

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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CAP1963

Published by the Civil Aviation Authority, 2020

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First published December 2020

The latest version of this document is available in electronic format at: www.caa.co.uk/CAP1963

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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.

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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.

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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.

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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.

Contents

The Review Team	3
Contents	8
Executive Summary	12
Abbreviations	19
Glossary of Terms and Definitions	21
List of Figures	23
List of Tables	24
Preface	25
Chapter 1 Introduction	26
Background	26
Aim of the Review	26
Scope	27
Levels of G Force in Scope	27
UK Civil Aviation Activities	29
Availability of Material	29
Chapter 2 Methodology	31
First Stage – Collation of Relevant Material	31
Background Material and Accident Reports	31
Scientific Literature	32
Consultation with Other National Aviation Authorities and Institutions	33
Second Stage – Review of Literature	34
Third Stage – Peer Review and Publication of Report	35
Chapter 3 Acceleration	36
Introduction	36
Acceleration and ‘G Forces’	36
What is Acceleration?	36
What are ‘G Forces’?	36
Direction and Magnitude of G Force	37

Acceleration in Flight	37
Acceleration Physiology	38
Cerebral Blood Flow	40
Siphon Effect	41
Arterial Blood Pressure and Baroreceptor Response	41
Respiratory Effects of +Gz Acceleration	43
Signs and Symptoms of +Gz Exposure	43
Cerebral Oxygenation	44
UK Military Accident Experiences	46
G Tolerance	47
Acceleration Onset Rate	48
Other Factors Influencing G Tolerance	51
Factors Beneficial for G Tolerance	53
G Protection	54
Training	56
Adaptation	57
Clinical Aeromedical Issues from Exposure to G Forces	59
Chapter 4 Acceleration and Cognitive Performance	60
Cognitive Performance	60
Cognitive Performance and Acceleration	60
Acceleration Levels in General Aviation and Cognitive Performance	66
Chapter 5 Information Received from National and International Organisations	75
Civilian Organisations	75
International Aviation Authorities	75
Accident Investigation Bodies	78
Summary	78
UK Military	78
Chapter 6 G Forces in Civil Aviation	81
Professional Pilots	81
Fixed Wing Commercial Operations	81
Rotary Commercial Operations	83
General Aviation	84

Training for Increased G Exposure	84
Display Flying	85
Aerobatic Aircraft and G Exposure	87
Recreational Aerobatics	87
Ex-Military Aircraft	87
Display and Competition Flying	88
+Gz Capability of Aircraft on the UK General Aviation Civil Aircraft Register	88
Exclusions	90
General Aviation Gz-Related Operational Risk	91
Chapter 7 Hypoxia	96
Human Physiological Systems	96
The Need for Oxygen	99
Hypobaric Hypoxia	101
Hypoxia and Neurological Effects	103
Hypoxia and Hyperventilation	104
Hypoxia in Low Altitude Flight	104
Ventilation/Perfusion Inequalities in the Lungs	105
Hypoxia with +Gz	105
Comparison of G-Induced Hypoxia with Altitude-Related Hypoxia	106
Cognitive Performance and Hypoxia	106
Chapter 8 Discussion	110
Introduction	110
Cognitive Effects	111
Cognitive Performance at Low +Gz	111
Cognitive Performance at High +Gz	115
Slow Onset	115
The Contribution of Hypoxia to Cognitive Function with +Gz	117
Hypoxic Hypoxia and Cognitive Function	117
Oxygenation of Cerebral Tissue with +Gz	118
Aerobatic Accidents Due to Pilot Incapacitation	120
Study Conditions	120
Study Environments	120

Study Subjects	121
Measuring Cognitive Function	121
Measurement Tools	122
Centrifuge Training	123
G Tolerance	123
Aerobatic Flying	124
G Tolerance	125
Aeromedical Aspects of Aerobatic Flying	126
Adaptation to Aerobatic Flying	127
Safety Culture	127
Chapter 9 Conclusions	128
General Comments	128
Aerobatic Flight	128
Physiological Hazards of Increased G Exposure	130
Cognitive Effects of Exposure to G Force	131
Impairment of Cognition	132
Is there an Alteration of Cognition at Low Levels of G?	133
Is there any Effect on Cognition Prior to Grey Out or Blackout?	133
Are Cognitive Effects Part of the Spectrum of Alteration of Consciousness?	134
Hypoxia: Ischaemic vs Hypoxic	134
Cognitive Function and Low +Gz	136
Chapter 10 Summary of Recommendations	138
Chapter 11 References	140
Appendix A Terms of Reference	155
Appendix B List of Citations Provided to the CAA from the AAIB	158
Appendix C References Reviewed But Not Cited in the Report	161
Appendix D Template of Letter Sent to International Organisations	169
Appendix E Additional Literature Suggested to the Review Team by External Parties	170
Appendix F Aircraft Categorised Risk Data Table	171
Acknowledgements	182

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.

