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Almost Loss of Consciousness: a Factor in Spatial Disorientation?

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Summary

During high-performance flight, aircrew exposed to +Gz-stress may exhibit symptoms ranging from light loss (LL) to +Gz-induced Loss Of Consciousness (GLOC). If the stress is insufficient to cause GLOC, a syndrome called Almost Loss Of Consciousness (ALOC) can occur, which features deficits in motor and cognitive function. It is possible that these types of deficits may influence the nature or extent of spatial disorientation symptoms. In order to produce a definitive description of ALOC symptoms, nine subjects (one female) (Ss) were exposed to a series of repeated short +6, +8, and +10 Gz pulses at the NAVAIR Warminster centrifuge facility, which were lengthened in 0.25s increments until they experienced GLOC. Of a total of 161 +Gz pulses, 66 episodes of ALOC were identified. A math task before and during each pulse was used to determine short-term memory loss. Ss were required to press and hold a button spanning the time from initial LL symptoms to full recovery of vision. ECG and near infrared spectroscopy (NIRS) of relative cerebral tissue oxygenation (rSO2) were also recorded. Data analysis included a description of physical, cognitive, and emotional signs and the timing of their occurrence and resolution, and the timing of the LL from its onset to full recovery. The primary manifestation of ALOC symptoms was a disconnection between the desire to do something and the actual ability to act upon it. This could linger well beyond the end of the +Gz exposure. Physical symptoms included tingling, twitching, uncontrollable hand movements, hearing loss and transient paralysis. Cognitive deficits included confusion, amnesia, delayed recovery, a "vacant feeling" and difficulty in forming words. Surprise, concern and pleasant feelings were some of the emotional signs. There was a significant increase in the reduction in rSO2, greater overshoot in rSO2 (increase in oxygenation above baseline after the +Gz exposure), faster fall in rSO2 during +Gz-stress and prolonged recovery time associated with ALOC as compared to +Gz exposures without symptoms. Evaluation and comprehension of the range of events associated with these altered states of awareness can provide new insights into the relationship between the effects of +Gz-induced changes in the cerebrovasculature and the resultant changes in behavior on understanding the causes of spatial disorientation. With a more complete picture of the responses of both the vascular and vestibular systems, as well as the resultant behavior changes to environmental stresses, a more comprehensive approach to avoiding aircraft mishaps can be developed.

Paper presented at the RTO HFM Symposium on "Spatial Disorientation in Military Vehicles: Causes, Consequences and Cures", held in La Coruña, Spain, 15-17 April 2002, and published in RTO-MP-086.

Introduction

When aircrew of high-performance aircraft are exposed to +Gz-stress, a spectrum of symptoms can occur ranging from loss of peripheral vision ("light loss" - LL) to blackout to +Gz-induced loss of consciousness (GLOC). If the stress is insufficient to cause GLOC, deficits in motor and cognitive function can occur. This syndrome has been called Almost Loss Of Consciousness (ALOC). While ALOC has been noted in centrifuge studies since the early 1980's, and a recent survey (6) reported that a significant number of aircrew experienced emotional or cognitive symptoms in flight, a definitive description of the motor and cognitive deficits associated with ALOC does not exist.

Gillingham (3) defined the term *spatial disorientation* (SD) as "the condition wherein one not only has an orientational illusion but also needs to have correct perception of orientation for controlling his position, attitude, or motion." An *orientational illusion* is a "false percept of position, altitude, or motion, relative to the plane of the earth's surface." Orientational illusions occur whenever there is a misperception of displacement, velocity, or acceleration. These illusions have been categorized in accordance to their main cause - visual misperceptions and vestibular errors.

Spatial Disorientation has been categorized into Type I: Unrecognized SD, when the pilot is oblivious to the problem (e.g., channelized attention and task saturation); Type II: Recognized SD, when the pilot knows "something is wrong," but may not know the cause of the problem (e.g., a conflict between vision and semicircular canal stimulation); and Type III: Vestibulo-Ocular Disorganization or Incapacitation, when the pilot knows there is a problem but cannot orient him/herself and control the vehicle (2,3,4,7). In various studies conducted between 1954 and 1972, the percent incidence of fatal aircraft mishaps where SD either contributed to or was deemed the causal factor ranged from 4.8% to 26%. In a 1980 USAF study, it was found to be 18.4%. Finally, it has been reported that of the 15 Navy aircraft lost to noncombatant action in Desert Storm, 7 were SD mishaps (3,4,8).

Disorientation in flight has been called a psychological problem in that "it is concerned with human experience…" and therefore should be discussed in terms of psychology (1). However, the stimuli leading to it are physiologic and the event may be misclassified into other types of altered states of awareness (and vice versa) thus, it is appropriate to refer to the problem as psychophysiologic. It appears that some of the cognitive and emotional ALOC symptoms are similar to those experienced during SD. When investigating SD, it is important to consider if these ALOC symptoms contribute to the development and/or reactions of aircrew to SD.

