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Enhanced Recovery of Aircrew from G Acceleration Induced Loss of Consciousness (G-LOC): A Centrifuge Study

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NOTICES

TECHNICAL REVIEW AND APPROVAL

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The voluntary informed consent of the subjects used in this research was obtained as required by Air Force Instruction 40-402.

This report has been reviewed by the Office of Public Affairs (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

FOR THE DIRECTOR

//Signed//

MARK M. HOFFMAN
Deputy Chief, Biosciences and Protection Division
Air Force Research Laboratory

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14. ABSTRACT
G-LOC is one of the main physiological threats to aircrew of high-performance aircraft. The primary focus on this study was to measure recovery latency periods for both the absolute and relative incapacitation period following a G-LOC event and what effect the G-LOC event may have on pre- and post-G-LOC performance of fine motor control and cognitive function tasks (simulated flying tasks). G-LOC events were produced using the Dynamic Environment Simulator (DES) centrifuge at Wright-Patterson AFB OH and the Air Force Research Laboratory centrifuge at Brooks AFB TX. At each facility, an identical compensatory tracking task was used to tap the motor skill required by a pilot. In addition to the tracking task, participants were also required to perform a computation task (addition and subtraction problems) to tap the cognitive skills required by fighter pilots. Following the collection of baseline data the participant experienced his/her first G exposure, which was used to establish his/her relaxed G tolerance. Following a rest period, the subject experienced G-LOC. Recovery time data were analyzed and they suggest that it would take a pilot approximately 64 sec to regain the same degree of decision making cognitive ability as he/she had prior to the G-LOC episode. This result has tremendous implications for pilot performance in fighter aircraft.

15. SUBJECT TERMS
G-LOC, cerebral oxygen saturation, %rS0O2, cognitive performance, cerebral hemoglobin volume, systolic arterial blood pressure, hydrostatic column pressure, hypovolemia, baroreflex activity, systemic vascular resistance, mean arterial pressure, cardiopulmonary (CP) baroreceptors, cumulative stress index, lower body negative pressure

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PREFACE

This project was completed under Project/Task/Work Unit 71844501. The research was conducted in the Air Force Research Laboratory's centrifuge facilities, part of the Human Effectiveness Directorate, located at Brooks AFB, Texas and Wright-Patterson AFB, Ohio. The Live Fire Test and Training Program Office of the Office of the Secretary of Defense funded Veridian Engineering through the Naval Air Warfare Center Training Systems Division, to investigate approaches that minimize the effects of G-LOC once it does occur.

The author wishes to express his appreciation to the men and women who volunteered as test subjects for this study and gave this effort 100 percent support.

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Overview

G Acceleration-induced Loss of Consciousness (G-LOC) is one of the main physiological threats to aircrew of high-performance aircraft. G-LOC has been present since the very earliest fighter aircraft were developed (circa 1919). It remains a problem today for successful mission accomplishment.

Once G-LOC has occurred, there are several promising, but untested, approaches to reducing the duration of G-LOC incapacitation and thus return the aircrew member to a functional state. Investigation of these approaches holds the promise of discovering practical, simple, and cost-effective countermeasures that greatly reduce the mishap rate due to loss of consciousness in aircraft in both peacetime and combat situations.

The Live Fire Test and Training Program Office (Code 4.9T) of the Office of the Secretary of Defense funded Veridian Engineering, Inc. to investigate approaches that minimize the effects of G-LOC once it does occur in flight. This work was conducted by both Air Force Research Laboratory centrifuge facilities located at Brooks AFB and Wright-Patterson AFB. Prior to conducting the experimental phase of this program, Veridian, through its primary subcontractor, Chi Systems, Inc., conducted a survey to identify the extent of acceleration-induced problems in aircraft (6).

Four separate experiments were funded by the Live Fire Test and Training Program Office:

<u>Physical Stimuli</u>: the effect of auditory, visual, and tactile stimulation on G-LOC recovery

<u>Previous G-LOC</u>: the effect of experiencing a previous G-LOC(s) on recovery time

<u>Anti-G Suit Inflation</u>: the effect of retarded G-suit deflation on G-LOC

<u>Reduced Recovery Acceleration Levels</u>: The effect of recovery of the aircraft to G<1 subsequent to G-LOC

Purpose of Study

This report presents the results of the previous G-LOC experiment. The primary focus of this study was to measure recovery latency periods (Figure 1) for both the absolute and relative incapacitation period following a G-LOC event across experimental test days and what effect the G-LOC event may have on pre-and post-G-LOC performance of fine motor control and cognitive function tasks.

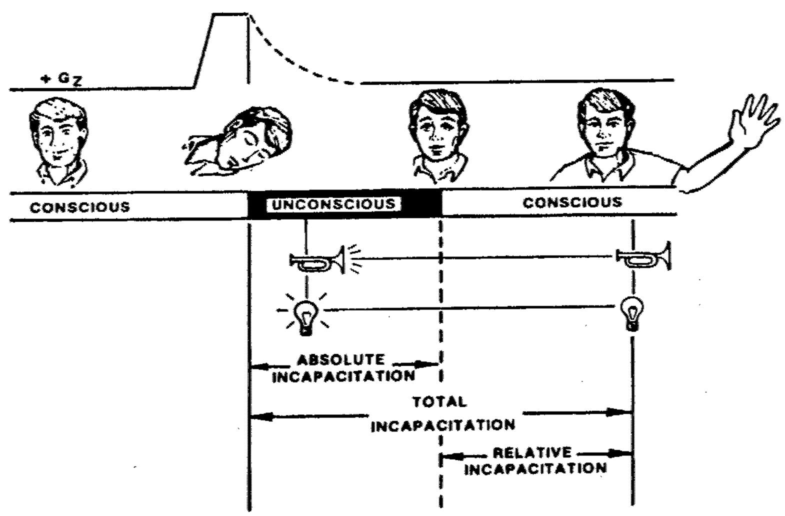

Figure 1. Major Phases of G-LOC (34)

Background

G Acceleration-induced Loss of Consciousness (G-LOC) remains a problem in the aviation community, particularly among US military tactical aircraft. An article reviewing USAF G-LOC experiences found 18 mishaps attributed to G-LOC between 1982 and 1990 (21). An earlier study examined USAF pilot training experience and estimated 1.7 episodes of G-LOC per month (31). A Navy study conducted in 1985 found a G-LOC incidence of 12.23% among all sample respondents (15). A recent analysis of G-LOC incidence by Deaton and Mitchell reported a most alarming statistic: if a pilot is flying in an operational training environment and experiences a G-LOC event the chances are one out of three that a fatality and/or loss of the aircraft will result (6). The actual incidence of G-LOC is most likely much higher than reported here (7). If a G-LOC event does not result in any damage to either aircraft or pilot, it may easily go unreported, particularly if such reporting results in what may appear to be negative consequences (i.e., additional G-LOC training or loss of flight status, etc.). It is also generally known that amnesia is associated with G-LOC incidents, leading to an underestimate of the actual G-LOC rate. These results underscore the need to consider approaches that will minimize the effects of G-

LOC once it does occur. Such post-G-LOC aircrew recovery approaches hold the promise of discovering practical and cost-effective countermeasures that may greatly reduce the mishap rate due to G-LOC.

Previous studies documented the average time of absolute incapacitation (unconsciousness) to be about 15 sec (36). These prior studies found that a relative incapacitation period characterized by confusion and disorientation immediately followed the absolute incapacitation period. Further research of both absolute and relative incapacitation periods resulting from G-LOC confirmed that absolute incapacitation was on the order of 15 sec with the relative incapacitation extending the overall incapacitation to approximately 30 sec depending on the +G onset rate (14). More recent research is beginning to acknowledge the concept of "almost loss of consciousness" (ALOC) as another aspect that should be considered when examining the entire spectrum of psychophysiological events from unconsciousness to dream-like states. In this case, ALOC is typically characterized by one or more of the following: euphoria, apathy, weakness, localized uncontrollable motor activity or paralysis, loss of short-term memory, dream-like states, confusion and loss of situational awareness, abnormal sensory manifestations, sudden inappropriate flow of emotion, and inability to respond to alarms or radio calls even though the participant appreciates them at the time and desires to respond (23). The latter research found that there are significant neurologic manifestations of $+G_z$ even without total loss of consciousness. This finding has important implications for training. That is, it is critical that aircrews are made aware of the potential for and identification of acceleration-induced neurologic manifestations other than vision loss and actual loss of consciousness. This is vital as Morrissett and McGowan's study showed that 73% of those who reported ALOC were in control of their aircraft at the time and at high risk for possible mishaps, while only 53% of those were actually performing an anti-G straining maneuver at the time.

Today's tactical aircraft have the capability of high (9-12 $+G_z$) sustained acceleration and very high onset rates. It is likely that this increased $+G_z$ stress will lead to an increased incidence of G-LOC even with the application of advanced protective devices and techniques. As mentioned earlier, other approaches to dealing with this problem might consider methods and techniques that are capable of improving aircrew ability to rapidly recover from G-LOC once it has occurred. The 24 sec incapacitation period is an extremely long time in the high-speed combat environment. Techniques to reduce both the absolute and relative incapacitation periods should be developed for operational aircrew to minimize the total period of time a pilot is incapacitated once G-LOC has occurred.

