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**+Gz Acceleration Loss of Consciousness: Time Course of Performance Deficits
With Repeated Experience**

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+Gz Acceleration Loss of Consciousness: Time Course of Performance Deficits With Repeated Experience

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ABSTRACT

Pilots of modern fighter aircraft encounter episodes of gravity-induced loss of consciousness (GLOC) consisting of complete unconsciousness and subsequent confusion. According to Whinnery, Burton, Boll, and Eddy (1987), pilots are totally incapacitated for 24 sec during such episodes. Current solutions to eliminate the GLOC hazard, including breathing and straining routines, anti-gravity pressure suits (G-suits), and reclined seatback angles, have proven not to be completely effective (Burton, Cohen, & Guedry, 1988; Tripp, 1990). It is conceivable, however, that with experience, pilots can learn to overcome the confusion and disorientation associated with GLOC and thereby, shorten the incapacitation time. Fourteen active duty members of the USAF (five women and nine men) participated in the study, conducted at the Air Force Research Laboratory's centrifuge facilities at Brooks and Wright Patterson Air Force Bases. Rapid G-onset rates of +3Gz/sec were used to induce GLOC in the participants on each of four testing days spaced one week apart. On each day, participants performed a compensatory-tracking task and a serial addition-subtraction math task concurrently for 5 min in a stationary centrifuge to provide baseline performance indices. They were also required to perform these tasks concurrently for as long as possible during +G-exposure and for 5 min following recovery from unconsciousness. The principal investigator and a flight surgeon, using real-time video images of participants and a protocol established by Whinnery et al. (1987), determined participants' entry and exit from GLOC. This study confirms the duration of total incapacitation described by Whinnery et al. (1987). It also indicates that the GLOC problem is more serious than they envisioned. Performance efficiency deteriorates from 3.20 to 7.44 sec *prior* to the onset of unconsciousness and does not return to baseline levels until 55.5 sec after the confusion phase has ended. Thus, at speeds of 500 mph typical of modern fighters, pilots can travel 12.1 miles while not in control of their aircraft. These effects do not appear to be reduced by repeated encounters with GLOC.

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CHAPTER 1

Introduction

The Challenge of High Performance Aircraft

A Plethora of Physiological Threats. The evolution of high performance combat aircraft has resulted in the imposition upon pilots of an ever-increasing amount of physiological stress stemming from noise, vibration, thermal extremes, hypoxia, spatial disorientation, and gravity induced loss of consciousness (GLOC). The most fatal of these are hypoxia, spatial disorientation, and GLOC. The latter is the focus of this investigation.

G-induced loss of consciousness has been defined by Burton (1988) as a “state of altered perception wherein one’s awareness of reality is absent as a result of a sudden critical reduction of cerebral blood circulation caused by increased G-force.” This phenomenon is not of recent origin. It was first noted in 1903 when Sir Hiram S. Maxim’s Chief Engineer lapsed into unconsciousness while riding Maxim’s “captive flying machine” at Crystal Palace Park outside London (Clark, Hardy, & Crosbie, 1961). The threat of GLOC became even more evident with the introduction of the first fighter aircraft in World War I and was clearly a problem with succeeding generations of fighter aircraft during World War II (DeHart, 1999). The extent of this problem is exacerbated in modern tactical (fighter) aircraft whose speed and maneuverability produce higher accelerations (G) than ever before.

The GLOC Hazard. G-induced alterations of consciousness while maneuvering modern tactical aircraft have been implicated in a substantial number of mishaps involving losses of planes and crew. Reviews of GLOC episodes among U.S. Air Force (USAF) pilots found that between 1982 and 1990, 22 fatal crashes could be attributed directly to GLOC (Albery & Van Patten, 1991; Lyons, Harding, Freeman, & Oakley, 1992). An earlier study devoted to USAF

