Department of Transport and Communications

Bureau of Air Safety Investigation

THE POSSIBILITY OF G-INDUCED LOSS OF CONSCIOUSNESS (G-LOC) DURING AEROBATICS IN A LIGHT AIRCRAFT

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Introduction

The Bureau of Air Safety Investigation recently conducted research into the rates of G onset and G levels experienced by a light aircraft pilot during normal aerobatics. The objective was to relate data obtained from the research to other data available from military authorities, in order to evaluate the possibility or otherwise of a light aircraft pilot sustaining G-induced loss of consciousness (G-LOC) during aerobatics.

The research followed a fatal accident in Australia during 1987 involving a pilot who was practising an aerobatic sequence in a Bellanca 8KCAB Decathlon aircraft.

The Bureau fitted a Decathlon aircraft with appropriate instrumentation to enable acceleration values in three axes to be recorded during a sequence of ten aerobatic manoeuvres. The axes were the x axis (longitudinal), y (lateral) and z (vertical).

Acceleration in the vertical axis is referred to as Gz, and is the principal consideration in the G-LOC phenomenon.

Loss of consciousness by pilots due to high positive Gz is a phenomenon which has been recognised since the early 1930's. With sustained moderate rates of onset of Gz, G-LOC is preceded by visual symptoms of grey-out followed by blackout. The matter addressed here, however, is the sudden or instantaneous loss of consciousness which occurs without the prior visual warning symptoms of grey-out and black-out at more rapid rates of onset of Gz.

Military research has demonstrated that sudden loss of consciousness may occur if a Gz onset rate of approximately 1G per second is sustained for more than 3 to 5 seconds. It is known that G-LOC occurs in normal people and is the normal outcome if the right circumstances prevail. The real frequency with which G-LOC occurs in aviation has only been recognised relatively recently, particularly in the case of instantaneous G-LOC.

For a variety of reasons military data cannot be directly related to civilian pilots flying aerobatics in a light aircraft. Military research has naturally studied the phenomenon in relation to high performance fighter aircraft and military pilots. The effect of different training and fitness levels between civilian and military pilots and the effect of age on Gz tolerance are also matters about which little is known. It is reasonable to assume, though, that there is a wider range of individual differences in Gz tolerance within the civilian pilot community than in the military, in view of the more highly selected population represented by the latter group.

A world-wide information search by BASI failed to locate any data concerning Gz parameters applicable specifically to light civil aerobatic aircraft.

Circumstances of the particular accident which initiated the research

The purpose of the flight was to practice an aerobatic sequence of ten manoeuvres in preparation for a competition. The pilot had arranged for an observer to assess his performance from the ground, and there were several other pilot witnesses to the sequence of events.

It was known that the pilot intended to practice the following sequence of manoeuvres:

1. A one-turn spin
2. Roll-off-the-top of a loop
3. 270 degree horizontal turn using 60 degrees of bank
4. 90 degree turn in the opposite direction using 60 degrees of bank
5. Loop
6. Reverse 1/2 Cuban 8
7. 1/2 Cuban 8
8. Aileron roll
9. Stall turn
10. Barrel roll

The pilot commenced aerobatics over the aerodrome probably at 4000 feet, but apparently stalled while inverted at the end of the second manoeuvre, the 180 degree roll-off-the-top of the loop. There was witness evidence that the pilot had heard on the preceding day that it was not possible to perform one and half rolls-off-the-top of a loop in a Decathlon, and also that he was anxious to attempt such a manoeuvre on the day of the accident.

After recovering from the inverted stall the pilot continued with aerobatic manoeuvres, but it was not possible to determine from the evidence whether he continued with the planned sequence, recommenced the sequence, or performed some other sequence of aerobatics.

Although it is not possible to perform one and a half rolls-off-the-top in a Decathlon, there was no means of determining whether the pilot was in fact attempting to fly such a manoeuvre. Equally, an aerobatic pilot would be aware that to lengthen the manoeuvre from a half roll to one and a half rolls would require some combination of a higher airspeed and/or tighter loop prior to attempting the manoeuvre.