Methods

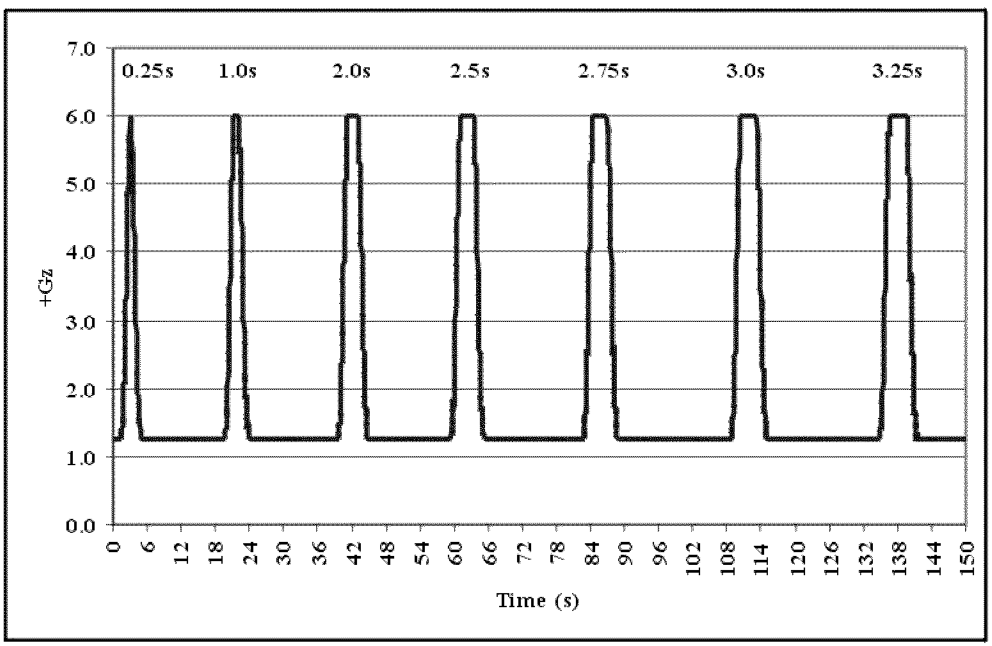
Nine (eight male) relaxed unprotected NAVAIR volunteers participated in this study. Subject characteristics are listed in Table I. All subjects indicated that they had no previous G-LOC experiences prior to this experiment. Subjects were exposed to a +6, +8, and +10 Gz pulse held for 0.25 second, then 1 second, then increasing in 1 second increments until LL reached 60° or 50% gray, at which point the increase was 0.5 second. Finally, when subjects reported total blackout, the increase was 0.25 second. There was a rest of at least one minute between each pulse. Figure 1 shows a typical pulse series. Onset time was 1.25 seconds to plateau, with an offset of 1.75 seconds to a rest plateau of +1.25 Gz. All nine subjects did not complete all six insertions. Physiologic monitoring included two channels of electrocardiography and relative cerebral tissue oxygenation was assessed using Near Infrared Spectroscopy (NIRS) probes on the forehead (5).

Subjects indicated their start of LL by pressing a button on an aircraft control stick in the centrifuge gondola. They were required to press and hold that button spanning the time from initial LL symptoms to full recovery of vision. Prior to and during each +Gz exposure until the onset of LL, subjects were asked to perform a math task (verbally reporting a running sum of a string of positive or negative numbers which were recited by the Flight Director over the communications system) that was used to evaluate if there was short-term memory loss after the +Gz exposure. This was determined after the run was completed and their vision was restored, by asking the subjects to state the last number they remembered.

Table I. The +Gz pulse length (seconds) in which ALOC symptoms were detected for each subject. A blank means that the subject had no pulse exposure at that +Gz level. Subject S3 repeated the +8 Gz pulse series (three days apart) without reaching GLOC each time. Subject S5 ended his first +6 Gz pulse series due to stomach discomfort, but completed a repetition six days later.

Subject	Gender	Age (yr.)	Height (in.)	Weight (lb.)	+6 Gz pulse length (s)	+8 Gz pulse length (s)	+10 Gz pulse length (s)
S1	M	26	70	130	2.5, 2.75	1.75, 2.0, 2.25	
S2	M	32	70	171	3.25, 3.5, 3.75, 4.0, 4.25, 4.5	2.0, 2.25, 2.75	
S3	M	38	70.5	215		1.0 (1st insert), 2.0, 2.5 2.0 (2nd insert), 2.5, 3.0	
S4	M	30	66	160	4.0, 4.5, 5.0, 5.5, 6.0	3.0, 3.25, 3.5, 3.75	2.5, 2.75
S5	M	26	69	145	4.0 (1st insert), 4.5, 4.75, 5.0 (2nd insert), 6.0, 6.5		
S6	M	25	72	175	5.0, 5.25, 5.5	1.5, 2.0, 2.25, 2.5	2.5, 2.75, 3.0
S7	M	44	67	170	4.0, 4.5, 5.0	2.5, 3.0, 3.5	
S8	M	29	70	225		3.0, 3.25	2.0
S9	F	34	64	135	5.0, 6.0, 6.5, 7.0	3.0, 3.5, 4.0	2.0, 2.5, 3.0

Figure 1. +6 Gz pulse series. The width of each succeeding pulse was dependent upon the light loss reported by the subject. Note that the rest interval between pulses has been shortened in this figure for clarity.



Every +Gz exposure was videotaped, and the video record included +Gz level, time of day, time at +Gz, heart rate (bpm), an indication of when the LL button was depressed and released, and analog traces of the +Gz and ECG signals.