pilot training estimated 1.7 episodes of GLOC per month in any given flight class (Whinnery, 1986) and CHI Systems (2000) has reported that if a student pilot experiences an in-flight GLOC event, there is a 33% chance that a fatality and/or loss of aircraft will result. The actual occurrences of GLOC among experienced and novice pilots may be even higher than indicated above (CHI Systems, 2000). If a GLOC event does not result in damage to either aircraft or pilot, it may go unreported, especially if negative consequences, like additional GLOC training or loss of flight status, result from such reports. It is also known that amnesia is associated with GLOC incidents. Memory loss may lead to an underestimate of the actual occurrences of GLOC since 50 percent of participants who experience GLOC during simulated flight on a centrifuge do not recall the event (Glaister, 1988). These results underscore the need to learn more about the effects of GLOC upon pilot performance and to discover practical and cost-effective countermeasures that may greatly reduce the mishap rate due to GLOC.

A Closer Look at GLOC

The Nature of Gravitational Force. G may be thought of as a force or thrust against a body induced by gravity. On the ground, gravity causes a static body to have a weight equal to one unit of gravitational force, or one G, measured in terms of the thrust of the body against the ground (USN Flight Surgeon's Guide, 1991). When an elevator, car, or airplane accelerates, slows down, or changes direction, occupants experience the effects of their body's resistance to the applied force or G (Burton & Whinnery, 1999).

In order to comprehend the effects of acceleration forces on pilots, it is necessary to understand that such forces can occur in six different directions (USAF Flight Surgeon's Guide, 2001). These directions are illustrated in Figure 1.

Figure 1. Direction of G-forces Experienced During Flight. (After USAF Flight Surgeon's Guide 2001.)

The symbol G_z is used to characterize gravitational forces acting along a mid-body axis. *Positive acceleration* occurs when a plane engages in a steep climb or enters a high-speed turn. The aircraft changes direction in such a way that the pilot tends to be forced into his/her seat along a *downward* vector. There will be a sensation of increased weight, and if the pilot were on scales, he/she would register more than their usual weight. The notation used to describe this acceleration direction is positive (+) G_z because the direction of gravitational force in a climb and centrifugal force in a turn is in the direction from head to foot. *Negative acceleration* occurs when a plane drops vertically towards the ground, as might occur when it encounters an air pocket and loses altitude. In this case, the aircraft changes direction in such a way that the pilot tends to be forced out of his/her seat along an *upward* vector. There may be a sensation of weightlessness, and if the pilot were on scales, he/she would register less than their usual weight. The notation used to describe this acceleration vector is negative (-) G_z because the direction of gravitational force is from the feet toward the pilot's head.

The symbol G_x is used to characterize gravitational forces acting along the body's medial or sagittal plane as the result of sudden changes in speed of linear motion. Acceleration in the chest-to-back direction is termed Positive (+) G_x . It is experienced by astronauts during rocket launches, by pilots catapulted from the deck of aircraft carriers, and it is also experienced by drivers when rapidly increasing the forward speed of their vehicles. Acceleration in the back-to-chest direction is termed Negative (-) G_x . It occurs in pilots when a plane is engaged by the barrier net while landing on an aircraft carrier and is experienced by drivers when suddenly decelerating the forward speed of their vehicles.

The symbol G_y is employed to characterize gravitational forces acting along the body's lateral plane that arise from left-to-right or right-to-left displacements of the body. Acceleration in the left-to-right direction is termed Positive (+) G_y , while that in the opposite direction is denoted as Negative (-) G_y . Pilots experience these accelerations when a plane encounters strong winds or air currents that produce a sheering action upon the aircraft. Due to aircraft design limitations and fighter tactics, + G_z is the sustained acceleration most typically encountered in military and civilian aircraft (Fong, 1992). It is also the force responsible for GLOC (Burton, Parkhurst, & Leverett 1973).

Effects on the Body. The subjective effects associated with increasing + G_z were described initially by Armstrong and Heim (1938) and by Gauer (1950) and have been portrayed more recently by Burton and Whinnery (1999). As acceleration increases the gravitational force exerted on the pilot from 1 + G_z to 2 + G_z , there is an awareness of increased pressure and a general feeling of heaviness in the seat, hands, and feet. Increases to 3 and 4 + G_z intensify these sensations. In addition, movement of the extremities becomes difficult, pilots lose the ability to keep the head and trunk erect, and there is a dimming of the visual field and/or a loss of

peripheral vision. At 5 +Gz pilots, may feel that their legs are swelling. They may also experience muscle cramps and labored breathing along with a complete loss of vision. Total loss of consciousness (GLOC) typically occurs at 6 +Gz or beyond.

