC. In this circumstance, depending on the use and effectiveness of an AGSM, and an AGS being worn (which would be normal practice in aircraft capable of rapid onset G) a G level of more than +6 Gz is usually associated with A-LOC and more than +6.5 Gz with G-LOC.

Are Cognitive Effects Part of the Spectrum of Alteration of Consciousness?

9.46 The signs and symptoms of G exposure are myriad, individual, complex, multifactorial and often confounded by other factors such as fatigue. In general, any cognitive effects linked with the spectrum of alteration of consciousness are seen in the high G exposure regime with A-LOC and G-LOC. The weight of evidence suggests that cognitive effects with alteration of consciousness are primarily restricted to the A-LOC and G-LOC phenomenon, and therefore by definition are a function of the high G environment beyond +4 Gz. No reference has been identified that describes cognitive effects leading to loss of consciousness. Cognitive effects seen with A-LOC, by definition, occur without loss of consciousness.

Hypoxia: Ischaemic vs Hypoxic

9.47 G forces can result in alteration of consciousness through two mechanisms. Failure of blood supply (ischaemia) from rapid exposure to high levels of G is the most commonly encountered, but a primary failure of oxygen supply (hypoxia) by the blood can also occur by G forces altering the ventilation of the lungs or the blood supply to the lungs. These mechanisms may co-exist though the time course usually differs with the former being associated with rapid exposure to high G and the latter with much longer exposure to more moderate levels of G.

9.48 Hypobaric hypoxia is an inevitable hazard of ascent to altitude and is well known to have a range of effects which may be very clear or subtle and potentially these effects can co-exist. However, in the UK display flying is largely conducted at relatively low altitudes or in aircraft which may climb swiftly to higher altitude but are equipped with well-proven life support systems which when fully functioning should provide protection against any significant degree of hypobaric hypoxia. Light aircraft without life support systems are less likely to ascend very rapidly for prolonged periods. Commercial aircraft use a form of cabin pressurisation that limits the altitude exposure to a relatively modest one, even when the aircraft itself is at its maximum operating altitude.

9.49 It is the different time course of exposure of the brain cells to lack of oxygen supply through these two hypoxia mechanisms that leads to different physiological effects. A lack of adequate oxygen at a molecular level would be expected to have detrimental effects on cell function; whether the cellular mechanism of hypoxia differs is not known but it would seem highly unlikely.

9.50 Investigation of the equivalence between hypoxic hypoxia and the ischaemic hypoxia that occurs with increased +Gz exposure is a possible future research avenue. This is likely only to be warranted if an analysis of errors during aerobatics suggests there is a safety case for further investigation. Australian data indicates that almost all of the loss of control events in aerobatic accidents occur at low altitude (under 6,000 feet) (personal communication D Newman).

9.51 Arterial deoxygenation that can occur from a ventilation/perfusion mismatch under +Gz is less significant to the brain than adequate blood flow. The 85% oxygenation seen at +5 Gz is the same level of oxygenation typically seen in the pilots, crew and passengers of a pressurised commercial aircraft cabin during the cruise phase of flight. Under high +Gz loads, cerebral perfusion pressure falls in line with the level of applied +Gz which leads to a reduced blood flow in the brain. While there are physiological mechanisms such as the baroreflexes and the venous siphon effect that mitigate the impact of this reduced-delivery pressure, at sufficiently high +Gz levels blood flow to the brain ceases and loss of consciousness will occur. +Gz tolerance is therefore primarily dependent on adequate blood flow to the brain.

9.52 Failure of blood flow is thus much more likely to exert an adverse effect than reduced oxygenation of the blood entering the brain. G-induced interruption of cerebral blood flow occurs over a much quicker time frame than any impairment due to reduced arterial oxygenation. Where lower oxygenation of the blood is likely to have an impact is with sustained +Gz exposure, where the AGSM is employed for some time. The lower blood oxygenation is likely to affect the muscles involved in performing the AGSM, leading to fatigue of those muscles and a subsequent degradation of G tolerance. During this situation, blood flow to the brain is maintained and adequate.