Each +Gz pulse run was examined for the presence of ALOC signs and symptoms. Video records of ALOC candidate runs were digitized and individual runs (including pre-run, the +Gz pulse, offset and the entire recovery period) ported into a PC computer via a FireWire IEEE 1394 link for video/audio analysis using MGI VideoWave 4 SE software. The following parameters were collected:

1. A transcript of the conversation between the subject and Flight Deck personnel;
2. Identification of potential ALOC episodes at each +Gz pulse level and duration;
3. LL timing from its onset to full recovery, including the +Gz level at onset and the time during the post-run rest period that LL persisted;
4. A description and frequency of occurrence of motor and other physical symptoms;
5. A description and frequency of occurrence of indications of cognitive deficits, altered states of awareness, and emotional signs and symptoms;
6. Subject performance in the math task.

NIRS analysis provides an indication of the relative change in cerebral tissue oxygenation, or rSO2 (5). rSO2 is a dimensionless quantity. Due to technical difficulties, not all NIRS data sets were suitable for analysis. Six sets were available at +6 Gz, and five each for the +8 and +10 Gz series. NIRS data analyses computed the following values and timing parameters:

1. A 60 second average preceding the onset of each pulse was calculated and served as the baseline (rSO2base). Subsequent baselines were calculated for each pulse in a given series and compared to determine if rSO2 returned to the same level throughout the centrifuge insertion (ΔrSO2base).
2. The time from +Gz onset to the minimum rSO2 (Tmin) and the difference between the baseline and minimum rSO2 (rSO2min);
3. The time from minimum rSO2 to the maximum overshoot (Tmax) and the difference between the minimum and maximum rSO2 (rSO2max);
4. The total time (Ttotal) from +Gz onset until rSO2 returned to a value of zero after the run (rSO2zero);
5. The rate of change (slope) from +Gz onset to rSO2min (Δmin);
6. The rate of change (slope) from rSO2min to rSO2max (Δmax);
7. The rate of change (slope) from rSO2max to rSO2zero (Δzero);
8. The time from rSO2min to rSO2zero (Tmin2zero);
9. The time from rSO2max to rSO2zero (Tmax2zero).

Statistical analyses included general linear model analysis of variance with a Fisher's least squares difference post hoc test to determine the source of any detected differences. Subjects were treated as random variables and fixed variables included +Gz level and symptom type (GLOC, ALOC, or normal). Additional tests were run on the NIRS data in which the order of the symptom type was a factor. This used GLOC, the previous three ALOC incidents preceding the GLOC (A1 was the pulse immediately preceding GLOC, A2 preceded A1, A3 preceded A2), and next two +Gz pulses without symptoms prior to the ALOCs ("normal", N1 before A3 and N2 before N1) as fixed factors. Statistical significance was set at the alpha < 0.05 level.

Results

During the +Gz pulses (a total of 161), 66 instances were identified in which ALOC symptoms occurred. At +6 Gz, there were 29 episodes from seven subjects, at +8 Gz, there were 28 episodes from eight subjects, and nine episodes from four subjects occurred at +10 Gz. Table I lists the pulse durations at each +Gz level where ALOC was identified for each subject.

Table II contains a summary of the persistence of LL and the +Gz pulse length when ALOC or GLOC occurred. Total LL includes the time during and after the +Gz exposure in which the LL button was depressed. LL often continued after the centrifuge returned to the rest plateau. There was no statistical difference in the total LL time or the persistence of LL into the rest period as the +Gz level increased.

Table II. Duration (mean ± standard deviation) and range of reported light loss (seconds) and +Gz pulse duration (seconds) during 66 ALOC and 20 GLOC episodes.

	+Gz level	Duration	Range
Total Light Loss Period	6	8.9 ± 3.5	3.1 to 14.9
	8	7.9 ± 4.8	1.2 to 20.4
	10	11.0 ± 4.4	4.9 to 16.6
Persistence of Light Loss after completion of the +Gz pulse (i.e. during rest plateau)	6	4.7 ± 3.5	0.0 to 11.3
	8	5.2 ± 4.2	0.5 to 15.9
	10	8.1 ± 5.0	0.7 to 14.1
Length of +Gz pulse during ALOC	6	4.8 ± 1.1	2.5 to 7.0
	8	2.5 ± 0.7	1.0 to 4.0
	10	2.6 ± 0.4	2.0 to 3.0
Length of +Gz pulse during GLOC	6	5.7 ± 1.6	2.75 to 7.5
	8	3.3 ± 0.6	2.5 to 4.25
	10	2.9 ± 0.4	2.5 to 3.25

The mean length of a +Gz pulse associated with ALOC was significantly longer during +6 Gz than +8 or +10 Gz, based on a one factor ANOVA ($F = 48.0$, $p < 0.001$). Results of an ANOVA comparing the pulse length during ALOC and GLOC episodes indicated that the pulse length associated with GLOC was significantly longer at +8 Gz ($F = 6.5$, $p < 0.015$), but not at +6 Gz ($p = 0.078$) or +10 Gz ($p = 0.124$).

The most consistently reoccurring physical, cognitive, and emotional symptoms are summarized in Table III, along with the number of incidents, the number of subjects reporting those experiences, and the number of subjects who experienced those symptoms during more than one pulse exposure.

Table III. Summary of the most prevalent physical, cognitive and emotional responses during ALOC, including the total number of episodes, number of subjects demonstrating symptoms, and number of subjects expressing these symptoms more than once.