The principal physiological basis for GLOC is the reduction of cerebral perfusion resulting from a differential blood pressure gradient (the hydrostatic column effect) that exists between the heart and the brain within the +Gz force field (Burton & Whinnery, 1999). This gradient is illustrated in Figure 2.

Figure 2. The hydrostatic column effect illustrating the result of increasing sustained acceleration on eye-level cerebral blood pressure. The analogy of increasing +Gz is lengthening the distance between the eye and the heart. (After Fong, 1992.)

As the level of +Gz increases, blood pressure to the brain is decreased. The systolic arterial blood pressure under normal 1 +Gz is approximately 120 mm Hg. If one measures

systolic blood pressure in the brain from arteries located at eye-level (30 cm above the heart), approximately 98 mmHg of systolic pressure is available for cerebral perfusion. For each additional 1 +Gz increase, there is a 22 mm Hg reduction in brain blood pressure at eye-level. Theoretically, this would result in zero blood pressure in eye-level brain arteries at 5.5 +Gz and negative blood pressure and hypoxia at higher +Gz levels (Gauer, 1950; Gauer & Zuidema, 1961; Gillingham & Fosdick, 1988; Wood, 1990). The decrease in blood pressure with increased +Gz leads to hypo-perfusion of the cerebral tissue, reduced cerebral oxygen saturation, and to consequent GLOC (Burton, 1988; Howard, 1965; Whinnery, 1989; Whinnery, Burton, Boll, & Eddy, 1987).

Additionally, as +Gz is increased, blood also pools in the capacitance vessels (large veins in the legs and abdomen) which leads to decreased blood return to the heart and to subsequent reductions in the blood supply to the brain and to a reduced degree of cerebral tissue perfusion. In turn, this leads to reduced levels of cerebral oxygen saturation. Therefore, venous pooling provides an additional cardiovascular pathway for the development of GLOC (Tripp, Chelette, Savul, & Widman, 1998; Tripp, Jennings, Seaworth, Howell, & Goodyear, 1994; Werchan, 1991).

As a result of unconsciousness, a pilot experiencing GLOC typically releases the flight controls and the aircraft's rate of climb or turn becomes less severe. This reduces the +Gz force exerted upon the pilot. In turn, that reduction permits a resurrection of cerebral blood flow and a return to consciousness (Forster & Cammarota, 1993; Wood, 1990).

Stages of GLOC. In a landmark study, Whinnery et al. (1987) noted that GLOC not only involves unconsciousness but also a subsequent period of confusion. As a result, they characterized the GLOC experience as consisting of two phases: an *absolute incapacitation*

phase, defined as the period from the onset of unconsciousness (eyes closed, upper body muscles relaxed) to a point when the subject awakens (eyes open), and a *relative incapacitation phase*, featuring confusion and disorientation following the return of consciousness. The second phase was considered to terminate when the observer regained control of the aircraft as indexed by the ability to depress a single stop switch to extinguish a master caution light and a warning tone.

The phases of GLOC are illustrated in Figure 3.

Figure 3. The phases of GLOC. The horn and light symbolize warning signals to which observers must react. (After Whinnery et al. 1987.)

In their characterization of GLOC, Whinnery and his associates (1987) suggested that each of the two phases lasts for about 12 sec, resulting in a 24-sec period of total incapacitation (absolute plus relative incapacitation). Experiments by Houghton, McBride, and Hannah (1985) and by Whinnery and Whinnery (1990) have supported these values. Given the capability of modern tactical fighters to achieve speeds of 500 mph or 733 feet/sec (Burton, 1988), Whinnery et al.'s (1987) estimate of the duration of a GLOC event means that these aircraft could cover

17,592 feet or 3.3 miles while the pilot is totally incapacitated under GLOC. The probability of a serious mishap under such conditions is obvious.