However, after completing a number of manoeuvres following the inverted stall, the aircraft was observed to enter a steep spiral dive which continued without any apparent control input until it struck powerlines, caught fire and fell to the ground, killing the pilot.

Investigation

An intensive examination of the wreckage did not reveal any pre-existing mechanical defect. No evidence was found of any physical or psychological factors which might have impaired the pilot's flying ability.

Consideration was given to the possibility of temporary loss of consciousness of the pilot induced by the positive Gz forces associated with the aerobatic manoeuvres being flown. The question of G-LOC arose due to a number of witness comments which strongly suggested that the manoeuvres were flown with unusual tightness. Such comments, if correct, would not be inconsistent with an attempt, or attempts, by the pilot to complete a one-and-a-half rolls-off-the-top manoeuvre.

Although there was no evidence to show that the pilot in the Decathlon accident had suffered G-LOC, equally it was difficult to ignore the consistent witness evidence concerning the tightness with which the manoeuvres were apparently flown. For example, one pilot witness described some of the high-G manoeuvres prior to the descent to the ground as being the most excessive manoeuvres he had ever seen during ten years of observing aerobatics over the particular aerodrome.

G-induced LOSS of Consciousness (G-LOC)

G-LOC is due to the reduced flow of blood to the brain when the magnitude of Gz passes beyond a particular value, the G-LOC threshold. Before the G-LOC threshold becomes a critical factor, a physiological reserve period of 3–5 seconds exists, after which, at the G-LOC threshold, neurones fail to function in the absence of the oxygen replenishment provided by the normal blood flow.

The subjective visual symptoms of grey-out followed by black-out which often precede G-LOC are well known. These occur as the arterial blood flow to the retinae of the eyes is progressively reduced. Grey-out is a partial loss of vision, commencing with peripheral vision, while black-out results in total loss of vision.

It is emphasised that grey-out and black-out do not involve loss of consciousness and are not synonymous with G-LOC.

Grey-out and black-out may provide the pilot with useful warning signs of imminent G-LOC and are phenomena which have been experienced by many pilots. They disappear as soon as back pressure on the elevator control is relaxed, i.e. as Gz is reduced, or when the G-LOC threshold is raised by reflex or straining action.

However, it is not well known that quite moderate rates of Gz onset sustained for longer than the body's physiological reserve period may result in instantaneous loss of consciousness if the G-LOC threshold is exceeded within this time. Loss of consciousness will then occur without the prior visual warning symptoms of grey-out or black-out. Within this 3–5 second period, very high onset rates and levels of Gz may be tolerated without visual symptoms or G-LOC, provided that the Gz is reduced below the G-LOC threshold by the end of the period. Figure 1 summarises the effect of Gz onset rates on G tolerance.

The G-LOC threshold varies slightly with time: the lowest values occur at the beginning of the period of onset of Gz while the output of the heart is changing to compensate for the effects of Gz. The G-LOC threshold is also subject to considerable inter- and intra- individual variation, but population means for fit individuals range from approximately 4 to 6 Gz.

Fatigue reduces Gz tolerance, as does a lack of frequent and recent exposure to Gz. Other factors which may reduce Gz tolerance include chronic or acute hypotension (low blood pressure), recent exposure to alcohol, hypoglycemia (low blood sugar), self-imposed or environmental stress, dehydration and illness. In some cases pilots with a constitutionally slow heart rate can also have reduced tolerance to high rates of onset of Gz. A pilot's ability to endure G forces is greatest when the pilot is fresh. The reason for this is thought to be associated with the depletion during time under high G of autonomic stress hormones such as adrenalin, or of tissue energy stores such as glycogen, or both.

Centrifuge research has shown that there is a period of functional incapacitation following G-LOC lasting an average of 15 seconds. Full recovery may take 30 seconds or longer from the initiation of the manoeuvre that induces G-LOC. Clearly, an aircraft descending vertically at, say, 120kts will only take 30 seconds to reach the ground from 6000 ft.

Centrifuge research, and the use of on-board video and cockpit voice recording equipment, have also revealed that following G-LOC it is common for pilots to experience total amnesia with regard to the occurrence. It is believed that this aspect of G-LOC is one of the reasons why the phenomenon has been infrequently recognised.