Category	Symptom	No. Episodes	No. Subjects	Repetitions
Physical	Tingling in the hands, arms, and face	40	7	6
	Dazed or blank facial expression	27	8	6
	Twitching in arms and hands	20	8	5
	Eye movements	18	5	3
	Whole body shaking	16	4	2
	Facial relaxation	10	5	2
	Overall loss of control	10	5	3
	Hearing loss	8	4	2
	Transient paralysis	6	4	2
Cognitive deficits	Confusion	34	9	9
	Amnesia	22	7	6
	Delayed recovery	18	7	5
	Difficulty in forming words	8	3	2
	Disorientation	7	6	1
Emotional	Pleasant feeling	13	7	4
	Concern	7	6	1
	Surprise	5	3	2
	Unpleasant feeling	4	2	2

Listed in Table III there are various signs and symptoms associated with delayed cognitive ability. These include an inability to remember or a delay in regaining full faculties after the end of the +Gz exposure. The general category "amnesia" included the inability to recall: (a) the offset of the +Gz pulse; (b) when the subjects released the LL button; (c) what to do; and (d) events during the pulse. Subjects either reported being generally confused or they stated specific symptoms related to confusion, such as: (a) "I don't know how I got here / where I am?"; (b) "I know where I am but not why I'm here"; (c) "I don't know what's happening"; (d) "I don't know why I'm twitching"; (e) "I don't know why the GLOC beeper is on"; and (f) "I don't know what to do". Loss of memory occurred during 37% of all ALOC episodes.

The most common emotional signs and symptoms described by the subjects included pleasant, unpleasant, concerning and surprising feelings. Under the category of "pleasant" feelings, subjects described their sensations as energized, enthralled, giddy, or pleasurable. When subjects reported being concerned, it was related to their inability to move or speak or when they expressed apprehension that they were getting close to GLOC. Reactions described as surprise were related to either not experiencing GLOC when they thought that they had, or to hearing the GLOC beeper when they thought they did not GLOC.

Table IV lists symptoms under the category of "altered states of awareness (ASA)." This includes the subjects' perceptions of unusual sensations and whether or not they felt that they had experienced ALOC or GLOC. ASA includes a vacant feeling (19% of all ALOCs), aptly described by subjects as a "numbness of the brain" and a "frozen moment in time." Subjects indicated that they experienced a sort of a void in that they knew where they were but could do nothing, physically or mentally, during that period. Another sign was a floating sensation (Table III) and/or a feeling of being suspended in the ejection seat (32% of all ALOCs). While these symptoms only appeared in four subjects, they were very consistent in three of them and occurred at more than one +Gz level. Table IV also includes some subjects' perceptions of whether or not they experienced ALOC or GLOC.

Table IV. Symptoms of "altered states of awareness" during ALOC episodes at given +Gz levels, including the total number of incidents, the number of subjects experiencing a given symptom, and the number of subjects experiencing the symptom multiple times.

Symptom	No. Episodes	No. Subjects	Repetitions
Thought that they experienced ALOC	9	3	2
Thought that they experienced GLOC	5	3	1
Not sure if they experienced GLOC	5	4	1
Knew that they had not experienced GLOC	5	2	2
Floating Sensation	15	4	3
Fuzzy Headed	5	3	1
Light Feeling or Suspended Sensation	5	3	2
Lightheaded	3	3	0
Mumbles or Speaks During LL	5	3	1
Vacant Feeling ("Numbness of the Brain" or a "Frozen Moment in Time")	12	5	3

Tables V-VII summarize the events and responses relative to the math task. There were 35 correct and 31 incorrect responses during the math task. For the latter, the last number recalled was often prior to the pulse, and seven subjects recalled a number that was not in the sequence (during eight pulses). Table V summarizes the mean pulse length in which subjects correctly and incorrectly recalled the last number in the math task at each +Gz level. While the incorrect responses tended to occur at longer +Gz pulse lengths, this was not always the case. For example, during his series of +6 Gz pulses, subject S4 had incorrect responses at 4.5 and 5 seconds and correct responses at 5.5 and 6 seconds. The difference in the pulse length between correct and incorrect responses was not statistically significant.

Table VI lists the point and mean time during the +Gz pulse when subjects spoke the last number in the sequence. Subjects said the last number during the first 2.0 ± 1.2 seconds of the plateau portion during 26 of 29 ALOC episodes at +6 Gz (three during G onset). Of these, 14 were said 1.3 ± 0.8 seconds before the onset of LL and 12 were stated 1.1 ± 0.7 seconds after LL onset. During the +8 Gz pulses, the last number was said twelve times during the first 0.6 ± 1.1 seconds at plateau, eleven times during 0.9 ± 0.5 seconds during G onset, and five times 0.7 ± 0.4 seconds before the pulse began. During the +10 Gz pulses, the last number was said five times during the first 0.9 ± 1.0 seconds at plateau, two times during G onset, once before the pulse began, and once during G offset.

Table V. +Gz pulse length (mean ± standard deviation in seconds) corresponding to correct and incorrect recall of the last number during the math task. A number without a standard deviation means that there was only one response at that pulse level. A '-' indicates that there was no corresponding response at that +Gz level. A blank means that the subject had no pulse exposure at that +Gz level.