Preliminary investigations into the ability to reduce the absolute incapacitation period using modified anti-G valve deflation rates and deflation profiles and modified G-offset rates have provided promising results, averaging from 3-5 sec reductions (35,37). The capability to reduce the period of confusion and disorientation (relative incapacitation) following the recovery of consciousness from G-LOC has been demonstrated as well (33). These latter studies involved individuals who had never experienced G-LOC. They were taken to G-LOC twice, and the times of relative incapacitation were compared between the two exposures. When G-LOC experienced participants were exposed to G-LOC, the relative incapacitation was markedly decreased by 8.5 sec (12 sec decreased to 3.5 sec). The decrease in relative incapacitation caused the total incapacitation to decrease from 24 sec to 16 sec. This 9-sec decrease could translate into as much or more than 5,000 ft. of lost altitude (33). It was hypothesized that the test participants' ability to recognize that a G-LOC episode had occurred and to reorient themselves (regain aircraft control) more rapidly was evident following subsequent exposure to an initial G-LOC episode. The apparent fact that repeated G-LOC episodes result in a decreased relative incapacitation time was recognized as early as 1954 in which G-LOC experienced participants were aware of the confusion after a shorter period of acceleration than were inexperienced participants (2). Additional supporting evidence for decreased relative incapacitation time associated with repeated G-LOC episodes comes from research in which baboons were exposed to multiple G-LOC exposures. It was found that time of performance recovery became significantly shorter after exposure to multiple G-LOC sessions (4). Whinnery and Burton concluded that this situation is analogous to the hypoxia demonstration often used in physiologic altitude training (33). Altitude hypoxia training is clearly an accepted physiological safety-enhancing procedure. In much the same way, experiencing G-LOC gives the individual an opportunity to experience the symptoms associated with G-LOC. This recognition more than likely reduces the relative incapacitation by allowing a more rapid recognition, and thus a faster reaction to a familiar situation. It is also of interest to note that Navy and Air Force aircrew undergoing G-tolerance improvement training were strongly convinced that experiencing a G-LOC episode during centrifuge training was extremely beneficial and may serve to save their lives and their aircraft, should G-LOC ever occur in flight (33). Previous recommendations for

G-LOC training to be a part of all fighter aircrew training have been made, and therefore it is critical that we evaluate these psychophysiological techniques directly to maximally reduce G-LOC relative incapacitation.

This research required participants to experience multiple G-LOC episodes. The impact of these previous G-LOC exposures on recovery time as measured by specific tasks designed to assess cognitive/psychomotor performance. As mentioned earlier, this procedure has been recommended frequently by aircrew in the G-tolerance improvement program questionnaires (33). The goal for this study was not only to evaluate recovery times associated with the absolute, relative, and total incapacitation phases, but also to evaluate neurocognitive task performance pre- and post-G-LOC.

G-LOC Adaptation

It is clear, at this point, that current physiological/engineering solutions are not able to eliminate the G-LOC hazard. It is possible, however, that a human factors solution, anchored in perceptual adaptation, may serve to minimize the negative consequences of G-LOC. As Whinnery and Burton have noted, techniques to decrease the time that a pilot is incapacitated during a G-LOC episode would reduce the time that an aircraft is out of control and ineffective as a weapon system (33).

A large body of research is available that testifies to the remarkable capacity of human observers to adapt to distortions and rearrangements of their perceptual-motor environments (7,13, 25, 30). This research dates back to the classic work conducted by Stratton and Kohler who described the ability of observers to adjust to prism-based optical rearrangements of the visual environment and to perceive and act veridically in the face of these distortions (17, 18, 26, 29). Later research has shown that such adjustment not only extends to displacements in spatial location, but also to distortions in target form and size (25, 30). In addition, other studies have indicated that observers can adapt to an even broader range of perceptual and motor aberrations including distortions in size and distance (22, 24), apparent curvature (27), and illusory motion (8) that occur underwater and the disabilitating effects produced by time-delayed visual feedback on perceptual-motor performance in virtual environment. Of particular relevance to the G-LOC problem are studies demonstrating sensory-motor adaptation to aberrations that appear in the microgravity conditions of parabolic and orbital flight (19). It is conceivable, therefore, that with experience, pilots can learn to overcome the confusion and disorientation associated with a G-LOC episode and thereby, shorten the time that they are incapacitated. This possibility was recognized by Whinnery and his associates (33, 34) who noted that the period of relative incapacitation during G-LOC tends to be shorter when observers have had prior G-LOC experience than when they have not. To date, however, no systematic experimental effort has been devoted to examining adaptation to G-LOC.

Pre-G-LOC Performance

An additional assumption in the Whinnery, Burton, Bolls, and Eddy (32) characterization of the G-LOC episode is that that the pilot's flight performance is adequate up to the point of loss of consciousness. Accordingly, no efforts have been made to examine performance efficiency *prior* to the onset of G-LOC.

In modern high performance tactical aircraft such as the F-15, F-16, and F-18, climbing and turning maneuvers often result in the sudden application of $+G_z$ forces sufficient to produce a rapid drop in cerebral blood pressure and consequent unconsciousness (12). Under such circumstances, however, there are approximately 5 to 7 sec when pilots can perform their flight tasks before brain tissue oxygen reserves become depleted to the point at which unconsciousness sets in (12, 38). Research has indicated that observers undergoing hypoxia are subject to mental blocks, a general slowing of early information processing, and a deterioration of sensory functions (dark adaptation), cognitive functions (concentration, verbal and visual memory, target acquisition) and motor skills (tracking, complex psychomotor performance) (3, 5, 9, 10, 11, 16, 20). Consequently, it is conceivable that flight skills will deteriorate within the 5 to 7 sec period *before* unconsciousness occurs in a G-LOC episode; a result that would exacerbate the G-LOC hazard. Accordingly, this research explored that possibility using tracking and math tasks similar to those employed by Houghton and his associates (14).

Post-G-LOC Performance

A central feature of Whinnery et al.'s characterization of the G-LOC event is the assumption that flight performance would return to pre-G-LOC levels at the end of the 12-sec relative incapacitation phase that marks the termination of the 24 sec event (32, 33, 34). There is reason to believe, however, that this assumption may be incorrect. G-LOC-based disruptions in pilot efficiency may require a period of recovery that extends beyond the termination of G-LOC. Thus, Whinnery and his colleagues may have underestimated the duration of the G-LOC–based window of disrupted flight performance and the severity of the G-LOC hazard.

In a recent study, Arnold, Tripp, and McCloskey (1) examined the time needed to recover a subject's arterial blood oxygen saturation after exposure to hypoxia. They found that 90 sec were needed for arterial blood saturation to return to pre-hypoxia levels. This value suggests that the period of disruption following a G-LOC event may be considerably longer than the 24 sec (absolute/relative incapacitation periods) proposed by Whinnery et al. (32, 33, 34), especially if testing is carried out on tasks requiring a higher level of information processing than merely pressing a stop switch to extinguish visual and auditory warning signals.

Houghton et al. (14) carried out a study to examine post-G-LOC performance. Their study featured a compensatory tracking task in which participants were required to maintain the intersection of two orthogonal cross hairs displayed on a cathode ray tube (CRT) screen within a small target area, and a numerical computation task involving two-digit arithmetic problems. These tasks were selected to emulate the types of motor and cognitive activities (aviate and navigate) needed to pilot modern tactical aircraft. Efficiency was assessed in 1-min intervals for 7 min after participants resumed task performance following the unconsciousness phase of the G-LOC episode. Houghton and his associates found that 3 min (180 sec) were required for performance on the math task to return to pre-G-LOC levels (14). This recovery period, together with the 24 sec total incapacitation time of the G-LOC episode itself means that a plane flying at 500 mph could cover a distance of 149,532 feet or 28.3 miles while the pilot's cognition may be impaired.

In the Houghton study, only performance of the math task required a considerable period of time to recover from G-LOC; performance on the tracking task appeared to recover immediately following the relative incapacitation period (14). A result of this sort suggests that cognitive but not motor functions are subject to impairment after a G-LOC episode. It is worth noting, however, that Houghton and his associates assessed performance in relatively long 1-min intervals. It is possible that tracking performance is impaired post-G-LOC but that recovery occurs quickly and that a more fine-grained temporal analysis is necessary to observe it. Given that the speed of modern tactical aircraft renders even a few seconds of impairment potentially important, one goal for the present study was to examine post-G-LOC tracking in a more temporally detailed manner than that employed in the Houghton et al. study. Such information is needed in order to gain a more complete understanding of the effects of G-LOC on pilots' ability to control the aircraft post-G-LOC.

METHODS

Participants

Fourteen active duty members of the United States Air Force (five women and nine men) volunteered to participate in the study. They ranged in age from 25 to 36 years, with a mean of 29 years. All participants were members of the sustained acceleration stress panels at Brooks AFB TX and Wright-Patterson AFB OH. As part of the requirement for membership on the stress panels, all participants completed the Air Force's extensive G-training program to ensure that their tolerance to acceleration and their nystagmic responses under acceleration were similar to those of pilots flying high performance aircraft.

In order to qualify for service in the study, all participants were required to have normal or corrected-to-normal vision and normal vestibular functioning. Additionally, they had to undergo an extensive physical examination, and were required to have no history of neurological pathology or of having experienced episodes of loss of consciousness. Information about these qualifying factors was obtained from screening the participant's medical records. Prior to final acceptance into the study, all participants underwent a rigorous physical examination including x-rays of the skull and spine, tests of the integrity of the cardiovascular, pulmonary, and nervous systems, and a comprehensive blood chemistry work-up. On the basis of this examination, all participants were determined to be in excellent health by a flight surgeon. Female volunteers who were pregnant were not accepted for participation in the study because the risks to the developing fetus under acceleration and G-LOC are unknown.

Facilities

The study was conducted at the Air Force Research Laboratory's centrifuge facilities at Brooks AFB and Wright-Patterson AFB. Half of the participants were tested at each of the two facilities. Photographs of the centrifuge at each facility are presented in Figures 2 and 3.