List of Figures

Figure A	G Tolerance Curve
Figure B	Flight Data Monitoring analysis of vertical acceleration during flight Jan-Dec 2019: Fixed Wing operations
Figure C	Flight Data Monitoring analysis of vertical acceleration during flight Jan-Dec 2019: Rotary operator
Figure D	Oxyhaemoglobin dissociation curve of blood

List of Tables

Table A	Acceleration and Human Performance Literature Review Summary
Table B	Normalised Data from Literature across Cognitive Abilities
Table C	Volume of flying display permissions issued for display seasons 2017-2019
Table D	Aircraft Groups and Categories as defined in CAP 1724
Table E	Excluded aircraft
Table F	Aircraft risk categories
Table G	Environmental risk categories
Table H	Overall risk matrix
Table I	Gz-related risk of aircraft on the UK Aircraft Register
Table J	Aircraft categorised as having High Gz-related risk
Table K	Hypoxia and cognitive performance literature review summary

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 (rSO₂) 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 rSO₂ 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**.

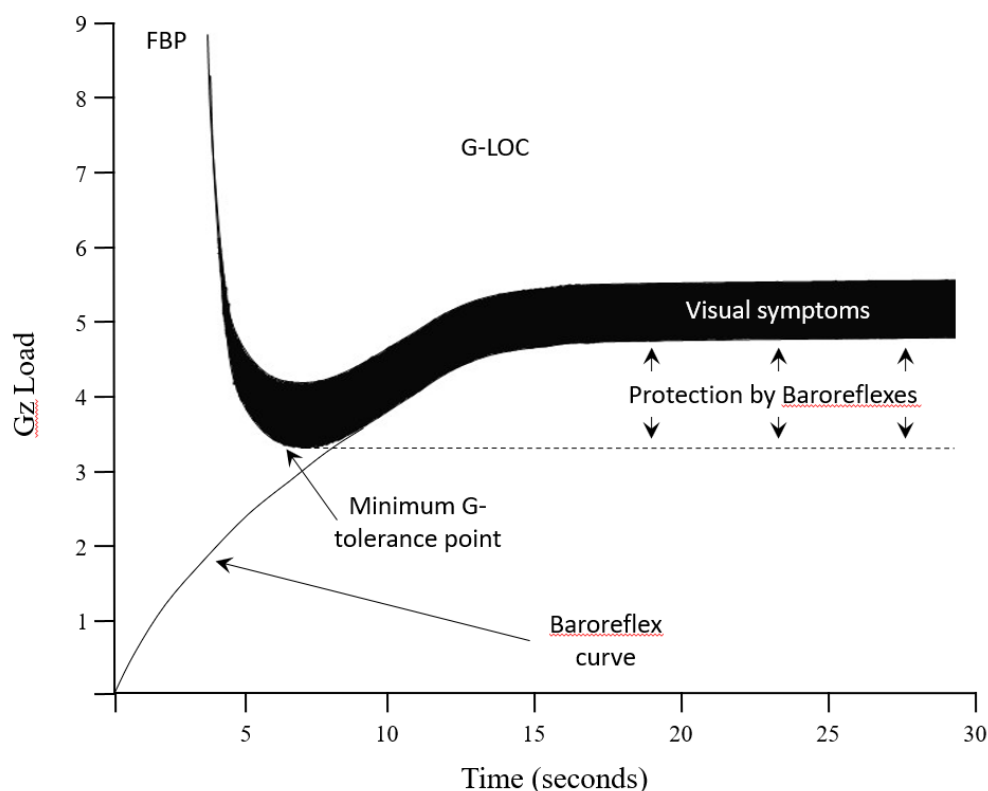


Figure A

G Tolerance curve

taken from Newman 2015¹⁹² (after Stoll 1956²⁶⁴) 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