Subject	+6 Gz		+8 Gz		+10 Gz	
	Correct	Incorrect	Correct	Incorrect	Correct	Incorrect
S1	2.50	2.75	1.75	2.13 ± 0.18		
S2	3.67 ± 0.38	4.08 ± 0.52	2.38 ± 0.53	2.50		
S3			1.88 ± 0.63	2.75 ± 0.35		
S4	5.17 ± 1.04	4.75 ± 0.35	3.50 ± 0.35	3.25 ± 0.35	2.38 ± 0.53	-
S5	4.00	5.35 ± 0.86				
S6	5.13 ± 0.18	5.50	2.00 ± 0.50	2.25	2.50	2.88 ± 0.18
S7	4.50 ± 0.71	4.50	-	3.00 ± 0.50		
S8			2.50 ± 0.50	3.25	2.00	-
S9	6.17 ± 1.04	6.00	3.25 ± 0.35	4.00	2.00	2.75 ± 0.35
Group Mean	4.45 ± 1.19	4.70 ± 1.08	2.46 ± 0.68	2.89 ± 0.62	2.22 ± 0.26	2.81 ± 0.09

Table VI. The point during the +Gz exposure when the last number was stated.

Symptom	Total No. Subjects	Total No. Incidents	Incidents at +6 Gz	Incidents at +8 Gz	Incidents at +10 Gz
Said last number before the pulse began	5	5	-	4	1
Said last number during the G onset	7	16	3	11	2
Said last number during the +Gz plateau	9	43	26	12	5
Said last number during the G offset	1	2	-	1	1

The inability to recall the last number spoken may be an indication of short-term amnesia. In about half of the ALOC cases, even though subjects continued to respond during the +Gz exposure, they forgot what they said after the run was completed – either only remembering a number prior to G-onset (sometimes several numbers in the sequence before the last number), stating a number not in the sequence, or remembering only one of two digits of the number. Table VII lists the point during the +Gz exposure when the incorrectly recalled last number occurred. It is interesting to note that in 14 of 20 cases, the number that the subjects thought was the last number said **during** the +Gz pulse was actually said **before** the pulse began. For the eight instances in which the number they recalled was not in the sequence, six responses were off by one digit. In five of six cases, it appeared that the number in the sequence that the subjects recalled was not one that they said, but was the number (or part thereof) voiced by the Flight Director. For example, the sequence might have contained 12 **+ 7** = 19, and the subject said that the last number was 1**7**.

When subjects recalled an incorrect number after a +6 Gz pulse, the last number the subjects stated occurred 1.5 ± 0.2 seconds before LL began (by two subjects during five pulses) and 1.2 ± 0.7 seconds after LL onset by five subjects (during nine pulses). If the last number was correctly recalled, it typically was said before the onset of LL, according to the results of a Kruskal-Wallis Multiple-Comparison z Test ($z=2.67$, $p=0.002$).

When subjects incorrectly recalled the last number in the math task, there were other indications of amnesia or delayed cognitive ability. For the +6 Gz pulses, incorrect responses coincided with forgetting the G offset (3 of 4 cases), inability to remember events during the pulse (2 of 3 cases), and not remembering when they released the LL button (2 of 2 cases). Six of ten symptoms relating to confusion coincided with incorrect recall and in three of four cases, subjects held onto the LL button too long. Also, there was a statistically significant relationship between incorrect recall and when the last number was said after the onset of LL. After the +8 Gz pulses, eight of thirteen indications of amnesia and 13 of 16 signs of confusion were noted along with incorrect recall. Five of the nine reports of slow recovery also corresponded to incorrect recall.

An example of the rSO2 response to a +6 Gz pulse is shown in Figure 2. ALOC symptoms occurred during this run. The rSO2 overshoot after the completion of the +Gz exposure was typical. Table VIII lists a summary of the mean NIRS timing parameters and also includes light loss and the timing of the last number spoken during the math task for comparison. The table indicates that rSO2min occurred after the end of the +Gz plateau, either during the +Gz offset or after the run was completed. The overshoot (rSO2max) occurred after the run is finished and complete vision had been restored. Vision is restored before rSO2max, particularly during the ALOC runs. Table IX contains the mean slope, rSO2min and rSO2max values.

Table VII. The point and frequency during the +Gz exposure when the incorrectly recalled number occurred and the number of responses that were not in the number sequence at all. Of the eight incidents listed in which the number recalled was not in the sequence, six were off by one digit (indicated in **bold** font).

Point at which incorrect number was recalled	Total No. Subjects	Total No. Incidents	Incidents at +6 Gz	Incidents at +8 Gz	Incidents at +10 Gz
Before the pulse began	8	14	3	8	3
During G onset	3	3	1	1	1
During the plateau	3	3	3	-	-
Number recalled not in sequence	7	8	4 (**3**)	4 (**3**)	-
Number not in sequence off by one digit	6	6	3	3	-

There were no differences between the rSO2 baseline computed before and after the various pulses. rSO2min was significantly smaller during +6 Gz pulses than +8 or +10 Gz pulses ($F = 6.6$, $p = 0.002$) and smaller during normal as compared to ALOC or GLOC runs ($F = 20.7$, $p < 0.001$). Tmin was significantly longer during +6 Gz pulses than +8 or +10 Gz pulses ($F = 6.8$, $p < 0.002$) and shorter during normal as compared to ALOC or GLOC runs ($F = 34.4$, $p < 0.001$). rSO2max was significantly smaller during +6 Gz pulses than +8 Gz pulses ($F = 4.6$, $p = 0.013$) and varied between the three symptom types, with normal the smallest, followed by ALOC, with GLOC with the largest ($F = 36.8$, $p < 0.001$). Tmax was shorter during +8 Gz compared to +6 and +10 Gz pulses ($F = 5.6$, $p < 0.005$). Ttotal was shorter during normal as compared to ALOC or GLOC runs ($F = 7.8$, $p < 0.001$). It took less time to reach rSO2min (Δmin) at +8 and +10 Gz than during +6 Gz pulses ($F = 15.0$, $p < 0.001$). The rate of change between rSO2min and rSO2max varied between the three symptom types, with normal the most gradual, followed by ALOC, with GLOC with the fastest Δmax ($F = 6.5$, $p = 0.002$). Tmin2zero was less during normal compared to ALOC runs ($F = 4.9$, $p < 0.010$) and Tmax2zero was less during normal compared to both ALOC and GLOC runs ($F = 6.9$, $p < 0.002$).