9.53 The physiological effects arising from exposure to G forces vary and it is reasonable to assume that the physiological effects from exposure to the hypoxic hypoxia experienced through an increase in G will also vary from one individual to another.

9.54 In summary, aerobatic and display flying in the UK in fully serviceable aircraft operated within the design envelope by a fit pilot appears not to be associated with a significant risk of hypobaric hypoxia having a detrimental effect on physiological performance.

Cognitive Function and Low +Gz

9.55 There is documented evidence of the effects on pilots of sustained, low levels of +Gz exposure. Evidence to suggest that there are effects arising from low levels of +Gz exposure for a short duration are less clear. Some effects have been reported but the time course for these exposures is relatively long. This type of prolonged exposure is not commonly encountered in normal aircraft flight or even aerobatic manoeuvres.

9.56 The probability of A-LOC or G-LOC occurring on exposure to +Gz above an individual's tolerance level can be reduced and mitigated. It cannot be eliminated as it is a normal physiological response to +Gz.

9.57 A considerable number of international regulatory authorities were asked, for the purpose of this review, for any information on concerns they may have been aware of relating to cognitive impairment with G force. No substantive concerns were reported.

9.58 The skill and experience of a pilot undertaking aerobatics is of prime importance. They should also have a safety conscious attitude, be aware of safe parameters for their flight routine, be in an optimum mental state and physically and psychologically prepared for their intended flying. Satisfactory cognitive function depends on these factors. Exposure to short bursts of G is physiologically challenging but is something that is regularly encountered by pilots undertaking aerobatics. The way that flying training has evolved is to avoid situations where vision is impaired to the extent that flight is endangered. Effective cognition is also essential to safe flight. Pilots who have been trained to undertake aerobatic manoeuvres have to undertake numerous functions in addition to flying the aircraft; some are skill based and some require executive functioning to make decisions. An understanding of the challenges and appropriate mitigation in the form of G-protective measures are key to ensuring that aerobatics can be undertaken safely.

9.59 Capturing quality performance measurements in response to a highly transient phenomenon such as +Gz is challenging and it is considered not currently possible to obtain performance measurements during short (approximately 3 second) exposures at +2 to +3 Gz so the evidence does not and could not exist. However, a number of studies do show impairments as low as +3 Gz at the longer durations necessary to obtain measurements. In the absence of direct evidence there remains the possibility that some aspects of pilot performance could be affected at levels of +Gz lower than those associated with effects on vision and consciousness, though these may only relate to longer durations of exposure. It is not possible to state from the data available whether any of the impairments would have occurred at much shorter durations than those used in the experiments.

9.60 There is no evidence to suggest that cognitive effects can be demonstrated at low levels of G force when experienced for the short period of time associated with aerobatic displays. The overwhelming weight of available scientific evidence does not show any demonstrable, practical and meaningful cognitive impairments under +4 Gz that would point to impaired flight safety.

9.61 The Review Team has concluded that there is no identifiable risk of cognitive impairment in civil pilots experiencing G forces at levels, and for durations recorded by accident investigators as having been experienced by the Shoreham pilot.

9.62 This review makes a number of recommendations for the CAA to consider. The recommendations are weighted towards improving the safety of flights where aerobatic manoeuvres are undertaken as these are the flights where levels of G above +2 Gz are likely to be experienced and physiological effects could be encountered. The focus has been on safety improvement.

9.63 None of the recommendations are considered to be urgent safety recommendations.

Chapter 10

Summary of Recommendations

Recommendation 1

The CAA should consider undertaking an analysis of UK aerobatic accidents and incidents to review the likely G exposure and potential causes of any errors and poor decisions. Such analysis could include comparison of pilot performance in flights involving exposure to different levels of +Gz (eg up to +2 Gz, up to +5 Gz or greater than +5 Gz) to facilitate recognition of patterns of association.