The full operational consequences and frequency of occurrence of G-LOC have been appreciated only relatively recently because of its identification as the primary causal factor in the loss of many high performance military aircraft.

Recent RAF, USN, and RAAF surveys of military aircrew have also revealed that the problem of G-LOC is not confined to high performance aircraft. Indeed, in these surveys a significant proportion of G-LOC incidents, including some at Gz levels of 4G and below, have occurred in low performance training aircraft. Centrifuge studies have supported the results of these surveys.

The US Naval Aerospace medical Research Laboratory suggested to the Bureau that in such aircraft, the greatest danger may occur in manoeuvres which subject a pilot to negative Gz just before exposure to a high rate of onset of positive Gz. Negative Gz sustained for more than a few seconds will initiate a slowing of the heart rate, and this will markedly reduce positive Gz tolerance if the positive Gz exposure immediately follows the negative Gz.

Since no data on typical Gz onset rates and durations could be found for a light aircraft, it was decided to conduct a series of recording flights with an appropriately equipped Decathlon flying the same sequence of ten manoeuvres listed above.

Method and equipment used in the recording flights

Three linear servo-accelerometers were mounted on a bracket beneath the forward pilot's seat, and aligned to measure accelerations in the longitudinal, lateral and vertical axes. For the purposes of measuring Gz, the vertical axis was defined as a line parallel to the pilot's backbone. For practical purposes such a line is also parallel to the back of the pilot's seat, and consequently the Gz accelerometer was aligned with that axis.

A Data Electronics (Aust) Pty Ltd Data Logger model DT100 was carried in a specially made box and fixed to the rear seat of the Decathlon. The Data Logger carried its own internal battery power, and the box contained 12V batteries to provide the power source for the accelerometers. The wiring connections included an On-Off switch so that the pilot could initiate logging as he made the run-in at 4000 ft to commence the aerobatic sequence, and then end logging at the end of the sequence. This was necessary in order to avoid exceeding the memory capacity of the logger.

The data were logged six times per second per accelerometer. At this rate it was estimated that there was sufficient memory for approximately ten minutes of flight. As it took slightly less than three minutes to complete a sequence, it was possible to fly the sequence twice during each flight.

After two sequences of accelerometer data had been captured in the logger, the aircraft would land. The data were then transferred from the logger memory into the memory of a battery-powered Toshiba T1100 lap top portable computer via the commercially available communications software package 'Crosstalk'. The computer was configured with 640K of memory and two 720K disc drives running MSDOS as the operating system. The data were then transferred to a T1100 diskette.

The data logger memory was cleared before the aircraft departed to fly the sequence twice again. This process was continued until sufficient data had been collected. Field checks were made throughout the programme to ensure that valid data was being collected.

The T1000 was then taken back to the BASI office where it was transferred to a mini computer, again using the Crosstalk package. The data for each flight sequence were subsequently printed as raw data. The data were also plotted as time against acceleration using standard plotting software on the mini computer.

Preparation for the recording flights was spread over several months, although the actual flights were all completed in three flying hours on the one day.

The flying was carried out by an experienced flying instructor. The sequence was flown twice on each of six flights, and the flights were divided into two groups. On the first three flights the pilot was asked to fly the aircraft as he would if instructing a pupil in aerobatics. In the second group of flights the pilot was asked to fly in the way that he would if he was engaging in a competition.

Results

Some data were rejected as they were adversely effected by low battery voltage in the data logger towards the end of the flying programme. However, the bulk of the data were good and exhibited an unexpectedly high degree of consistency from one sequence to the next.

Data in table 1 show the magnitude and duration of significant and continuous Gz changes for each of the ten manoeuvres in the sequence. The Gz changes and their related durations are simply the significant segments taken from what was otherwise a continuous stream of data.

Gz/second was then calculated for manoeuvres where the data were considered to be of importance.

Column A provides mean results from the first group of six sequences where the pilot carried out the aerobatics in the same way as he would if instructing a pupil.