Table VIII. Mean NIRS timing parameters (seconds) relative to the +Gz onset. The mean length of the +Gz pulse, the time the subjects said the last number, the time from +Gz onset when light loss (LL) began and ended are also shown. EOP: time from +Gz onset to the end of the plateau; EOR time from +Gz onset to the End Of the Run.

Symptom	EOP	EOR	Last No.	LL onset	LL ends	Tmin	Tmax	Ttotal	Tmin2zero	Tmax2zero
+6 Gz pulse										
N2	4.35	6.10	1.89	3.56	9.14	5.66	20.42	38.74	33.07	18.32
N1	5.17	6.92	2.76	3.85	10.36	6.47	21.69	41.65	35.18	19.96
A3	6.00	7.75	3.58	3.85	13.20	7.16	19.60	40.72	33.55	21.12
A2	6.50	8.25	3.85	4.08	12.88	7.01	23.12	46.85	39.84	23.73
A1	6.88	8.63	4.25	3.62	13.86	7.42	19.95	47.47	40.04	27.52
GLOC	7.40	9.15	3.86	3.08	19.69	8.13	21.46	54.75	46.62	33.29
+8 Gz pulse										
N2	2.50	4.25	-0.19	2.87	4.95	4.93	27.10	41.05	36.11	13.94
N1	3.25	5.00	0.73	3.63	9.35	6.02	19.88	46.16	40.14	26.27
A3	3.85	5.60	1.25	3.03	11.68	5.94	25.55	52.04	46.09	26.49
A2	4.25	6.00	2.04	3.00	11.24	6.40	23.41	46.21	39.81	22.79
A1	4.60	6.35	1.30	3.05	11.49	6.64	20.38	48.13	41.49	27.74
GLOC	4.80	6.55	1.48	3.52	15.66	7.14	17.55	42.25	35.11	24.70
+10 Gz pulse										
N2	2.50	4.25	1.51	4.07	7.17	4.99	23.93	39.76	34.77	15.83
N1	3.10	4.85	1.15	3.59	8.92	4.51	22.06	52.70	48.19	30.64
A2	4.08	5.83	1.23	3.11	14.53	5.95	24.61	55.76	49.81	31.15
A1	4.19	5.94	1.79	2.64	14.01	5.96	21.31	51.02	45.06	29.72
GLOC	4.40	6.15	2.20	3.43	16.32	5.03	24.14	46.90	41.87	22.76

Figure 2. Example of NIRS response to 3.25 s +6 Gz pulse. rSO2min occurs at 6.8s, rSO2max at 14.8s, and rSO2zero at 35.2 s.

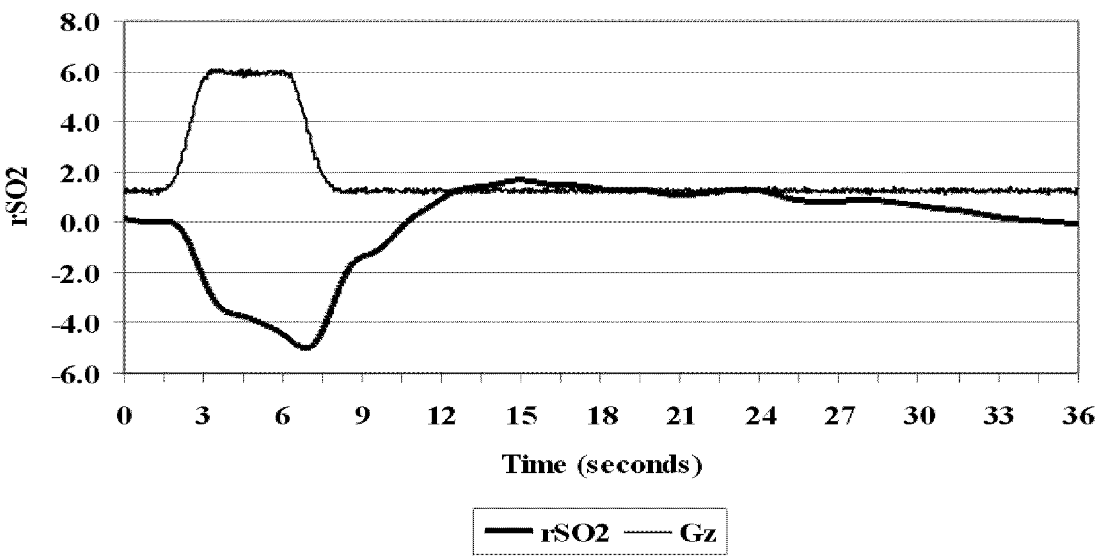


Table IX. Mean NIRS rSO2 values and slopes (change in rSO2 over time in seconds). The mean length of the +Gz pulse (seconds) is also shown. EOP: time from +Gz onset to the end of the plateau; EOR time from +Gz onset to the End Of the Run.