Recommendation 2

The CAA should ensure that the training of pilots in aerobatic manoeuvres should include an awareness of the basic physiological principles of exposure to G force and the effects of increased G, the factors that increase or decrease the risk of G-related impairment or incapacitation, that a pilot's G tolerance can vary and alteration of consciousness can affect any pilot undertaking aerobatic manoeuvres. There should be awareness of the anticipated levels of G associated with each manoeuvre the pilot is taught. Pilots should be made aware that visual or other premonitory symptoms may not necessarily occur with rapid onset high G and G-LOC may occur without warning. Pilots should keep a log of all G-related training.

Recommendation 3

The CAA should ensure that when applying for the issue, renewal or upgrade of an aerobatic DA the pilot should demonstrate an understanding of the factors that may influence their own G tolerance, knowledge of the symptoms of G-related impairment and incapacitation and how to respond to these symptoms if they occur during a display flight. They should also be able to demonstrate how they assess the aerobatic manoeuvres they intend to perform for their potential to alter consciousness and how the mitigating measures they have in place alter this assessment.

Recommendation 4

The CAA should consider adding a specific question on the medical certificate application form about whether the applicant intends to undertake aerobatics.

Recommendation 5

The CAA should consider whether any aeromedical advice is required to be published for pilots intending to undertake aerobatics and for the doctors who may be involved in their medical assessments.

Recommendation 6

The CAA should ensure that the medical oversight of AMEs and aviation medicine training providers should include confirmation that medical considerations for aerobatic flight is included in the AME training syllabus and Basic Certificate in Aviation Medicine course programme and that existing AMEs can demonstrate knowledge of the medical considerations of aerobatic flight.

Recommendation 7

The CAA should consider undertaking a survey of pilots with an aerobatic rating including DAs to determine whether incidents of G-related impairment are occurring that are normalised and are not being reported with a view to proposing changes to the UK's Mandatory Occurrence Reporting Scheme if appropriate.

Chapter 11

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Appendix A

Terms of Reference

Civil Aviation Authority

Enquiry into the Risk of Cognitive Impairment due to G forces

Background

On 22 August 2015 one of the aircraft flying in the display at the Shoreham Air Show crashed outside the perimeter of the aerodrome resulting in the deaths of 11 people. The pilot, Andrew Hill, was subsequently tried for gross negligence manslaughter. On 8 March 2019 the jury returned not guilty verdicts on all counts. Mr Hill's defence rested, in part, on the assertion that he may have been cognitively impaired to have flown in the manner that he did; this impairment was attributed to him being adversely affected by the level and duration of G forces he experienced during the manoeuvres he performed immediately prior to the accident.

Scope

The CAA considers that it is necessary to conduct a medical review of the risk of cognitive impairment in pilots due to G forces. This review will be limited to fully investigating the existence of cognitive impairment of the type described during the criminal trial (referenced above) with the potential risks and consequences that could result. Once the relevant materials identified below have been made available, the CAA anticipates that the review will take between 9-12 months to complete. Given the importance of this matter the CAA's Chief Medical Officer, will advise other national aviation authorities and interested parties of the review, explaining the need for the review and requesting any assistance and evidence they can provide.

The following will be reviewed:

- The evidence submitted to the Court for the purposes of the criminal trial by the medical expert witnesses, the medical evidence submitted by both the Crown Prosecution Service and the Defence, and any other relevant evidence related to the actions of the pilot during the accident flight. Where such evidence has not already been made available to the CAA, or is protected from disclosure, appropriate permissions will need to be obtained from the parties controlling such material or disclosed by order of the Court.