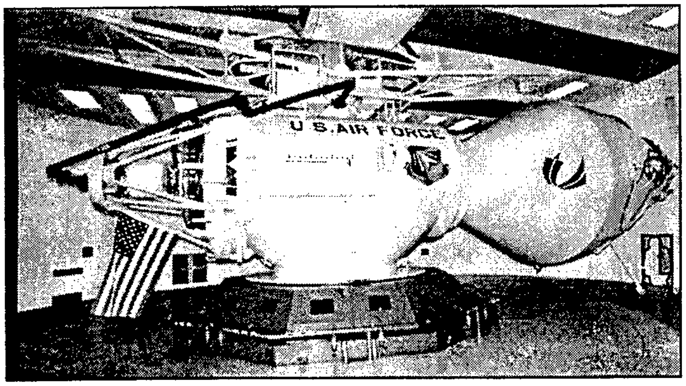

Figure 2. Dynamic Environment Simulator
Wright-Patterson AFB OH

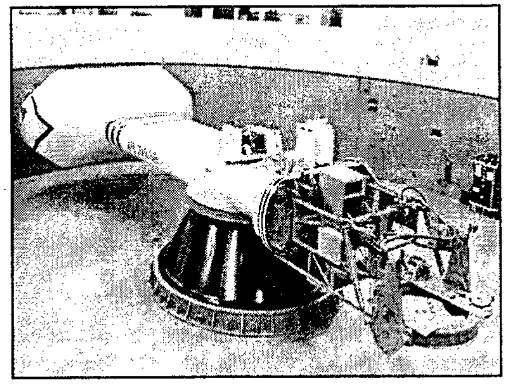

Figure 3. USAF/SAM Centrifuge
Brooks AFB TX

Although the facilities differ from each other in physical appearance and in size (the facility at Brooks is smaller than the one at Wright-Patterson), the performance characteristics of the two centrifuges were the same for the purposes of this study. Each has a 19 ft radius arm. The acceleration rates needed to achieve given +G levels in the two acceleration vehicles were identical. In addition, each centrifuge permitted the generation of identical acceleration profiles (rate of G-onset and the G-plateau attained) under computer control.

The gondola of the centrifuge at each facility was equipped with an F-16-like ACES II ejection seat with a seatback reclined to 30° from vertical. As illustrated in Figure 4, the seats at each facility had adjustable head and shoulder supports that prevented the participant's head and torso from sliding off of the seat during a G-LOC episode.

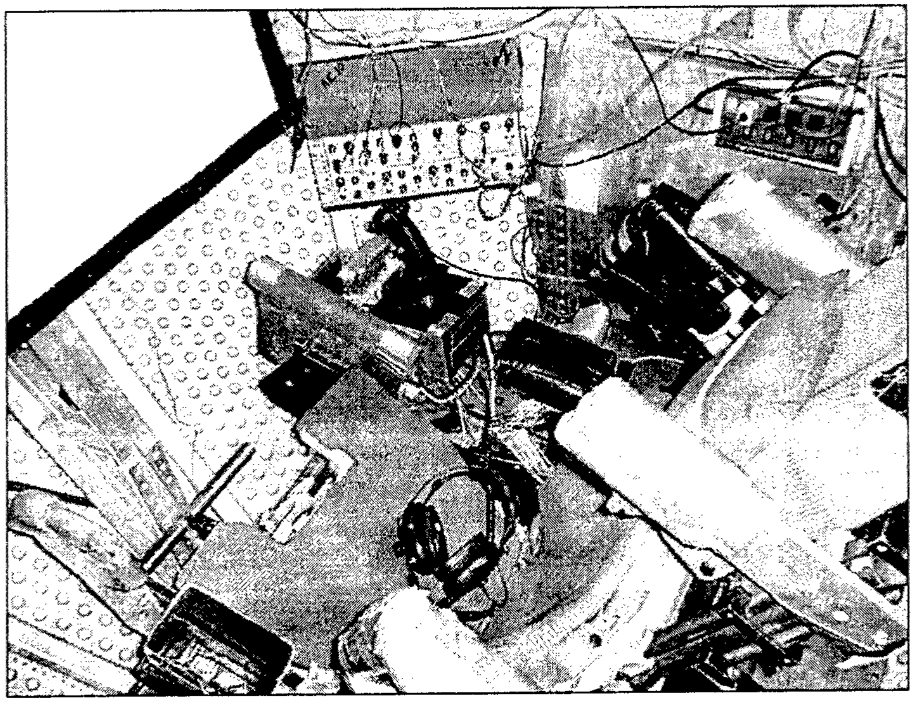

Figure 4. Aircraft Seat with Head and Shoulder Supports

Each facility made use of an aircraft IC-10 communication system to provide two-way voice-communication between the research participant and the investigator. The participant's microphone was fixed in the open position to allow the participant "hands-free" communication. Participants were also provided with an emergency abort switch that enabled them to stop the centrifuge at any time during testing. Participants wore a standard Air Force issue Nomex® flight suit and a Gentex (Carbondale PA) HGU-55/P flight helmet during all testing runs.

The gondola at each facility was outfitted with a simulated fighter cockpit. As can be seen in Figure 4, the cockpit incorporated a flight stick (Happ Controls, Elk Grove IL, model B6) mounted on the participant's right side, which was used to secure responses to the performance tasks described below, and a viewing screen representing a 70° (vertical) x 140° (horizontal) visual field mounted directly in front of the participant, on which the performance tasks were projected.

Continuous surveillance of participants was afforded during each run by two closed-circuit television cameras. The cameras provided a close-up view of the participant's head and a wide-angle view of the participant from head to foot. Study personnel housed in a control room observed the video images. A video mixer was used to generate a composite picture of the two views of the participant along with the time, date, and G_z acceleration in a given run. Video data were stored on ½ inch VHS videotape for later analysis.

A TELEX (Minneapolis MN) model P1000 video projection system at Wright-Patterson AFB and a plasma visual display at Brooks AFB were used to present the stimuli for the performance tasks and the image for assessing visual field loss as a function of increasing G. Each display system's picture resolution was standardized to 1024 x 768 pixels. Identical computer systems at each facility orchestrated stimulus presentations and stored participant's responses to the performance tasks.

Acceleration Profiles

Computer control systems at each facility were used to generate two acceleration profiles. The first was a gradual G-onset rate (GOR) of 0.1 G/sec. This profile was employed to establish the participant's relaxed G-tolerance level (the G level at which eye-level blood pressure can no longer be maintained) on a given test day. As the centrifuge was slowly accelerated, participants were asked to view the red central target that represented 10 degrees of the visual field. They were instructed to execute an anti-G straining maneuver (AGSM) when the visual field blackened out and all that could be seen was the target, i.e., central light loss or CLL occurred. The test director aborted the acceleration profile upon observing the participant initiating an AGSM. The G level at which this occurred was termed GOR_{max}.

The second G profile, which was run after the determination of GOR_{max}, featured a rapid G-onset rate (ROR) of 3 G/sec to a pre-established target level that was set *individually* for each participant on *each* testing day. The target level was determined by adding +1 G_z to the GOR_{max}. The principal investigator terminated the ROR profile when G-LOC occurred or the G profile reached a time limit of 15 sec. The presence of G-LOC was determined subjectively using the Whinnery, et al. criteria that include the following signs: (1) slumping of the head and upper body, (2) dual eye closure, and (3) jaw muscle relaxation reflected in a gaping mouth (32). All three signs needed to be present in order to determine that a participant had gone into G-LOC and the principal investigator and the flight surgeon had to be in *total agreement* in order to make the call. Figure 5 shows a participant undergoing a G-LOC episode.

Figure 5. A Participant Exhibiting the Signs of G-LOC
(Note the head and upper-body slumping, eyes closed, and jaw muscles relaxed)

Performance Tasks

At each facility, an identical compensatory tracking task was used to tap the motor skill required by a pilot to maneuver an aircraft in flight. Participants performed this task by using the flight stick to maintain the *independent* alignment of white horizontal and vertical (72.5 x 51.5 cm) moving cross hairs over the appropriate horizontal and vertical centerlines of a fixed target made up of green cross hairs whose heights and widths were identical to those of the moving cross hairs.

The fixed target was centered in the middle of an otherwise black projection screen. Both the horizontal and vertical components of the moving cross hairs were driven from their respective centerlines of the fixed display in a pseudorandom fashion by a force function comprised of three sine waves (1/3, 1/7, and 1/11 Hz) at amplitudes ranging from 22.2-44.4% of the screen width or height. The forcing function made the tracking task difficult. The task, which is illustrated in Figure 6, was similar to the tracking task employed by Houghton et al. (14).

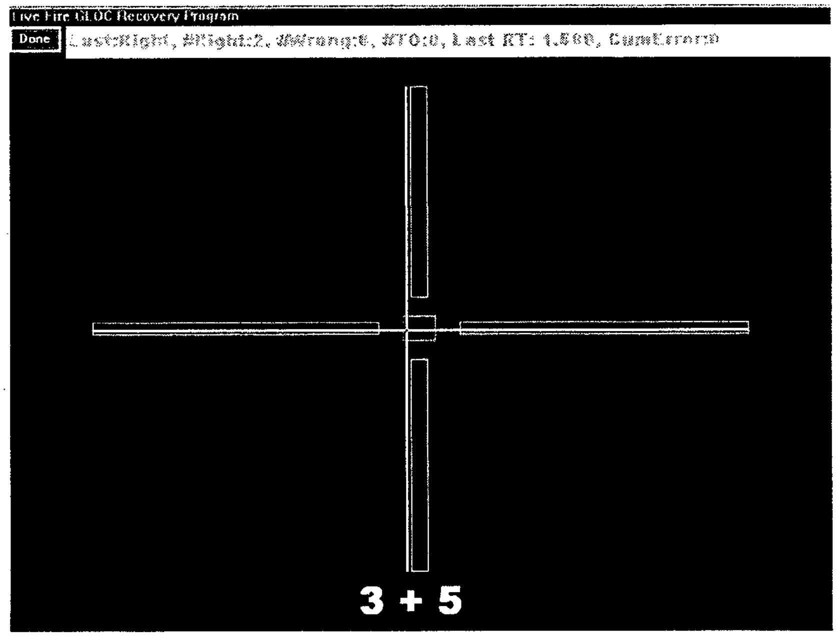

Figure 6. Compensatory Tracking and Math Task

In addition to the tracking task, participants were also required to perform a computation task designed by Shingledecker to tap the cognitive skills needed by fighter pilots to navigate their aircraft (28). The task involved a series of addition and subtraction problems featuring paired white digits (0.7 cm x 2.1cm) ranging from 1 to 9 (e.g., 3 + 5; 8-1). Participants were required to push the trim switch (located on the flight stick) up if the solution to a given problem was greater than 5 and down if the solution was less than five.