Expanding the GLOC Window

Post-GLOC Performance. A central feature of Whinnery et al.'s (1987) characterization of the GLOC event is the assumption that flight performance would return to pre-GLOC levels immediately at the end of the 12-sec relative incapacitation phase that marks the termination of the 24-sec episode. There is reason to believe, however, that this assumption may be incorrect -- GLOC-based disruptions in pilot efficiency may require a period of recovery that extends beyond the termination of the episode. Thus, Whinnery and his associates may have underestimated the duration of the GLOC-based window of disrupted flight performance and the severity of the GLOC hazard.

In a recent study, Arnold, Tripp, and McCloskey (1995) examined the time needed to recover arterial blood oxygen saturation after exposure to hypoxia. They found that 90 sec were needed for arterial blood saturation to return to pre-hypoxic levels. This value suggests that the period of disruption following a GLOC event may be considerably longer than the 24 secs (absolute/relative incapacitation periods) proposed by Whinnery et al. (1987), 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 caution/warning signals.

To date, Houghton et al. (1985) have carried out the only study to examine post-GLOC performance. Their investigation, which preceded the Whinnery et al. (1987) paper, 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 GLOC episode. Houghton and his associates (1985) found that 3 min (180 sec) were required for performance on the math task to return to pre-GLOC levels. This recovery period together with the 24-sec total incapacitation time of the GLOC 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.

The experiment by Houghton and his associates (1985) implies that Whinnery et al. (1987) underestimated the duration of performance disruption following a GLOC event. However, their study is troubled by a problem with the GLOC onset rates that they employed. In either an aircraft or a centrifuge, the rate of acceleration used to reach the critical +G-level needed to produce unconsciousness can be gradual (gradual +G-onset rate; GOR) or rapid (rapid G-onset rate; ROR). Due to an extended time period in the presence of excessive +G force, GOR's produce greater ischemic effects, and therefore, greater levels of hypoxia, than do ROR's (Burton & Whinnery, 1999). Consequently, one might anticipate that performance recovery times would be longer following GLOC events brought about by gradual than by rapid +G-onset rates. Unfortunately, +G-onset rates were confounded in the Houghton et al. (1985) study so that the relative contributions of GOR's and ROR's to the time course of performance disruption following GLOC episodes is difficult to discern. This is an important issue given that pilots of modern high-performance aircraft are far more likely to encounter rapid rather than gradual +G-onset rates, in combat missions (Gillingham & Fosdick, 1988) and that Whinnery et al. (1987) based their estimates of the durations of the relative and absolute incapacity phases of GLOC

events on those produced by ROR exposures. Accordingly, one goal for this study was to examine performance recovery following a rapid G-onset rate. Toward that end, tracking and math tasks similar to those employed by Houghton et al. (1985) were used.

A second aspect of the Houghton et al. (1985) study that also warrants addressing concerns their finding that that only the math task required a considerable period of time to recover from GLOC; performance on the tracking task appeared to recover immediately following the relative incapacitation period. A result of this sort suggests that cognitive but not motor functions are subject to impairment after a GLOC 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-GLOC 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, another goal for the present investigation was to examine post-GLOC tracking in a more temporally detailed manner than that employed in the Houghton et al. experiment. Such information is needed in order to gain a more complete understanding of the effects of GLOC on pilots' ability to control the aircraft post-GLOC.

Pre-GLOC Performance. In addition to the rapid recovery assumption in their characterization of the GLOC episode, Whinnery et al. (1987) also assumed 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 GLOC. However, as was the case with Whinnery et al.'s post-GLOC assumption, there is reason to believe that their pre-GLOC assumption may also be incorrect.