Column B shows the largest individual Gz change which was recorded for each type of manoeuvre in the first group of six sequences. The duration of the Gz change associated with that specific manoeuvre is shown, along with the Gz/second where appropriate.

Column C shows the greatest Gz changes and associated durations recorded from the second group of sequences, where the pilot flew the aerobatics in the manner he would have flown them as an individual pilot engaging in a competition.

It is quite clear that although the absolute Gz levels are not excessive, the sequence of manoeuvres is quite demanding in terms of the duration for which positive acceleration is maintained. There is also a general increase in both negative and positive accelerations in the second group of sequences, and it is not difficult to envisage that a pilot who flew the sequence in a particularly aggressive manner could achieve much higher Gz values and rates of onset.

Specifically, manoeuvres 2, 5 and 6 have definite potential for G-LOC due to the onset rate, level and duration of Gz experienced. manoeuvre 6(a) is the worst case, where peak positive Gz is preceded by peak negative Gz. Although not shown in the table, these negative and positive peaks with 6(a) were also each sustained for several seconds. Column C 6(a) shows that it would take little additional effort on the part of a pilot to commence the reverse 1/2 Cuban 8 at -2Gz, and achieve +4Gz in 5 or 6 seconds. Much greater Gz magnitudes and onset rates are clearly possible.

The entry to the reverse 1/2 Cuban 8 is slightly different to other similar manoeuvres, because in order to sustain smoothly flowing flight through to the end of the 1/2 Cuban in manoeuvre 7 the entry to 6 is made at a higher airspeed along with a positive pull-up.

Manoeuvre 2 is less likely to be a problem than 5 or 6 if the pilot was flying the sequence only once, as he or she would be fresh and anticipating the task. The combination of manoeuvres following each other in quick succession is considered to aggravate G-LOC potential, due to fatigue and the need to focus attention continuously on performing the manoeuvres accurately.

Conclusions

The research undertaken by BASI was on a relatively small scale due to limitations on the available resources. It would require a more comprehensive experimental design, duplication of measuring and recording devices and a much greater degree of repetition across a representative sample of pilots before fully validated conclusions could be drawn.

Nevertheless the project successfully explored in a broad-brush fashion the order of magnitude of Gz changes and their durations during aerobatics in a light aircraft. It provided information useful to the particular investigation and to the aviation community in general.

There can be little doubt that instantaneous G-LOC is a real possibility in such aircraft. International studies have revealed that the phenomenon is a possibility in medically normal individuals at levels as low as +2 to +3Gz. In recent surveys in the RAF, USN and RAAF numerous occurrences of G-LOC have been disclosed involving low performance aircraft similar to the Decathlon.

These latter surveys have shown that approximately 20% of military pilots have either suffered loss of consciousness themselves, knew someone who had, or had seen someone lose consciousness. The possibility that civilian pilots may have generally lower G-LOC thresholds than military pilots cannot be ignored, not only because of possibly different fitness levels but because of a number of other factors including a lower frequency of exposure to Gz amongst civilian pilots. The effect, if any, of ageing on tolerance is largely unknown.

The reality of the fact that instantaneous loss of consciousness may occur without any prior warning is a matter viewed by many civilian pilots with an air of disbelief. These pilots assert that the subject is really only greying-out or blacking-out.

In Australia there seems to be a relatively low level of awareness of the possibility of instantaneous G-LOC. When BASI informally contacted some flying organisations specialising in aerobatics, and flying schools as well, only one instructor was found who had heard of G-LOC, although he could not explain the phenomenon.

Unfortunately little research or data collection has been undertaken concerning the effects on the body of negative Gz rapidly followed by positive Gz, although negative Gz sustained for more than a few seconds will initiate slowing of the heart rate which will markedly reduce tolerance to following positive Gz.

Recommendation

As a consequence of the investigation, BASI recommended to the Flight Standards Division of the Department of Transport and Communications that a general safety education programme on G-LOC be undertaken, targeted at all civilian pilots.