Numerical pairings yielding solutions equal to 5 were not employed. Consequently, the test ensemble consisted of a total of 136 problems, half summation and half subtraction. The stimuli for the computation task was the presentation of the white 0.7 x 2.1 cm figures at the center of the viewing screen below the area occupied by the tracking task, as illustrated in Figure 6.

Problems were exposed until the participant responded or until 2.5 sec had elapsed. A new problem appeared immediately after each response. The order in which a participant experienced the problems in the ensemble was varied at random during each run. The tracking and computation tasks were performed concurrently. Participants were told that each task required equal attention and that the tasks were weighed equally in terms of the scoring of the responses.

Prior to their participation in the study, subjects were required to undergo a training program to perform the tracking and math tasks at a pre-established level of competency. The approach used to train participants was standardized at each facility with training using the same experimental configuration applied in the experiment. Each training session lasted for 30 minutes. Participants were required to achieve a stable level of performance on the two tasks prior to their participation in the study. Stable performance was defined as less than 10% variability in tracking root mean squared error (RMSE) and 90% accuracy for the math task over two consecutive training days. An additional two days of task training were performed in the dynamic G environment prior to the commencement of data collection. This training allowed the subject to gain experience and to compensate for any effect the +Gz acceleration may have on their ability to manipulate the flight stick in the hypergravitational environment.

Procedures

On a typical experimental test day at each facility, participants arrived at the laboratory, donned a flight suit and were instrumented with electrocardiogram leads, a cerebral tissue oxygen sensor, an arterial oxygen saturation sensor, and multi-channel electroencephalogram electrodes. A brief medical examination by the flight surgeon and medical history were also accomplished. The participant then proceeded to the centrifuge where he/she donned a parachute harness and flight helmet. After entering the gondola of the centrifuge the participant was secured to the aircraft seat using a three-point aircraft restraint system. The various physiologic measurement sensors were connected and the signals were verified prior to securing the gondola of the centrifuge. At this point the tracking/math tasks were started and baseline performance data were collected for 5 minutes. Following the collection of baseline data the participant experienced his/her first G exposure, which was used to establish his/her relaxed G tolerance.

The relaxed G tolerance profile was a GOR exposure terminating when the participant experienced CLL. At this point the participant performed an AGSM and the G exposure was terminated. The participant then rested for 6 minutes, which allowed enough time for their physiology to return back to the pre-acceleration exposure levels. Following the rest period, the G-LOC exposure began with the participant performing 15 sec of pre-acceleration baseline for tracking and math task data that continued on through the ROR acceleration profile. The participant remained relaxed during this exposure and continuously performed the tasks for as long as possible prior to the loss of consciousness episode. The loss of consciousness episode was determined using the G-LOC criteria established by Whinnery (32, 33, 34).

Once the participant was determined to be unconscious, the centrifuge was brought to a full stop and he/she regained consciousness. Following the G-LOC episode, the participants re-engaged the tracking and math tasks as soon as he/she was able and continued performing these tasks for 5 minutes. At no point after the participant regained consciousness was there any communication between the investigator and the participant. Following the completion of the post-G-LOC performance tasks the participant egressed the centrifuge and was immediately examined by the flight surgeon and then was released to return to his/her normal duties. A short description of the electroencephalogram (EEG) recording system and the cerebral oximeter system is given below:

The VitaPort II ambulatory physiological recording system produced by TEMEC Instruments B.V., was used to collect 9 channels of EEG, vertical and horizontal eye movements, and electrocardiogram (EKG). The EKG was recorded on only a few runs. The left mastoid was used as reference for the EEG and the right mastoid was used for ground in all the recorded channels. The VitaPort II recorder used four AA batteries to operate. Data were digitally stored onto a compact flash adapter memory card.

The INVOS cerebral oximeter system monitors changes in the regional oxygen saturation, or rSO_2, within a sample of blood in the cerebral cortex. Soma-Sensors were placed on the left side of the subject's forehead with an elastic bandage. These sensors are then connected to the INVOS system and the monitor. A harmless near-infrared light is passed through the subject's forehead into the brain to obtain the rSO_2 measurements. The depth of the light signal is related to the distance between the light source and the photo detectors. The majority of the blood in the region of brain monitored is "venous" blood. Therefore, the critical balance between arterial oxygen delivery and cerebral consumption influences changes in INVOS values. Imbalances are identified by changes in rSO_2.

The INVOS system measures cortical saturation levels at a rate of fifteen times per second, updates within 4 sec to changing rSO_2 levels, and displays the results from each SomaSensor. The dual detector provides spatial resolution to suppress the effects of extra-cerebral tissue.

RESULTS

G-LOC Recovery Data

Recovery time data were analyzed using a subject by day repeated measures ANOVA, which was accomplished for the absolute, relative, and total incapacitation times. Box's correction was also performed as part of this analysis to control for Type 1 errors (obtaining a significant result when it does not exist). One subject withdrew their participation from this study. No significant decrease in recovery time was found for the absolute, relative, or total incapacitation recovery times across the four experimental test days ($\underline{F}$ (3, 36) = 0.699, $\underline{p}$=0.535, $\underline{F}$ (3, 36) = 2.594, $\underline{p}$=0.071, $\underline{F}$ (3, 36) = 2.450, $\underline{p}$ = 0.150, respectively). It was initially thought that there was a bi- day trend for the relative incapacitation data. However, it became evident from the individual subject plots that data from two of the thirteen subjects had a significant influence on the outcome of this analysis. In light of this finding it became obvious that a trend towards significance for the relative incapacitation data did not exist. Figures 7 through 9 show the mean values for absolute, relative, and total incapacitation recovery time data plotted across the four experimental test days and the Standard Error of the Mean (SEM) associated with these data.