Symptom	EOP	EOR	rSO2min	rSO2max	ΔrSO2base	Δmin	Δmax	Δzero
+6 Gz pulse								
N2	4.35	6.10	-4.42	6.43	0.08	-0.80	0.68	-0.15
N1	5.17	6.92	-4.81	6.89	-0.04	-0.76	0.72	-0.13
A3	6.00	7.75	-4.89	6.99	0.10	-0.67	0.79	-0.11
A2	6.50	8.25	-4.37	6.76	-0.06	-0.61	0.64	-0.15
A1	6.88	8.63	-4.36	6.73	0.13	-0.59	0.71	-0.09
GLOC	7.40	9.15	-5.01	8.16	0.09	-0.57	0.67	-0.10
+8 Gz pulse								
N2	2.50	4.25	-5.17	6.99	0.12	-1.05	0.53	-0.20
N1	3.25	5.00	-5.08	7.12	0.09	-0.89	0.67	-0.12
A3	3.85	5.60	-5.84	7.73	-0.07	-0.98	0.52	-0.11
A2	4.25	6.00	-6.13	8.17	0.11	-0.99	0.70	-0.13
A1	4.60	6.35	-6.52	9.08	-0.10	-1.03	0.72	-0.15
GLOC	4.80	6.55	-6.92	9.73	0.09	-0.98	1.14	-0.14
+10 Gz pulse								
N2	2.50	4.25	-4.80	6.31	0.06	-1.17	0.47	-0.11
N1	3.10	4.85	-4.17	6.10	-0.09	-0.85	0.41	-0.06
A2	4.08	5.83	-6.01	7.91	0.11	-0.99	0.50	-0.07
A1	4.19	5.94	-5.16	8.39	0.04	-0.83	0.60	-0.11
GLOC	4.40	6.15	-5.45	8.65	0.07	-1.01	0.63	-0.16

In the results of the statistical analyses runs to determine the effects of order, there was an effect for Tmin. While N2 was significantly shorter than each of the ALOCs and GLOC, N1 was only less than A1 and GLOC ($F = 5.2$, $p < 0.001$). For Ttotal, while N2 was shorter than the other pulses, there were no differences between N1, the ALOCs or GLOC ($F = 2.7$, $p = 0.027$). As seen in the other ANOVA, rSO2min was less during N1 and N2 compared to GLOC, though not the ALOCs ($F = 2.5$, $p = 0.037$). For rSO2max, N2 was less than GLOC, A1 and A2, N1 was only less than GLOC and A1, and A3 was less than GLOC ($F = 8.3$, $p < 0.001$).

Discussion

Detecting the occurrence of ALOC by an external observer is difficult (Table III). There are a few physical manifestations that occurred in most of the subject pool. A dazed or blank expression and a relaxation of the facial muscles is a visual indication of ALOC (occurring in 59% of all ALOCs). Involuntary movements may be seen in the arms and hands (21% of all ALOCs). This myoclonus often continued after the centrifuge returned to the rest plateau. For example, the sensation of muscle twitching in the hand persisted as long as three minutes in S3. The use of the light loss button was a useful tool in this respect in that when subjects repeatedly pressed the button, in several cases it appeared to indicate a lack of voluntary control of their hands. Also, two subjects consistently noted that their whole bodies were shaking.

In order to detect the other physical symptoms listed in Table III, tingling in the hands and arms (33% of ALOCs), tingling in the head and lips (30% of all ALOCs), a sensation that subjects momentarily lost control (16% of all ALOCs), hearing loss (13% of all ALOCs), and transient paralysis (10% of all ALOCs), subjects would have to be specifically asked. As for the latter symptom, subjects indicated that while they wanted to move their arms, for example to turn off the GLOC beeper, it took a while before they could do so.

One clear cognitive symptom of ALOC was a delay in the subjects' ability to regain full function after the ALOC episode. Seven of nine of the subjects indicated that during at least one ALOC episode (14% of all ALOCs), they continued to depress the LL button even though they realized that their vision recovered. A majority of the subjects indicated that it took a long time to fully recover or it "took a while to realize what to do."

A dramatic cognitive deficit was the inability of some subjects to speak after the run was completed. They knew what they wanted to say but they could not form the words. This indicated the presence of a disconnection between cognition and ability to act upon it. Typically, the Flight Director did not talk to the subjects after the run until they released the LL button. When subjects were obviously having difficulty speaking (14% of all ALOCs), it persisted a few seconds after full vision returned. While this symptom occurred in a minority of the subjects, it is a clear indication of the operational significance of ALOC – nothing could be more hazardous than a situation in which a pilot cannot physically act on what his mind is directing him to do.

Subjects frequently expressed confusion during ALOC episodes. It was not unusual for subjects to express confusion at more than one pulse length for a given +Gz level and at more than one +Gz level. 25% of all ALOC events were associated with a generalized state of confusion. They often could not clearly articulate why they were confused or when they could, they indicated that they did not have a clear grasp of what was happening or why something was happening.

The NIRS results provide an indication of the relation between the behavioral symptoms and the underlying changes in cerebrovasculature. The greatest drop in head level oxygenation typically occurs during the +Gz offset or continues into the rest period. Symptoms continued to persist well into the period of oxygen recovery (the rSO2max) during the rest plateau, including light loss, confusion, tingling and involuntary movements. An important finding with implications for the SD community is the significant increase in the reduction in rSO2 (rSO2min), greater overshoot (rSO2max), faster change in rSO2 during +Gz-stress (Tmin2zero) and prolonged recovery time associated with altered states (ALOC) as compared to +Gz exposures without symptoms.