In modern high-performance tactical aircraft such as the F-15 and F-16, climbing and turning maneuvers often result in the sudden application of +Gz forces sufficient to produce a rapid drop in cerebral blood pressure and consequent unconsciousness (Gillingham & Fosdick, 1988). Under such circumstances, however, there are approximately 5 to 7 seconds when pilots can perform their flight tasks before brain tissue oxygen reserves become depleted to the point at which unconsciousness sets in (Gillingham, 1988; Wood, 1990). Research has indicated that observers undergoing hypoxia are subject to mental blocks and to a general slowing of reaction time and early information processing, as well as to a deterioration of sensory functions (dark adaptation), cognitive functions including working memory (concentration, verbal and visual memory, target acquisition), and motor skills (complex psychomotor performance); (Bouquet, Gardette, Gortan, & Abraini, 1999; Chelette, Albery, Esken, & Tripp, 1998; Fowler, Elcombe, Kelso, & Porlier, 1987; Fowler, Banner, & Pogue, 1993; Fowler & Nahthoo, 1997; Fowler & Prlic, 1995; Kobrick, Zwick, Witt, & Devine, 1984; Lindeis, Nathool, & Fowler, 1996; McCarthy, Corban, Legg, & Faris, 1995; Noble, Jones, & Davis, 1993; Sells & Berry 1961). Of particular relevance for the present investigation are studies indicating that early information processing and working memory functions are suppressed by the hypoxia inherent in GLOC (Burton, 1988; Howard, 1965; Whinnery, 1987; Whinnery, et al. 1987) and by studies indicating the types of performance tasks to be employed herein, arithmetic and complex tracking, are severely impaired by hypoxia. For example, Vaernes, Owe, and Myking (1984) have reported a 19 per cent decline in accuracy on an arithmetic computation task when performed under hypoxia while Sausen et al. (2001) have shown that tracking error increases by approximately 200 per cent when participants are rendered hypoxic. Consequently, it is conceivable that flight

skills, as reflected in performance on the math and tracking tasks to be employed in this study, will deteriorate during the 5 to 7 sec period *before* unconsciousness occurs in a GLOC episode, a result that would exacerbate the GLOC hazard. Accordingly, a third goal for the present investigation was to explore that possibility.

Solutions to the GLOC Problem

Breathing, Dressing, and Positioning. Given the potential for aircraft mishaps to result from GLOC, the development of techniques to prevent this hazard or to lessen its severity is imperative (Gillingham & Fosdick, 1988; Wood, 1990). A combination of approaches involving muscle tension and assisted breathing, anti-G clothing, and pilot positioning has been employed for that purpose. The first of these is the anti-G straining maneuver (AGSM), in which pilots are taught to combine whole body muscle tensing with a modified breathing technique to elevate cerebral blood pressure and increase G-tolerance. The maneuver is based on work conducted by Strainforth more than half a century ago indicating that tensing the abdominal and leg muscles could raise G-tolerance by 2 G's (NATO Advisory Group for Aerospace Research and Development, 1990). As currently practiced, the AGSM involves rigorous tensing of muscles in the abdomen, chest, and limbs to prevent venous pooling and to promote cardiac blood return. The AGSM also includes a cyclic breathing technique to increase blood pressure in the thoracic cavity that, in turn, increases cerebral blood pressure.

The breathing technique followed in the AGSM requires a pilot to alternately breathe in for 0.5 sec and breathe out for 2.5 sec. A problem with this procedure is that if done improperly, it has an adverse effect on the amount of air that is exchanged in the lungs during the inspiration and expiration phases of the maneuver. This leads to a drop in intrathoracic air pressure and consequently to a drop in cerebral blood pressure. Thus, if done incorrectly, the AGSM breathing

technique is self-defeating. One way to counter this problem is with the addition of assisted positive pressure breathing at high +Gz. Toward that end, The U.S. Air force has implemented a helmet oxygen mask system called the Combined Advanced Technology Enhanced Design G-Ensemble (COMBAT EDGE) to be used by all aircrew flying high performance fighter aircraft. The COMBAT EDGE ensemble is illustrated in Figure 4.