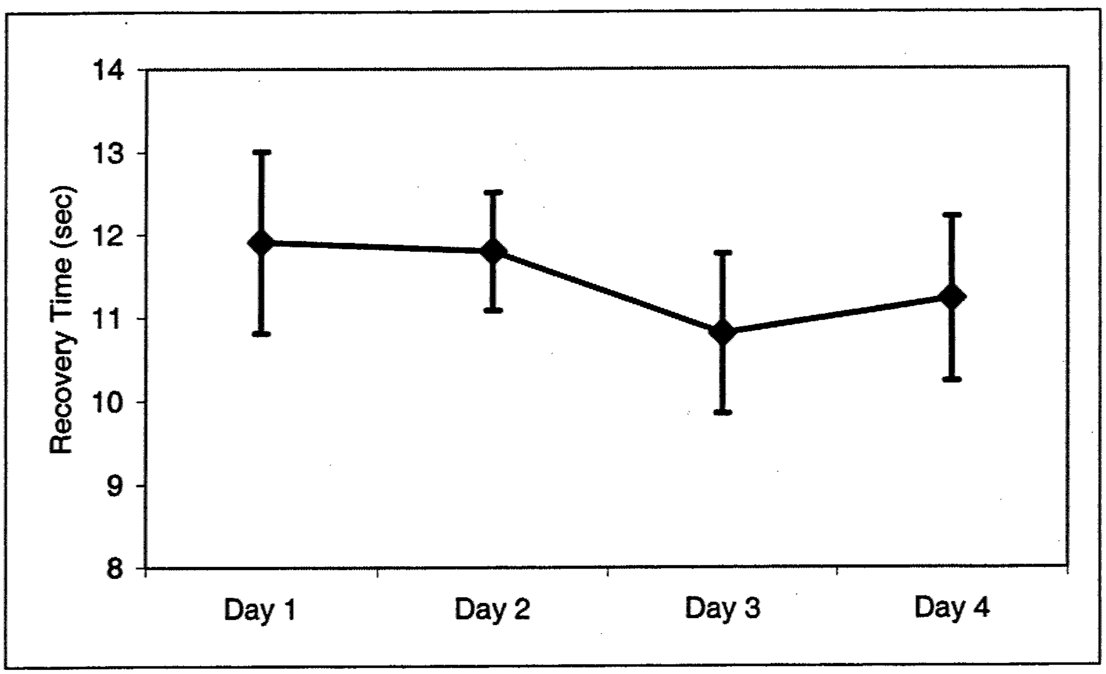

Figure 7. Mean Absolute Incapacitation Recovery Time (±SEM) n=13

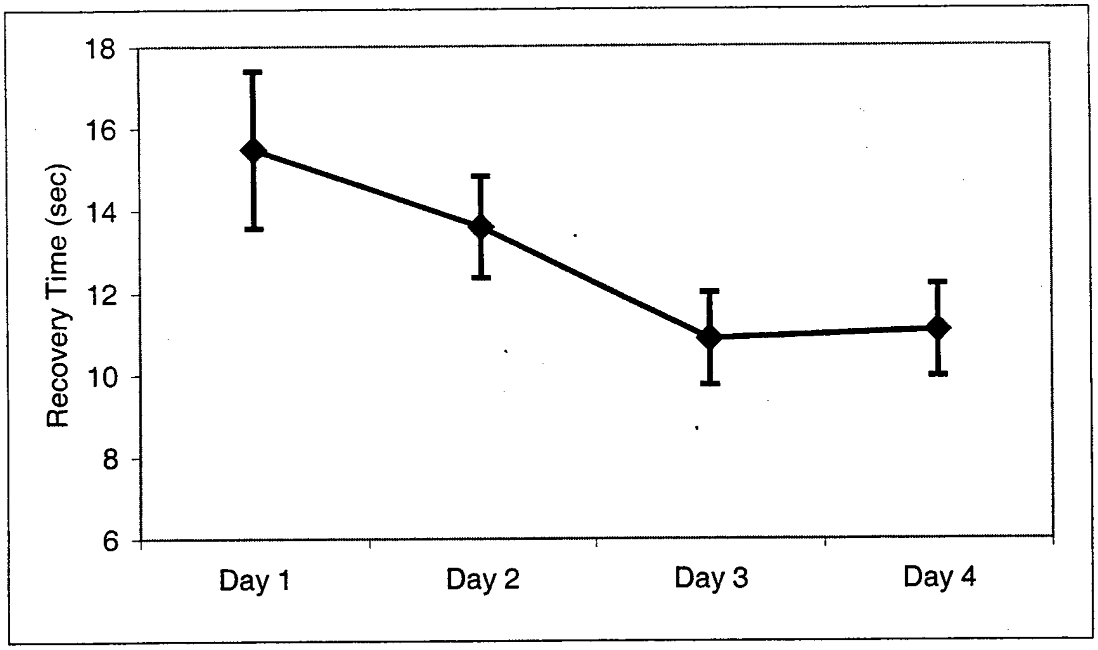

Figure 8. Mean Relative Incapacitation Recovery Time
(±SEM) n=13

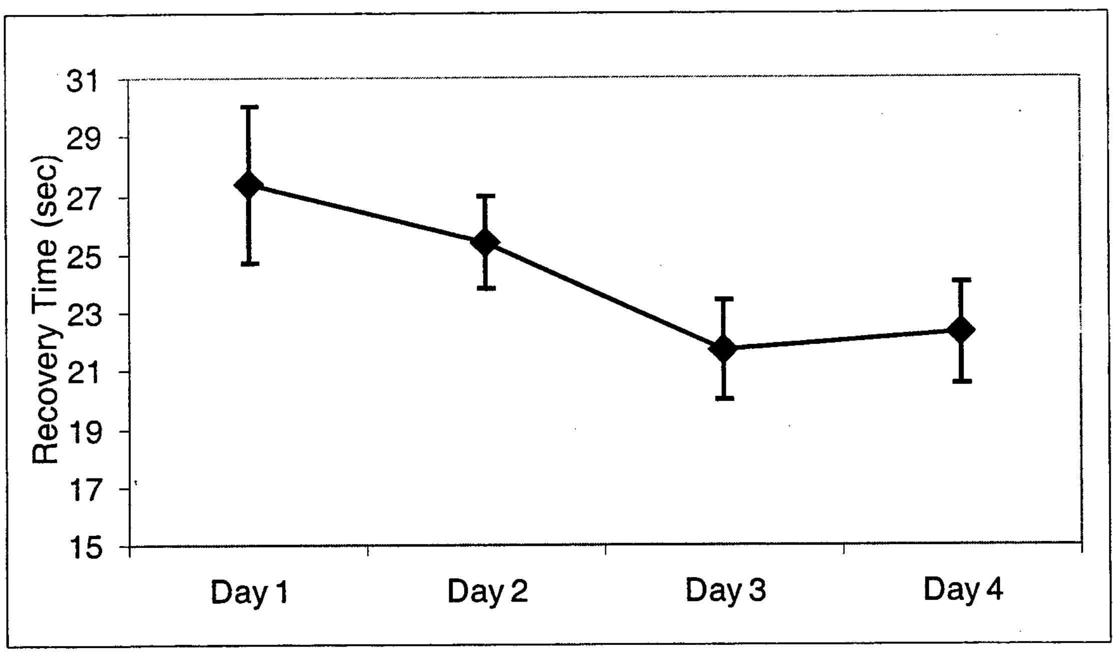

Figure 9. Mean Total Incapacitation Recovery Time
(±SEM) n=13

Performance Data

Determination of Return to Baseline Performance: Data used were the last 4 minutes of pre-G-LOC baseline and the 5 minutes immediately post-G-LOC. Pre-G-LOC baseline data before that last 4 minutes were not used due to some subjects showing initial learning (or warm-up).

The following is a step-by-step approach to determine when the mean performance rate post-G-LOC returned to within 10% of the baseline performance. Both RMS errors from the tracking task and reaction times from the math task were plotted for each subject as well as for the group means. These data appeared to be positively skewed. A log transformation was performed on the data. The procedure was as follows; the mean was defined as: (1) log the values, (2) average the logged values, and (3) transform the mean of logged values back to the original units. This method is equivalent to the geometric mean (GM).

Tracking Data

The mean time period that the subjects stopped the tracking task prior to G-LOC was calculated across experimental test days. Repeated measures ANOVA revealed no significant effect of the subject stopping the tracking task prior to G-LOC across test days ($\underline{F}$ (3, 36) = 0.722, $\underline{p}$=0.520). The Box correction was used in this analysis. With no significant difference across days, the data were collapsed across days and the mean time that the subject stopped tracking prior to the G-LOC event was calculated. This analysis showed that, on average, the subjects stopped tracking 3.2 sec prior to the G-LOC event. From an operational perspective pilots may not have fine motor control (control of the flight stick) prior to the G-LOC incident. Figure 10 shows the time at which subjects stopped tracking across days.

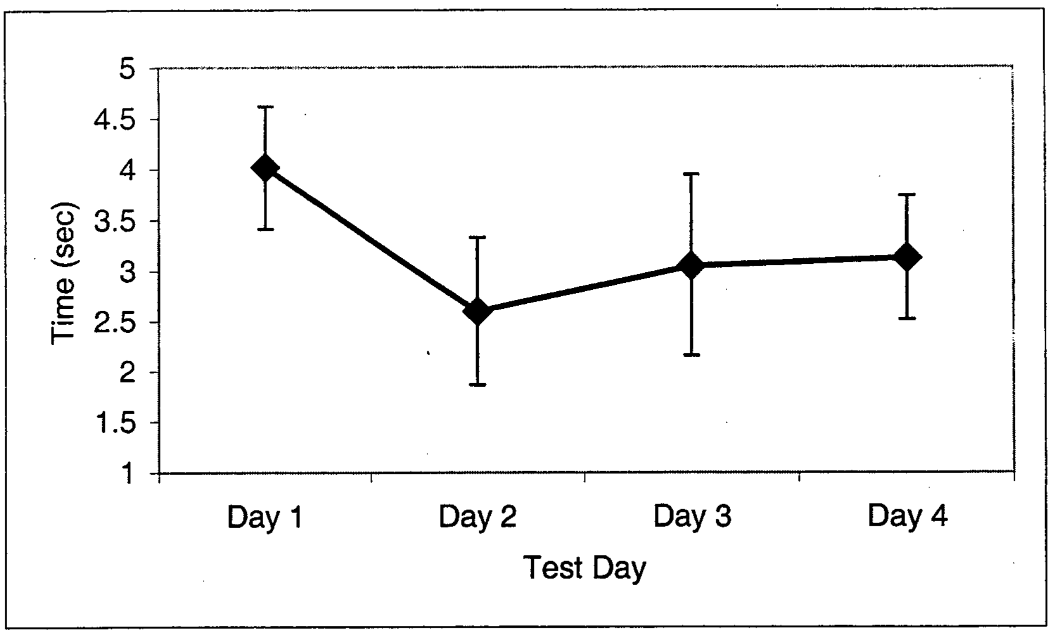

Figure 10. Period of Time Subject Stopped Tracking Prior to G-LOC
(±SEM) n=13

Following the G-LOC event subjects resumed the tracking task as soon as they were able to resume the tracking task. A repeated measures subject by day ANOVA was performed. No significant difference in tracking across days was observed (F (3, 36) = 0.063, p=0.966). It is, however, interesting to note that the average time to resume performing the tracking task to the level achieved prior to G-LOC was 47 (SD ±1.75) sec. Figure 11 depicts the mean time to resume tracking across days following G-LOC.