- The supplement to the Final Accident Report (1/2017) that will be published by the Air Accidents Investigation Branch. The CAA anticipates this document will contain full details of the review conducted of material presented to the AAIB in June 2019 relating to the Shoreham accident, focused specifically on the potential effects of G forces on the pilot. The CAA may require access to all or some of the underlying material relied upon by the AAIB.
- The medical opinion on the implications for high-G operations following the Shoreham trial verdict provided by the Royal Air Force Centre of Aviation Medicine. Again, the CAA may require access to all or some of the underlying material relied upon by the RAF to produce this opinion.
- A literature review of other relevant medical evidence that is available in the UK or internationally.

Points to be Determined

Whether the nature, degree and duration of acceleration experienced by Andrew Hill poses a risk for the safety of other civilian flights where a pilot may experience the same nature, degree and duration of acceleration as in the accident flight.

Out of Scope

Loss of consciousness due to high levels of G forces (known as G-LOC) will not be considered for reasons that will be outlined in the enquiry report.

Project stages and working methods

The project will be carried out in stages:

- Stage 1 – collate relevant documentation and evidence, including evidence used at and material prepared for Mr Hill's trial subject to the appropriate permissions being obtained (see above)
- Stage 2 – consideration of all relevant documentation and evidence by the CAA's Chief Medical Officer and members of the CAA's Aeromedical Team
- Stage 3 – preparation of draft report and appropriate recommendations for follow up actions, if any to be reviewed by an independent expert challenge panel
- Stage 4 – publication of final report

It is anticipated that Stage 2 of the review will take up to six months from the date on which relevant documentation is made available in full. The CAA team will comprise Dr Sally Evans (MBE FRCP FRCP Edin FFOM DAvMed) and Dr Stuart Mitchell (BSc(Hons) FFOM DAvMed FRAeS). The CAA will seek assistance as needed from external independent experts, such as the UK Military Aviation Authority and other national and international aviation safety authorities. Other parties will also be consulted as necessary.

Recommendations for the UK CAA

If appropriate, recommendations to improve flight safety will be made.

The Civil Aviation Authority will publish a report of its findings.

Civil Aviation Authority

20 August 2019

Appendix B

List of Citations Provided to the CAA from the AAIB

List 1

BASI research report 872-1017: THE POSSIBILITY OF G-INDUCED LOSS OF CONSCIOUSNESS (G-LOC) DURING AEROBATICS IN A LIGHT AIRCRAFT. https://www.skybrary.aero/bookshelf/books/2754.pdf

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Appendix D

Template of Letter Sent to International Organisations

OFFICIAL – SENSITIVE

Dear Sir, Madam

The UK CAA is currently undertaking a review of medical literature relating to the risk of cognitive impairment in pilots who experience acceleration forces (‘g forces’) below those known to cause ALOC or GLOC during the course of civilian flying activities. I have been appointed as the Chair of this review.

During a recent UK criminal trial, involving a civil air display pilot who crashed whilst performing aerobatic manoeuvres in an ex-military jet aircraft, the defence put forward the proposition that the accident pilot may have suffered a degree of cognitive impairment whilst subjected to g forces below those known to cause ALOC or GLOC. The UK CAA has therefore committed to review the risk of cognitive impairment in civilian pilots who experience lower level g forces so that recommendations may be made, or regulatory action may be taken, if appropriate.

I am now writing to enquire whether you have any experience of such a phenomenon either in aeromedical research, in commercial or recreational flying, or in accident investigation reports or safety reviews where g forces below those known to cause ALOC or GLOC have been encountered?

I should be most grateful for any information, data or analyses that you are able to share with my Review Team.

If you have any questions about this request please do not hesitate to contact me by email at sally.evans@caa.co.uk or by telephone on 01293 573669.

Many thanks for your help.

Kind regards

Yours sincerely

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Appendix E

Additional Literature Suggested to the Review Team by External Parties

Accident Reports

- R45EN 1997/8 (Duxford, UK)
- G-GZOZ 8 July 2005 (White Waltham, UK)
- G-EDGJ 22 April 2015 (Old Buckenham, UK)
- USAF F-16 Thunderbirds 4 April 2018 (Nevada, USA)
- N79111 P-51D 16 September 2011 (Reno air races, USA)

FAA Advisory Circular

- Hazard in Aerobatics Effects of G-Forces on Pilots

Appendix F

Aircraft Categorised Risk Data Table

The table below is based on the table in Chapter 9, page 63 of the CAA's CAP 1724: Flying Display Standards Document. Additional columns have been added to assist in risk categorisation and analysis.