MANOEUVRE	1st Group Of Sequences						2nd Group Of Sequences		
	COLUMN A Mean Results			COLUMN B Greatest Single Gz Change Recorded for Each Manoeuvre			COLUMN C Greatest Single Gz Change Recorded for Each Manoeuvre		
	Gz Change	Time Taken (secs)	Onset Rate (Gz/sec)	Gz Change	Time Taken (secs)	Onset Rate (Gz/sec)	Gz Change	Time Taken (secs)	Onset Rate (Gz/sec)
1. One turn spin	1.08-> 0.25	4.0	ns	1.33-> 0.27	3.7	ns	1.46-> 0.20	5.2	ns
2. Roll-off -the-top (a) loop entry	-0.03-> 3.26	4.8	0.68	-0.33-> 3.50	5.6	0.68	-0.40-> 3.90	3.7	1.16
(b) roll	3.26->-0.78	7.3	ns	3.20->-1.00	7.5	ns	3.87->-0.60	5.9	ns
3. 270 deg turn 60 deg bank	1.00-> 1.92	11.4	ns	1.00-> 2.10	11.4	ns	1.00-> 2.00	12.0	ns
4. 90 deg turn 60 deg bank	0.80-> 1.65	2.7	ns	0.80-> 1.74	2.4	ns	0.80-> 2.30	2.3	0.65
5. Loop (a) loop entry	0.06-> 3.05	6.3	0.47	-0.33-> 3.00	5.9	0.56	0.10-> 3.67	4.3	0.83
(b) top to pull-out	0.28-> 3.00	5.3	0.51	0.33-> 3.20	4.2	0.68	0.61-> 3.40	4.3	0.65
6. Reverse 1/2 Cuban (a) entry	-0.93-> 3.20	8.2	0.50	-1.00-> 3.45	9.3	0.48	-1.80-> 3.73	6.4	0.86
(b) peak of pull-up to end of inverted flight	3.18->-0.73	9.5	ns	3.47->-0.87	11.0	ns	3.73->-0.87	8.6	ns
(c) pull-through from inverted flight	-0.72-> 2.40	3.2	0.97	-0.27-> 3.47	3.5	1.07	-0.60-> 1.60	1.8	1.22
7. 1/2 Cuban (a) peak of pull-up to inverted	2.51->-0.44	3.8	ns	2.87->-0.50	3.1	ns	2.90->-0.47	2.5	ns
(b) pull-through to roll upright	-0.41-> 1.53	3.1	0.63	-0.50-> 1.73	3.5	0.64	-0.47-> 1.80	1.9	1.19
(c) pull-up	0.35-> 3.10	2.5	1.10	0.27-> 3.27	3.0	1.00	0.06-> 3.80	2.7	1.38
8. Aileron roll +	0.00-> 0.00	8.0	ns	0.00-> 0.00	8.0	ns	0.00-> 0.00	8.0	ns
9. Stall turn (a) entry	0.13-> 2.82	4.1	0.66	0.00-> 2.80	4.4	0.64	0.00-> 3.60	3.2	1.12
(b) top to pull-up	2.82-> 1.11	1.2	ns	2.80-> 1.00	1.6	ns	3.60-> 1.50	0.5	ns
10. Barrel roll (a) entry	0.57-> 2.96	4.8	0.50	0.20-> 2.94	5.8	0.47	0.06-> 3.00	4.6	0.64
(b) exit	2.75-> 0.73	2.3	ns	2.94-> 0.27	2.7	ns	3.00-> 1.30	2.7	ns

ns = not significant

Data recorded 13 July 1987.

TABLE 1

Acceleration data recorded in a Bellanca 8KCAB Decathlon aircraft by the Bureau of Air Safety Investigation, Australia.

NOTES. The Columns record those segments of each manoeuvre characterised by significant Gz changes, and the time taken for those changes to occur. There are no reversals in the direction of Gz between the values separated by the arrows. For example, in Column A manoeuvre 5(a) the Gz changed from 0.06 to 3.05 in 6.3 seconds, and at no time during that change did the Gz decrease. There are also no plateaux in the Gz changes recorded, while the transitions from one level to the next were smooth and continuous.

+ Following 7(c), the Gz decayed from a peak to zero which was consistently sustained for 8 seconds. The No. 8 manoeuvre did not have G-LOC significance and is recorded in this fashion simply to show the period for which zero Gz was sustained.