As can be seen in the figure, the system consists of several components including an oxygen mask, external counter pressure vest, mask tensioning bladder, oxygen regulator, G-valve, integrated terminal block, and pressure sensor line. These components act in unison to sense and respond to high +Gz conditions. When such conditions are detected, the system increases the pressure of the oxygen enriched air that the pilot breathes through

Figure 4. COMBAT EDGE G-protection ensemble and anti-G suit.
(Adopted from Tripp, 1990.)

the mask up to a maximum of 1.2 psi above the ambient pressure in the mask. It also inflates the counter pressure vest that applies pressure to the pilot's chest. This counter-pressure prevents forced expansion of the chest cavity resulting from high altitude. By retaining the air pressure in the pilot's chest cavity, COMBAT EDGE reduces the work of breathing in a high +Gz environment and assists the heart in pumping blood to the eyes and brain. While COMBAT EDGE does not replace the straining maneuver of tensing body muscles during high +Gz loads, it significantly reduces the effort required to execute that routine, thus providing the pilot greater endurance to +Gz while reducing the fatigue that can compromise mission performance.

Along with muscle tension and assisted breathing, the anti-G suit, also illustrated in Figure 4, is a vital component of G-protection systems in high performance aircraft. It is used to help prevent pilots from losing consciousness, or "blacking out," under high +Gz conditions. A G-suit resembles a pair of cowboy chaparejos (chaps) that fit snugly around the lower abdomen and legs. Air bladders sewn into the suit's fabric inflate proportionately with increases in G above 2 +Gz. The inflated G-suit tightens about the pilot's lower body and legs to prevent the cephalocaudal drain of blood that causes loss of eye level blood pressure and partial or full blackouts. As the +G-force falls, the suit deflates proportionately until pressure in the suit is totally dissipated at 2 +Gz or below.

It is important to note that while the AGSM, COMBAT EDGE, and G-suit approaches can provide pilots with G-protection they are far from perfect and they do not always prevent pilots from losing consciousness in high +Gz environments (Burton, Cohen, & Guedry, 1988; Harding & Bomar, 1990; Tripp, 1990). As a further vehicle for G-protection, aircraft designers have advanced the strategy of having the pilot lie in a supine position in the cockpit. The logic for this strategy is that it would minimize the hydrostatic column effect which leads to hypoxia

and unconsciousness. Data are available to indicate that a supine position does enhance +G-tolerance (Gell & Hunter, 1954; Martin & Henry, 1950). However, supination has two major drawbacks; it increases G in the G_x (chest to back) vector making it difficult for the pilot to breathe (Stauffer, 1949) and it decreases the pilot's out-of-cockpit visibility and situational awareness (Von Beckh, 1972; 1981).

GLOC Adaptation. At this point, it is clear that current physiological/engineering solutions are not able to eliminate the GLOC hazard. It is possible, however, that a human factors solution, anchored in perceptual adaptation, may serve to minimize the negative consequences of GLOC. As Whinnery and Burton (1987) have noted, techniques to decrease the time that a pilot is incapacitated during a GLOC episode would reduce the time that an aircraft is out of control and ineffective as a weapon system.

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 (Doelzal, 1982; Harris, 1965; Rock, 1966; Welch, 1986). This research dates back to the classic work of Helmholtz (1866/1962), Stratton, (1897a; 1897b), and Kohler (1962; 1964) who described the ability of observers to adjust to prism-based optical rearrangements of the visual environment and to come to perceive and act veridically in the face of these distortions. Later research has shown that such adjustment not only extends to displacements in spatial location but to distortions in target form and size as well (Rock, 1966; Welch, 1986). 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 (Luria & Kinney, 1970; Ono & O'Reilly, 1971), apparent curvature (Ross, 1970), and illusory motion (Ferris, 1972) that occur underwater, and to the debilitating effects produced by time-delayed visual feedback on perceptual-motor

performance in virtual environments (Nelson et al., 1998). Of particular relevance to the GLOC problem are studies demonstrating sensory-motor adaptation to aberrations that appear in the microgravity conditions of parabolic and orbital flight (Lackner & DiZio, 1993). It is conceivable, therefore, that with experience pilots can learn to overcome the confusion and disorientation associated with a GLOC episode and, thereby, shorten the time that they are incapacitated. This possibility has been recognized by Whinnery and his associates (Whinnery & Burton, 1987; Whinnery & Jones, 1987) who noted while reviewing tapes of GLOC episodes in four participants that the period of relative incapacitation tended to grow shorter with repeated GLOC exposure. To date, however, no systematic experimental effort has been devoted to examining adaptation to GLOC. Accordingly, a final goal for this study was to provide that effort with reference not only to the relative incapacitation phase of the GLOC episode itself, but also to possible performance decrements that may proceed unconsciousness, and to the time needed to return to baseline levels of performance after the relative incapacitation phase had passed.