The table contains 92 aircraft types which include aircraft from the following aircraft categories: Single Engine Piston, Multi-Engine Piston Aeroplanes, Jet Powered Aeroplanes and Turboprop.

Vne is listed as KIAS rather than miles or kilometers per hour.

The positive Gno limit is listed as +Gzno.

The following aircraft categories have been excluded: L, M, N, O, P, T, U, V, W1, W2 and W3.

The Royal Air Force Battle of Britain Memorial Flight (BBMF) Gz limits have been used for representative aircraft such as the Spitfire and Hurricane as these limits are readily available.

Group	Aircraft	Hp	Category	Max IAS (Vne) (kts)	Gz Limit (Gno)	Environment	Overall Risk Categorisation	Notes
SEP	AUSTER 6A	145	A	110	No data	Benign	Low	Stall speed 30 kts
SEP	AUSTER AOP.9	145	A	110	No data	Benign	Low	Stall speed 28 kts
SEP	AVIAT A-1C-180 HUSKY	180	A	125	No data	Benign	Low	Stall speed 46 kts
SEP	BUCKER BU131 JUNGMAN	150	A	100	No data	Benign	Low	Stall speed 40 kts
SEP	BULLDOG	200	A	185	4.75	Benign	Low	
SEP	CAP 10C	180	A	184	4	Benign	Low	
SEP	CASA 1-131E SERIES 2000	125	A	160	No data	Benign	Low	Stall speed 40 kts
SEP	CESSNA 152	108	A	150	6	Benign	Low	
SEP	CHAMPION 8KCAB DECATHLON	180	A	175	6	Moderately Dynamic	Medium	

Group	Aircraft	Hp	Category	Max IAS (Vne) (kts)	Gz Limit (Gno)	Environment	Overall Risk Categorisation	Notes
SEP	CITABRIA 7ECA	160	A	105	5	Moderately Dynamic	Medium	
SEP	DH60M MOTH	120	A	90	No data	Benign	Low	
SEP	DH80A PUSS MOTH	120	A	80	No data	Benign	Low	
SEP	DH82A TIGER MOTH	130	A	90	No data	Benign	Low	
SEP	DHC-1 CHIPMUNK 22	145	A	155	6	Benign	Low	
SEP	DRUINE D.31 TURBULENT	30	A	110	No data	Benign	Low	
SEP	SLINGSBY T67 FIREFLY	160	A	180	6	Benign	Low	
SEP	GLOS-AIRTOURER SERIES 115	115	A	120	No data	Benign	Low	Stall speed 46 kts
SEP	GOMHOURIA 181 MK6 BESTMAN	105	A	240	No data	Benign	Low	
SEP	GROB G115E	186	A	185	6	Benign	Low	

Group	Aircraft	Hp	Category	Max IAS (Vne) (kts)	Gz Limit (Gno)	Environment	Overall Risk Categorisation	Notes
SEP	GROPPO TRAIL	80	A	110	4	Benign	Low	
SEP	KLEMM KL35D	80	A	114	No data	Benign	Low	
SEP	MONNETT SONERAI 2L	80	A	170	No data	Benign	Low	Stall speed 40 kts
SEP	PAZMANY PL-4	50	A	110	No data	Benign	Low	Stall speed 47 kts
SEP	PIPER J3C-65 PIPER CUB	65	A	76	No data	Benign	Low	Stall speed 33 kts
SEP	PIPER L18C	150	A	110	No data	Benign	Low	Stall speed 43 kts
SEP	PITTS S-1C	180	A	203	6	Moderately Dynamic	Medium	
SEP	PITTS S-1S	180	A	203	6	Moderately Dynamic	Medium	
SEP	PS-28 CRUISER	98.6	A	138	No data	Benign	Low	Stall speed 30 kts
SEP	RANS S9 CHAOS	50	A	74	6	Moderately Dynamic	Medium	Stall speed 29