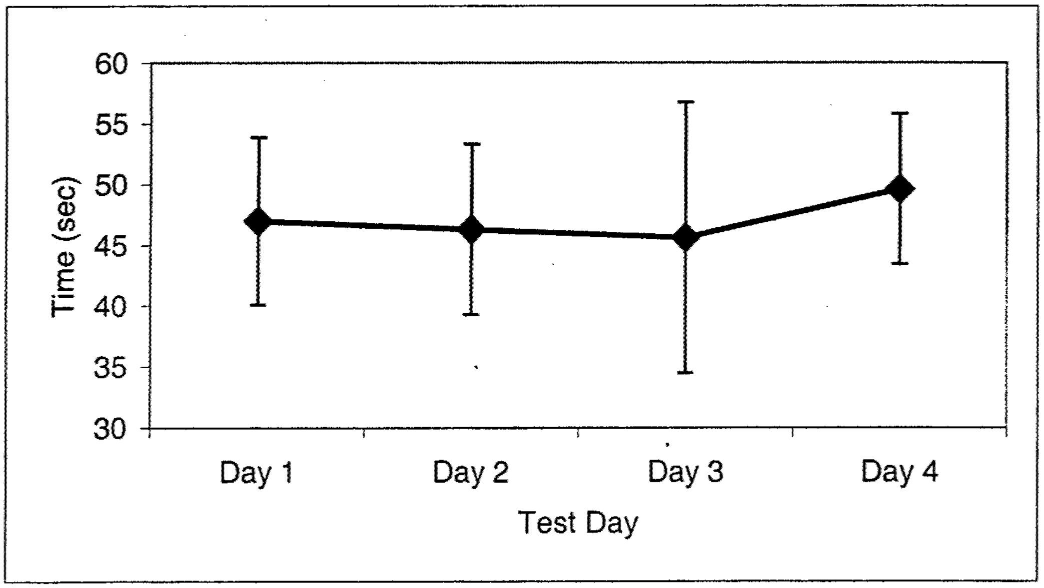

Figure 11. Mean Time to Resume Tracking Following G-LOC
(±SEM) n=13

Math Task

The arithmetic computation task was used to study cognitive function before and following G-LOC. The first analysis examined the time in which the subject stopped performing this task prior to G-LOC across experimental test days. A repeated measures subject by day ANOVA with the Box correction was used in this analysis. The result of this analysis showed no significant change in times that the subjects stopped performing this math task over days (F (3, 36) = 1.192, p = 0.326). With no day effect present, these data were then averaged across days and an average time that the subjects stopped performing the math task was obtained. Subjects stopped performing the math task 7.44 (SD ±0.60) sec prior to G-LOC. Figure 12 illustrates the time subjects stopped tracking across experimental test days.

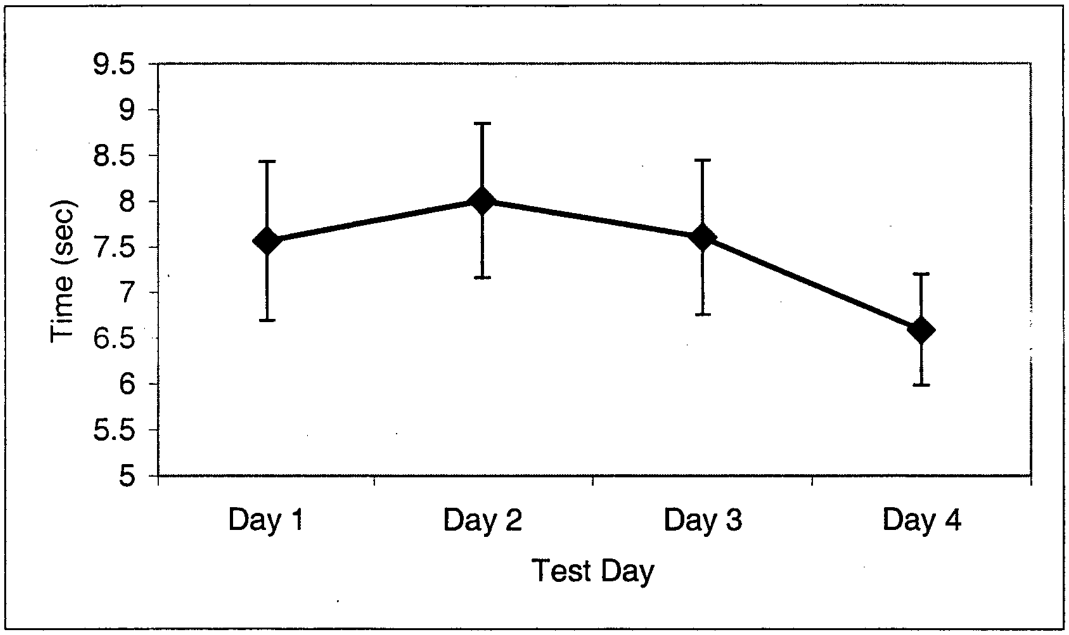

Figure 12. Mean Time Subjects Stopped Performing the Math Task Prior to G-LOC ($\pm$SEM) n=13

Following the G-LOC event, subjects resumed the math task as soon as they were able. A repeated measures subject by day ANOVA was performed on the time required to resume the math task. No significant difference in arithmetic computation across days was observed (F (3,36) = 0.722 p=0.520). It is, however, interesting to note that the average time to resume performing the math task to the level achieved prior to G-LOC was 64 (SD +9.40) sec. This finding is significant from an operational flight perspective. These data suggest that following the relative incapacitation period, it would take a pilot 64 sec, on average, to regain the same degree of decision making cognitive ability as he/she had prior to the G-LOC episode. Figure 13 depicts the mean time to resume performance of the math task across days following G-LOC.

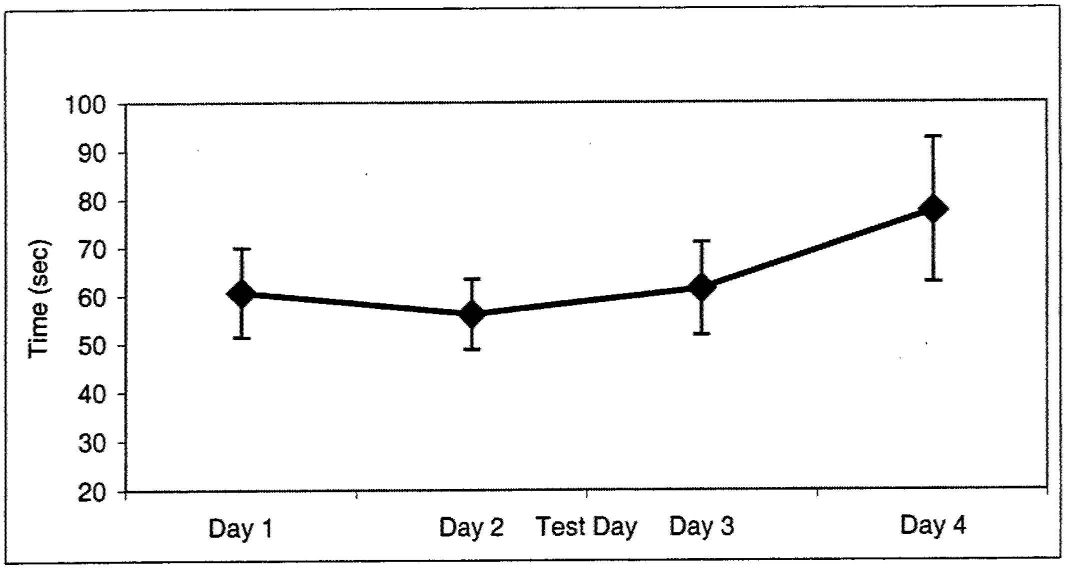

Figure 13. Mean Time to Resume Math Task Following G-LOC (±SEM) n=13

Math and Tracking Comparisons

With no significant difference found comparing the times that the subjects stopped tracking and when they stopped performing the math task, the mean stop tracking and math times were averaged across days and a t-test comparing the means of these variables was performed. Results from this analysis showed that subjects stopped performing the math task before they stopped performing the tracking. The time that the math task was stopped compared to the time that the tracking task was stopped was significantly different from one another (t (1, 12) = 4.953, p=0.0001). Figure 14 illustrates these time comparisons below.

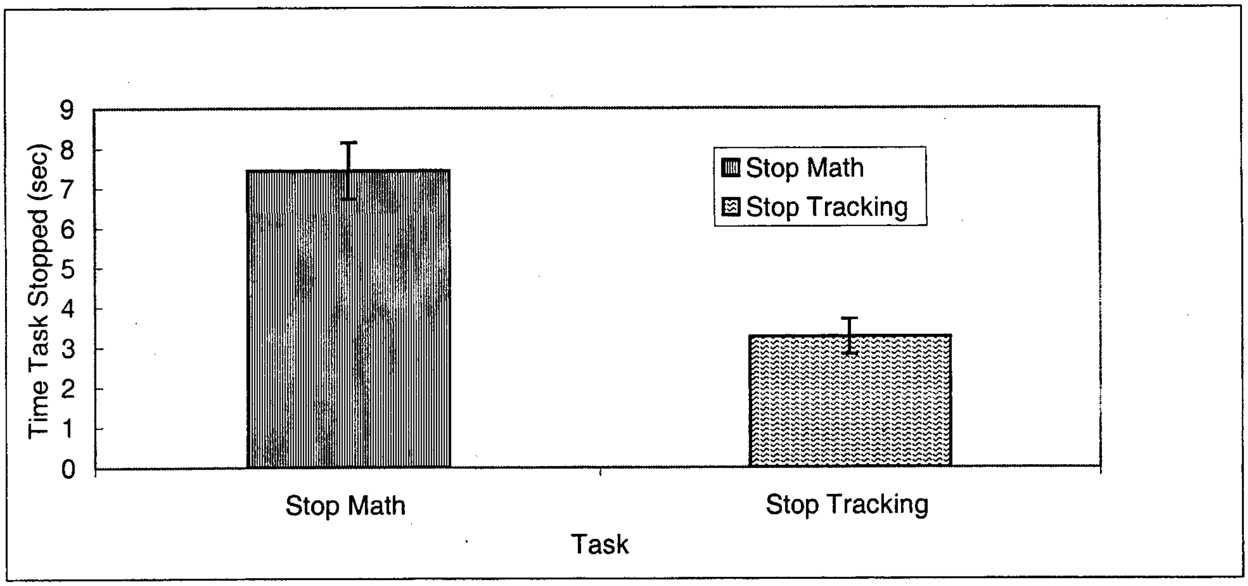

Figure 14. Mean Time Subjects Stopped Performing Math and Tracking Tasks Prior to G-LOC (+SEM) n=13

Data representing the time that it took to resume the tracking and math tasks were averaged across days and a one tailed t-test was performed comparing the average times that it took for the subjects to begin performing each task. The time that it took for the subject to begin the math task was significantly longer than the time that it took them to resume the tracking task (t (1, 12)=1.75, $p<0.05$). The graph in Figure 15 shows a comparison of the mean time required to resume both the tracking and the math tasks following the relative incapacitation period.