Gz ONSET RATE AND Gz TOLERANCE

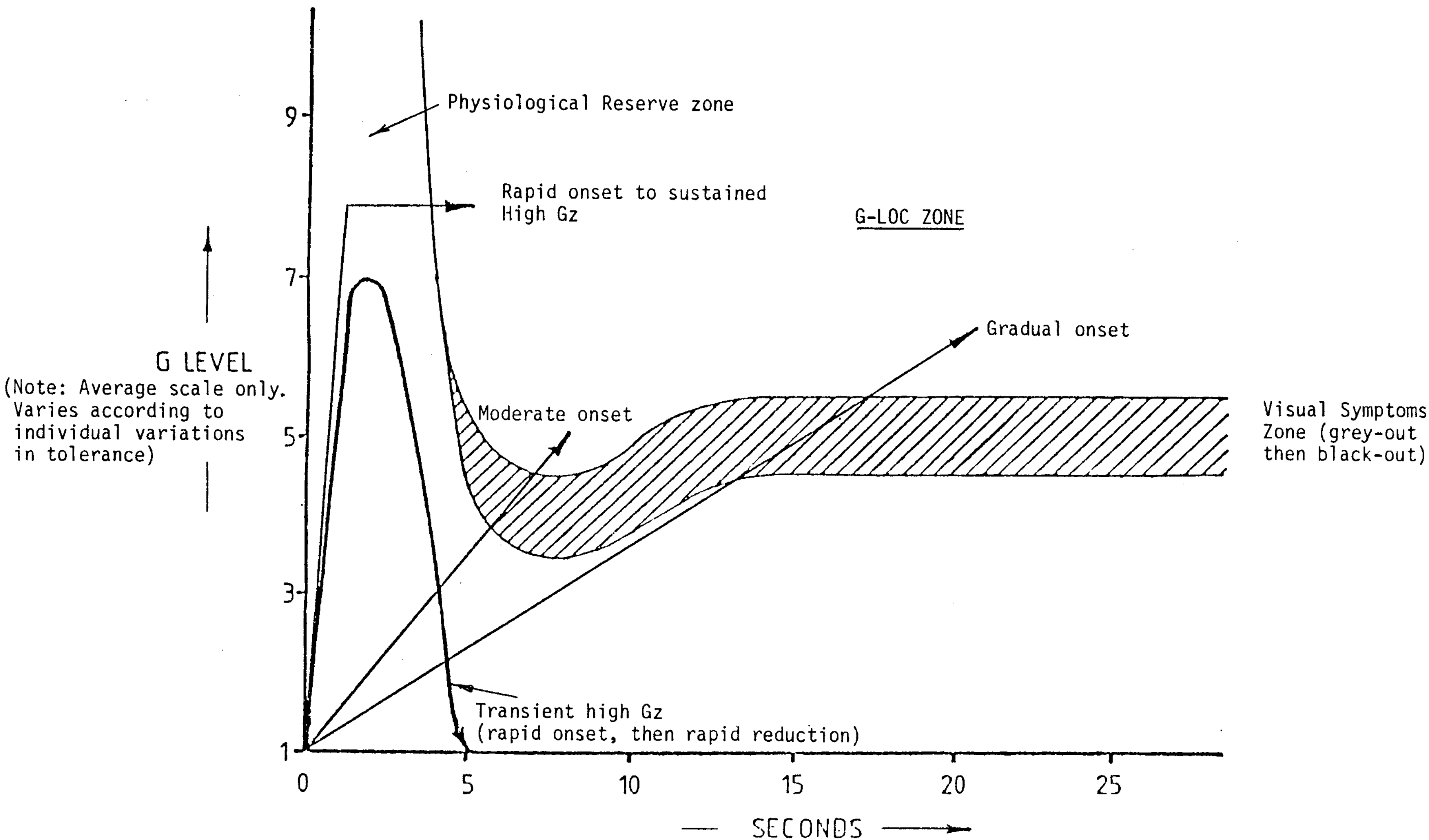

FIGURE 1