Group	Aircraft	Hp	Category	Max IAS (Vne) (kts)	Gz Limit (Gno)	Environment	Overall Risk Categorisation	Notes
SEP	REPLICA FOURNIER RF6B-100	120	A	152	6	Benign	Low	Stall speed 54 kts
SEP	RUTAN LONG-EZ	115	A	161	No data	Benign	Low	Aerobatic manoeuvres are prohibited
SEP	RYAN ST3KR	125	A	130	10	Highly Dynamic	High	
SEP	S200	115	A	135	4.4	Benign	Low	
SEP	SHERWOOD RANGER XP	93	A	86	6	Moderately Dynamic	Medium	Stall speed 35 kts
SEP	SILENCE TWISTER	54	A	160	6	Moderately Dynamic	Medium	
SEP	STAMPE SV4C	145	A	102	No data	Benign	Low	Stall speed 38 kts
SEP	T-6 TEXAN	600	A	180	5.67	Moderately Dynamic	Medium	
SEP	TAYLOR MONOPLANE	38	A	113	No data	Benign	Low	Aerobatics prohibited by the LAA
SEP	TAYLOR TITCH	85	A	170	No data	Benign	Low	Stall speed 43 kts, Aerobatics

Group	Aircraft	Hp	Category	Max IAS (Vne) (kts)	Gz Limit (Gno)	Environment	Overall Risk Categorisation	Notes
								prohibited by the LAA
SEP	TITAN T-51 MUSTANG	115	A	185	6	Moderately Dynamic	Medium	
SEP	VANS RV-6	180	A	173	6	Moderately Dynamic	Medium	
SEP	CHRISTEN EAGLE	200	A	185	9	Moderately Dynamic	High	
SEP	EXTRA 200	200	A	200	10	Moderately Dynamic	High	
SEP	FAIRCHILD M-62A-4	200	A	115	No data	Benign	Low	Stall speed 44 kts
SEP	VANS RV-7	200	A	200	6	Moderately Dynamic	Medium	
SEP	VANS RV-8	200	A	190	6	Moderately Dynamic	Medium	
SEP	BOEING A75 STEARMAN	225	B	163	No data	Benign	Low	Stall speed 55 kts
SEP	CAP 232	300	B	219	10	Highly Dynamic	High	
SEP	EDGE 540	310	B	230	12	Highly Dynamic	High	

Group	Aircraft	Hp	Category	Max IAS (Vne) (kts)	Gz Limit (Gno)	Environment	Overall Risk Categorisation	Notes
SEP	EXTRA 230	230	B	220	10	Moderately Dynamic	High	
SEP	EXTRA 300	300	B	220	10	Moderately Dynamic	High	
SEP	EXTRA 330LX	315	B	219	10	Moderately Dynamic	High	
SEP	GB1 GAMEBIRD	315	B	234	10	Moderately Dynamic	High	
SEP	MXS-R	320	B	240	14	Highly Dynamic	High	
SEP	P-47 THUNDERBOLT	2000	B	300	No data	Moderately Dynamic	Medium	
SEP	PIAGGIO FW P149D	270	B	164	6	Moderately Dynamic	Medium	
SEP	PISTON PROVOST	550	B	170	No data	Benign	Low	Stall speed 60 kts
SEP	PITTS S-2C	260	B	182	6	Moderately Dynamic	Medium	
SEP	PITTS S-2S	260	B	182	6	Moderately Dynamic	Medium	