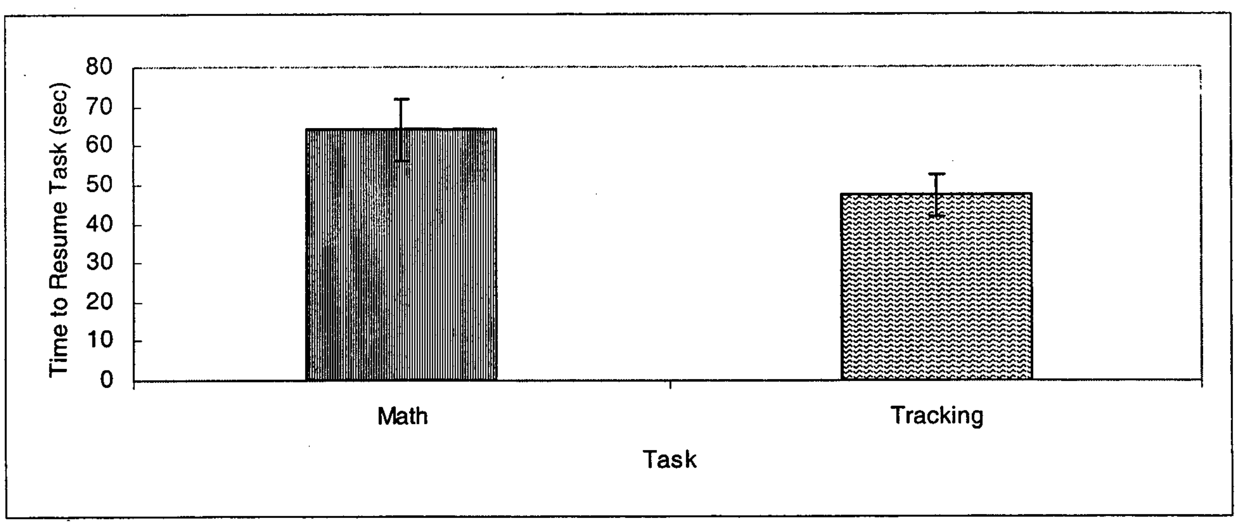

Figure 15. Mean Time Required for Subjects to Resume Math and Tracking Tasks (+ SEM) n=13

As Whinnery has previously shown, the mean total incapacitation recovery time from G-LOC following rapid acceleration onset rates is 24 sec (32, 33, 34). The graph in Figure 16 illustrates incapacitation time in terms of the amount of time that the subjects were incapacitated in performing the task when compared to their pre-G-LOC baseline. These times include the pre-G-LOC time that subjects stopped performing each of the tasks, the 24.2 sec of total incapacitation time, and the time that it took for the subjects to resume performing each task. These performance incapacitation times were then compared to the 24 sec of total incapacitation time reported by Whinnery. Figure 16 depicts the performance incapacitation times for the math and tracking tasks compared to the Whinnery 24 sec of incapacitation time previously reported. Both the math and tracking data shown in this figure include the time that the participants stopped performing both tasks prior to G-LOC, the 24 sec absolute and relative incapacitation periods, and the post-G-LOC time required to perform each task within 10% of the pre-G-LOC baseline performance.

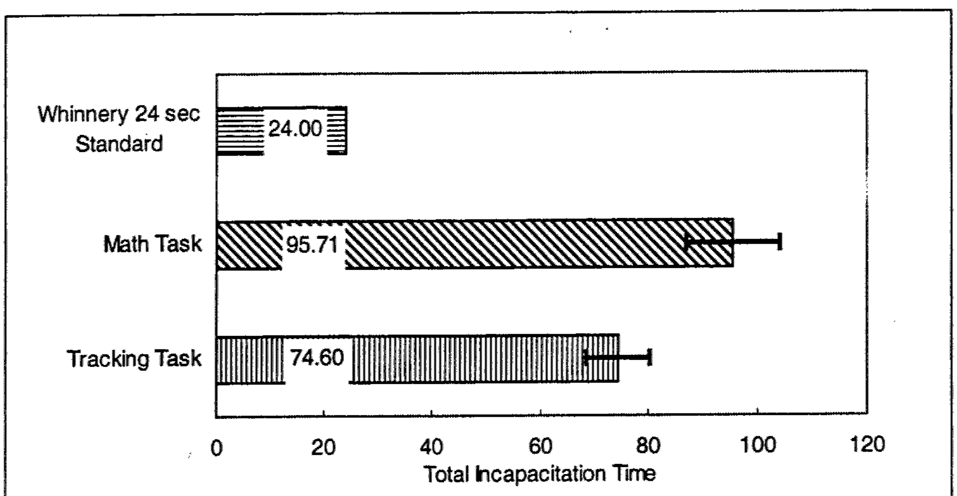

Figure 16. Mean Total Performance Incapacitation Time
($\pm$SEM) n=13

Figures 17 and 18 break down performance incapacitation time associated with the G-LOC episode for both the tracking and math tasks. These graphs illustrate, for each of the performance tasks, the amount of time the participant was incapacitated prior to, during unconsciousness, and during the post-G-LOC recovery period.

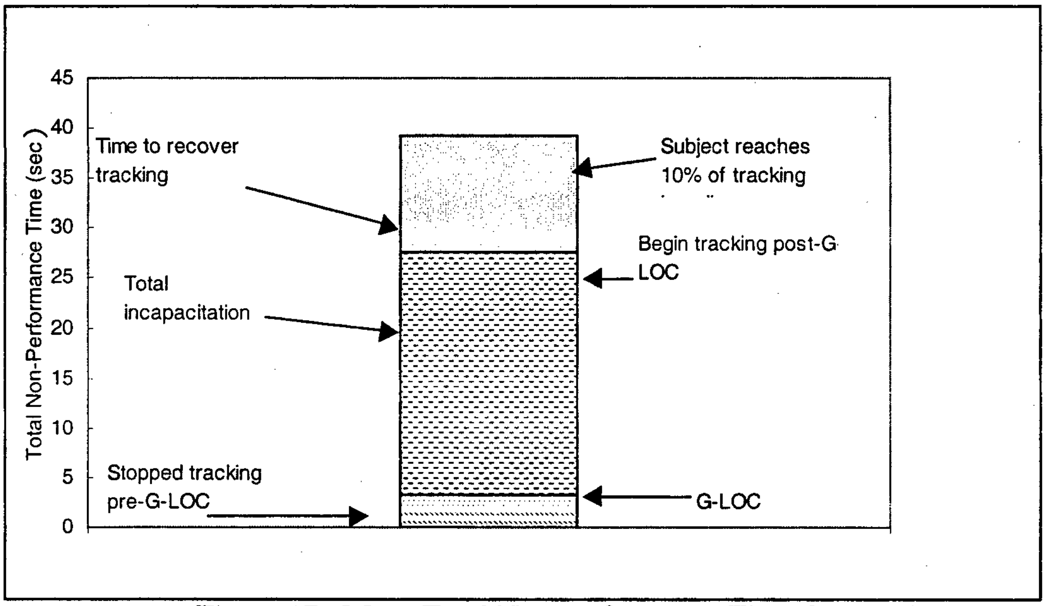

Figure 17. Mean Total Non-performance Time for Tracking
n=13

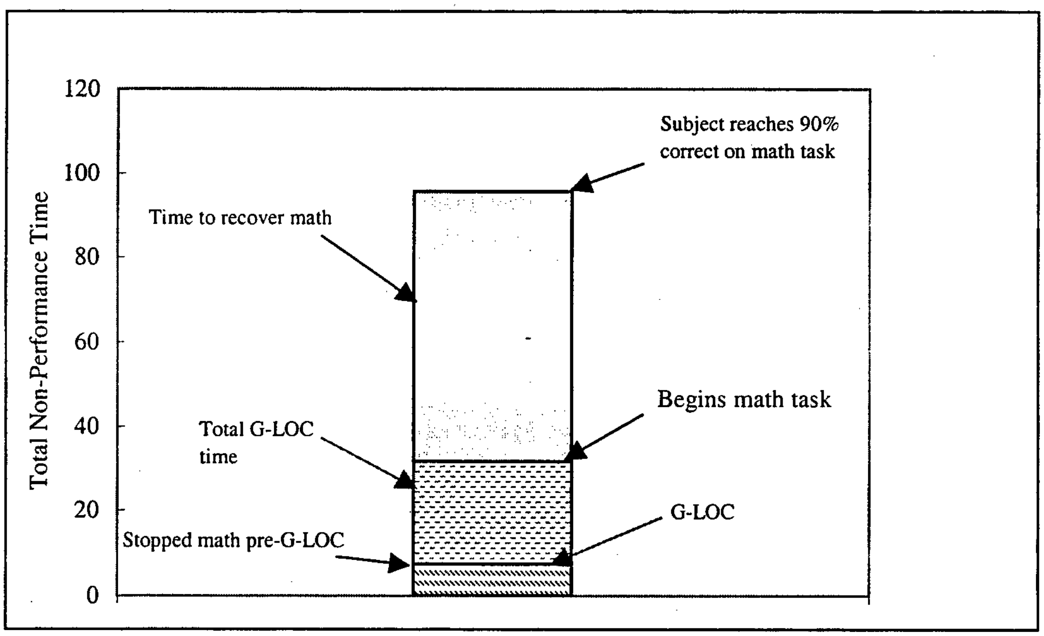

Figure 18. Mean Total Non-performance Time for Math
n=13

A repeated measures ANOVA was performed revealing no significant difference in the magnitude of the G level required to elicit unconsciousness (F (3, 36) = 0.055, p=0.957). Figure 19 shows the mean $+G_z$ level required to induce G-LOC across the four experimental test days.