These findings clearly have safety of flight implications and stress the need for training aircrew about ALOC. If after exposure to +Gz stress, aircrew require extra time to regain complete awareness and if they do not recognize that they are experiencing ALOC symptoms, the risk to life and aircraft grows.

Overall, there were fewer emotional than physical or cognitive symptoms reported. Subjects expressed more positive than negative emotions. This may be due to the fact that they were in the centrifuge (as opposed to in-flight). Several subjects commented that they knew they were safe because they knew that they were being closely monitored. While some subjects did express a mounting anxiety during succeeding pulse runs as they anticipated reaching GLOC, it is difficult, if not impossible, to completely emulate the complete experience of flight, *e.g.* mounting adrenaline levels associated with operating in a dangerous environment. It is interesting to speculate whether there would be fewer positive responses during actual flight conditions. Pilots have reported a feeling of euphoria/happiness/relaxation immediately upon regaining consciousness in-flight. Thus it may be difficult to assess this type of question in that emotions and behavior may change once the victim of altered states of awareness (GLOC, ALOC, SD, etc) realizes their true situation.

Many of the symptoms observed in this experiment were also reported in a USN and USAF survey of 70 pilots (6). The authors noted the occurrence of sensory and motor abnormalities, amnesia, confusion, euphoria, and reduced auditory response. This lends credence to the assumption that this is not simply a centrifuge related phenomenon. However, one may speculate that the heightened levels of hormonal flow during aerial maneuvers associated with increased attention or perception of danger (fight or flight), it is possible that recognition and recovery from ALOC symptoms may be different in-flight than was documented in the centrifuge.

Spatial Disorientation is classified as pilot error. Accident investigation boards that identify mishap causes necessarily derive them from a chain of events. The finding of "pilot error" may then be an attractive solution whenever the data available does not identify equipment, engine, or other component failure as the cause of the accident. Moreover, the pilot is not around to "explain him/herself." Certain accidents and incidents may be due to altered states of awareness such as frank GLOC or ALOC but are misclassified as SD and other errors for lack of relevant data. It is important to recognize this problem. For example, GLOC is a syndrome replete with sequelae that may either be confused with or facilitate SD. The problem becomes more difficult when addressing ALOC in that it defies a solid definition or a distinguishable sequence of events. Ercoline et al (2) discuss the various terms that have been assigned to Spatial Disorientation since the 1930's including Pilot Vertigo, Loss of Situational Awareness (LSA), Mid Air Collision, and Controlled Flight into Terrain (CFIT). For example, pilots experiencing SD also suffer from LSA and CFIT could be a result of any of the three types of SD. Indeed, these events, CFIT, ALOC, SD, GLOC, LSA are all altered states of awareness.

Consider the following hypothetical scenario describing a class A mishap during a fly-by: The pilot comes in low and fast at 200 feet, he then rolls hard into a +5 Gz turn until the last few degrees when the nose starts to slice down into the ground. Should we define the cause of the accident to be SD? At which point in the sequence of events did SD occur? There is a path of information flow that "involves the processing of largely numerical data from flight instruments into derived orientation information by higher cerebral centers" (3). Could the pilot have been momentarily confused due to his exposure to +Gz and subsequently unable to integrate information and make appropriate decisions? Would the pilot, if he had survived, have remembered and/or recognized the event as SD? What if the pilot experienced ALOC, would he report it as such or as SD? These would be difficult questions for a surviving pilot to answer. Some stories reported by pilots as SD events follow: "On my FIRST solo away from the field, severe VFR/CAVU, I practiced steep turns and got a 'dizzy' feeling, I tried to recover from the turn, but instantly felt a marked increase in G-forces. I immediately realized I was messed up, and *put my head in the cockpit, and recovered on instruments*.... no further problems..." "Learning aerobatics over the ocean. Instructor took over after I got confused trying to do a cloverleaf." "... I was lucky, and it made me a much better, *conscious instrument pilot*." (9)

Conclusions

ALOC is an insidious problem that affects cognitive, motor and emotional responses of aircrew. The gaps in memory, delayed recovery time, and reduced control over voluntary muscles all increase in-flight danger. The difference in the duration of +Gz stress necessary to induce GLOC as compared to ALOC was only shown to be significant for the +8 Gz pulses. Most importantly, the effects linger well beyond the end of the +Gz plateau, into the subsequent rest period. Recovery of cerebral oxygen levels from rSO2min took an average of 33 to 50 seconds. In some individual cases, recovery to within 10% of baseline rSO2 did not occur before the next run was initiated. Recognition of these symptoms by pilots may decrease the potential for LSA or SD, thereby reducing the number of mishaps attributed to "pilot error."

Unfortunately, the finding of SD as the cause of a fatal mishap cannot always be based on actual data, i.e. the testimony of the mishap pilot. It seems prejudiced to assign pilot error as the cause of a mishap when at best there may only be voice recorder data. More research is required by the Crew Systems community to understand this complex syndrome to better define protection system control specifications and training methods.

It is therefore proposed that consideration of the types and kinetics of these symptoms, as well as the responses of the vestibular system, is important towards understanding the overall phenomenon of spatial disorientation.

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