Group	Aircraft	Hp	Category	Max IAS (Vne) (kts)	Gz Limit (Gno)	Environment	Overall Risk Categorisation	Notes
SEP	PT-17 STEARMAN	225	B	163	No data	Benign	Low	Stall speed 48 kts
SEP	SPITFIRE MK 26	320	B	230	No data	Moderately Dynamic	Medium	3.5Gz Gno is BBMF standard limit to reduce aircraft fatigue
SEP	SUKHOI SU-26M	360	B	240	12	Highly Dynamic	High	
SEP	XA42	315	B	215	10	Highly Dynamic	High	
SEP	YAK 50	451	B	220	9	Highly Dynamic	High	
SEP	YAK 52	360	B	154	7	Moderately Dynamic	Medium	
SEP	YAK 54	360	B	243	9	Highly Dynamic	High	
SEP	YAK 55	360	B	240	9	Highly Dynamic	High	
SEP	YAK-18T	400	B	141	6.4	Moderately Dynamic	Medium	
SEP	ZLIN 50	260	B	158	9	Highly Dynamic	High	
SEP	ZLIN Z 526	208	B	170	6	Highly Dynamic	High	

Group	Aircraft	Hp	Category	Max IAS (Vne) (kts)	Gz Limit (Gno)	Environment	Overall Risk Categorisation	Notes
SEP	CORSAIR	2100	C	300	6	Moderately Dynamic	Medium	
SEP	GRUMMAN FM2 WILDCAT	1200	C	288	No data	Moderately Dynamic	Medium	No stall data available
SEP	HARVARD	600	C	164	No data	Moderately Dynamic	Medium	Stall speed 62 kts
SEP	HURRICANE	1185	C	300	3	Moderately Dynamic	Medium	3Gz Gno is BBMF standard limit to reduce aircraft fatigue
SEP	ME109	1455	C	280	6.4	Moderately Dynamic	Medium	
SEP	MUSTANG	1720	C	320	8	Moderately Dynamic	Medium	
SEP	SEAFIRE 1B	1585	C	312	3.5	Moderately Dynamic	Medium	3.5Gz Gno is BBMF standard limit to reduce aircraft fatigue
SEP	SPITFIRE I	1030	C	252	No data	Moderately Dynamic	Medium	3.5Gz Gno is BBMF standard limit to reduce aircraft fatigue

Group	Aircraft	Hp	Category	Max IAS (Vne) (kts)	Gz Limit (Gno)	Environment	Overall Risk Categorisation	Notes
SEP	SPITFIRE LF XVI	1250	C	290	6.2	Moderately Dynamic	Medium	3.5Gz Gno is BBMF standard limit to reduce aircraft fatigue
SEP	SPITFIRE MK.IIA	1030	C	252	No data	Moderately Dynamic	Medium	Stall speed 63 kts
SEP	T-28 TROJAN	1425	C	205	4.5	Moderately Dynamic	Medium	
SEP	YAK 3M	1290	C	349	No data	Moderately Dynamic	Medium	
MEP	B17	4 x 750	Z	200	No data	Benign	Low	
MEP	C-47 DAKOTA	2 x 1500	Z	180	3	Benign	Low	
MEP	OV-10B BRONCO	2 x 715	Z	244	No data	Benign	Low	Stall speed 40 kts
JET	AERO L-39C ALBATROS	Jet	G1	400	8	Highly Dynamic	High	
JET	BAC 167 STRIKEMASTER MK80	Jet	G1	420	5.5	Moderately Dynamic	Medium	

Group	Aircraft	Hp	Category	Max IAS (Vne) (kts)	Gz Limit (Gno)	Environment	Overall Risk Categorisation	Notes
JET	GALEB G-2A	Jet	G1	380	8	Highly Dynamic	High	
JET	JET PROVOST	Jet	G1	420	5.5	Moderately Dynamic	Medium	
JET	GNAT	Jet	G2	525	7	Highly Dynamic	High	
JET	HUNTER	Jet	G2	620	7	Highly Dynamic	High	
TURBOPROP	MARCHETTI SF.260C	260	I1	235	6	Benign	Low	

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