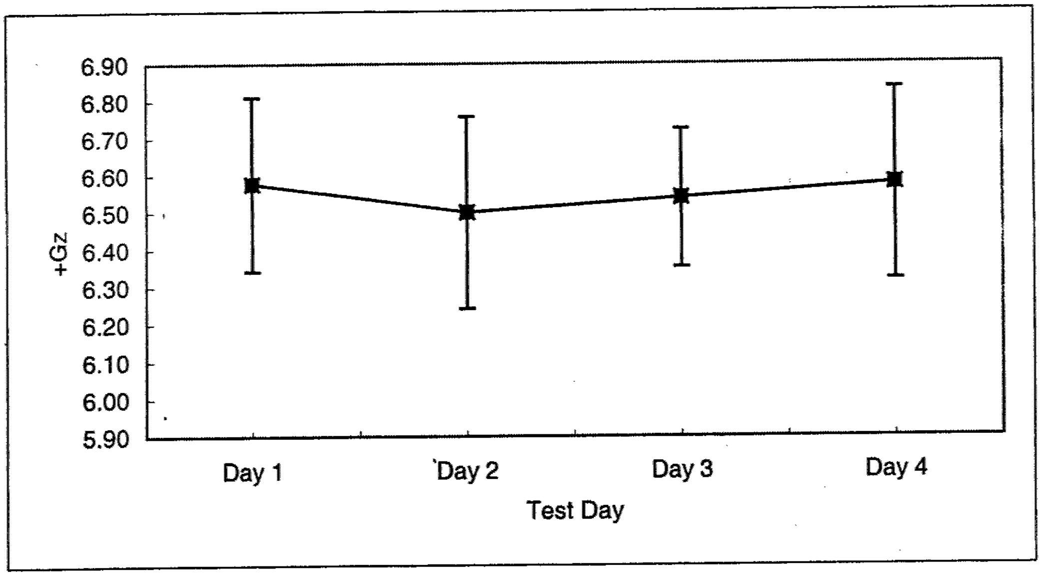

Figure 19. The Mean G_z Level Required to Induce Unconsciousness

DISCUSSION

Recurrent G-LOC

The first focus area to be addressed is the time required to recover from the G_z induced loss of consciousness event. The recovery or incapacitation period has previously been defined by Whinnery and Shaffstall and divided into two phases (36). The first of these phases is the absolute incapacitation period, which starts from the onset of G-LOC and continues until the pilot's eyes are open and the pilot is somewhat confused and disorientated. The second is the relative incapacitation phase, which begins at the point where the pilot opens his/her eyes and can respond to and suppress auditory and visual warning signals. Both the absolute and relative incapacitation phases last for 12 sec, each when the G-LOC event occurs as the result of rapid G onset rates (32, 33, 34). Whinnery and Jones reported that recurrent exposure to G-LOC reduced recovery time an average of 8.5 sec (34). Results from Whinnery's study provided the basis for the recommendation that G-LOC be implemented as a training tool for aircrew by incorporating it into the high-G training syllabus used at centrifuge facilities that provide high-G training to fighter pilots (33).

Whinnery and Burton have formulated a theory as to what may be contributing to the faster recovery during the relative incapacitation period (33). This theory is based on the recognition of symptoms that are associated with the loss of consciousness event. These symptoms are divided into two separate categories, psychologic and physiologic. Psychological symptoms include confusion and disorientation, suppression of G-LOC recognition, unreliability, altered judgment, embarrassment, dissociation, euphoria, anxiety, fear, antagonism, and a give-up attitude. The physiological symptoms include convulsive movements, tingling extremities and face, impaired motor coordination, amnesia, and a dream-like state. It is thought that having had experienced a G-LOC episode that a pilot would become familiar with his/her personal symptoms that are associated with the G-LOC event and that the recognition of those symptoms on a subsequent G-LOC experience would decrease the relative incapacitation period. During this phase of the recovery period is the point at which pilots try to make sense of their world about them. Whinnery likens this process to the hypoxia training that pilots receive in altitude chambers where they are taken to 25,000 feet and taken off oxygen so as to experience their personal symptoms of hypoxia. Experiencing G-LOC, then, would allow an individual to experience the unique symptoms that manifest themselves following a G-LOC event. The concept of post-G-LOC recognition was also alluded to in earlier work by Beckman, Duane, Ziegler, and Hunter when they reported that G-LOC experienced subjects were aware of the confusion after a shorter period of acceleration than were inexperienced subjects (2).

The current study failed to replicate the findings previously reported by Whinnery and associates. No significant decrease in recovery time was observed in the absolute, relative, or total incapacitation time across the four experimental test days. The argument could be made that the current study did not replicate Whinnery's study in which all of the G-LOC events occurred on a single experimental test day. In the current study subjects experienced one G-LOC per week over a four-week time period. This argument could be considered plausible. However, it should be noted that the present study approached the issue of recognition from a more temporal perspective, addressing a more global question concerning the preservation of symptom recognition over a short time span. If G-LOC were to be integrated into a pilot training regiment, one question which may arise, concerns the frequency at which the training would need to be refreshed. In the case of hypoxia refamiliarization training, which is part of the pilots' physiological training requirement, is accomplished once every three years. The present study was unable to discover evidence that familiarization of G-LOC symptoms was carried over to the following week or to the subsequent G-LOC episodes in the weeks that followed.

Performance and the G-LOC Event

The ability to perform the necessary procedures that are required to recover an aircraft following a G-LOC event is paramount in the prevention of an aircraft mishap. The combination of the airspeeds modern aircraft can achieve in combination with a diminution of these skills during a G-LOC episode could result in the loss of life and aircraft. Houghton, McBride, and Hannah carried out a study to examine post-G-LOC performance using a tracking and a math task that involved two-digit arithmetic problems (14). Houghton and his associates found that 3 minutes (180 sec) were required for performance on the math task to return to pre-G-LOC levels. This recovery period together with the 24 sec total incapacitation time of the G-LOC event itself means that a plane flying at 500 mph could cover a distance of approximately 28 miles while the pilot's cognition is impaired.

In the Houghton study, only the math task required a considerable period of time to recover from G-LOC; performance on the tracking task appeared to recover immediately following the relative incapacitation period (14). A result of this sort suggests that cognitive, not motor, functions are subject to impairment after a G-LOC event. It is worth noting, however, that Houghton and his associates assessed performance in relatively long 1-min intervals. It is possible that tracking performance is impaired post-G-LOC but that recovery occurs quickly and that a more fine-grained temporal analysis is necessary to observe it. Given that, the speed of modern tactical aircraft renders even a few seconds of impairment, potentially important. The present study examined post-G-LOC tracking and math in a more temporally detailed manner than that employed in the Houghton et al. study in order to gain a fuller understanding of the effects of G-LOC on pilots' ability to control the aircraft pre- and post-G-LOC (14). Although there were no statistically significant effects across experimental test days for either the tracking or math tasks in both the pre- and post-G-LOC conditions, the total length of time it took for the subject to perform the tasks within 10% of baseline is operationally significant. Results from the present study have shown that our previous assumption that incapacitation begins when the subject is rendered unconscious are false. Data from the current study have shown that the incapacitation period begins prior to the G-LOC event. Subjects stopped performing the tracking task 3.2 ($\pm$0.45 SEM) and the math task 7.8 ($\pm$0.66 SEM) sec prior to the G-LOC event. From the perspective of a pilot who experiences G-LOC in flight, his/her ability to process information for simple tasks stops almost 8 sec prior to the G-LOC event. The significance of this finding is that loss of aircraft control may have started before the G-LOC episode.

Additionally, performance decrements were found post-G-LOC for both the tracking and math tasks. These changes were not statistically significant across experimental test days; however, they are significant in terms of the magnitude of duration. As can be seen in Figure 14, the time required to perform both the math and tracking tasks to within 10% of the pre-G-LOC baseline following the G-LOC event was 64 ($\pm$7.47 SEM) and 47 ($\pm$4.93 SEM) sec, respectively. Historically our concept of incapacitation as it relates to G-LOC has been based primarily on the model developed by Whinnery, which describes 24 sec as the average time of incapacitation.

Data from the present study suggest that perhaps the definition of incapacitation should be altered from one that is based on psychophysiological responses to a performance-based model. This model would include the time period prior to the G-LOC episode that performance on the task is halted, the traditional 24 sec psychophysiological period, and the post-G-LOC task recovery time. Figure 15 is a composite summation of these three incapacitation components plotted separately for the cognitive and tracking tasks and compared to the more traditional definition of G-LOC described by Whinnery and others. This graph also demonstrates the 72-sec increase over what had previously been considered the incapacitation period. These data bring into focus that the G-LOC problem may be even more serious than previously thought. The data may provide designers of G-LOC autorecovery systems of the future with the information needed for the decision algorithm as to when to return the aircraft back to the pilot following a G-LOC episode.

CONCLUSIONS

There were no significant decreases observed for the absolute, relative, or total incapacitation recovery times across experimental test days. Repeated G-LOC exposures did not enhance subject recognition of G-LOC, thus reducing the total incapacitation recovery time as had been previously reported. Both the cognitive and tracking tasks were halted by the participants prior to the G-LOC event.

Both the cognitive and tracking tasks did not recover immediately following the G-LOC episode; each taking 72 and 51 sec, respectively, before the participant could perform each task to within 10% of the pre-G-LOC baseline. These findings indicate that G-LOC is more insidious than originally thought. Total incapacitation time and cognitive performance are seriously affected by G-LOC.

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