CHAPTER 2

Method

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. Military ranks from Airman to Major were represented in the sample. 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, the 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. None of the participants had prior experience with GLOC. Participants were fully briefed about the medical risks associated with this study (see Appendix B).

In order to qualify for service in the study, all participants were required to have normal or corrected-to-normal vision and normal vestibular function. Additionally, they had to meet Air Force flying class III medical, height, and weight standards and to have no history of neurological pathology or of having experienced episodes of loss of consciousness due to physical trauma, ill health, and/or surgical procedures. Information about these qualifying factors was obtained from 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 workup. On the basis of this examination, all participants were determined to be in excellent health by a flight surgeon. Female volunteers were not accepted for

participation in the study if they were pregnant because the risks to the developing fetus of acceleration and GLOC are unknown.

Facilities

The study was conducted at the Air Force Research Laboratory's centrifuge facilities at Brooks 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 5a and 5b.

Figure 5a. Dynamic Environment Simulator Centrifuge Wright-Patterson AFB, OH.

Figure 5b. AFRL Centrifuge Brooks AFB, TX.

Although the facilities differed from each other in physical appearance and in size, (the centrifuge at Brooks was smaller than the one at Wright-Patterson) the performance characteristics of the two centrifuges were identical for the purposes of this study. Each was capable of producing +G-forces at the center of the gondola ranging from 1 to 20 +Gz, and because each had a 19 ft radius arm, the acceleration rates needed to achieve given +Gz 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 a fan system that circulated fresh air and helped to maintain the temperature inside the gondola at 70⁰ F. Within

each gondola, the ambient noise level resulting from the operation of the fresh air system and the centrifuge drive system was 90 dB (A). Average ambient illumination of the centrifuge gondola at each facility was 19.3 cd/m². The aircraft seat employed at each facility was an F-16-like ACES II ejection seat with a seat-pan angle of 105⁰ and the seatback reclined at 30⁰ from vertical. As illustrated in Figure 6, 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 GLOC episode.

Figure 6. Aircraft seat facsimile 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 or "hot mike" 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. They wore a standard Air Force issue Nomex® flight suit and a Gentex (Carbondale, PA) HGU-55/P flight helmet without a visor during all GLOC runs. The helmet attenuated the noise level in the gondola by approximately 21

dB (A) and met the requirements for sound attenuation prescribed by Military Standard MIL-E-83425. The absence of a visor maximized the ability of the investigator and flight surgeon to observe participant's facial activity during GLOC (see below).

The gondolas at each facility were outfitted with a simulated fighter cockpit. As can be seen in Figure 6, the cockpit incorporated a pressure sensitive flight stick (Happ Controls, Elk Grove IL, model B6) mounted on the participant's right side that was used to secure responses to the performance tasks to be described below. A viewing screen ($70^{\circ} \times 40^{\circ}$ visual field) was mounted in front of the participant, with the center of the screen located 98 cm from the canthus of the participant's left eye. Stimuli for the performance tasks were projected on the screen. A 10° solid red circle, used when assessing visual field loss under high +G, was also projected onto the viewing screen. At each testing facility, *continuous real-time surveillance* of participants was afforded during each run by two closed-circuit infrared television cameras (Panasonic CCTV model WV-CD810). The images were observed by study personnel (test director, flight surgeon, and principal investigator) housed in a control room. The cameras provided a close-up view of the participant's head and a wide-angle view of the participant from head to foot. A video mixer (Pelco model QD 104C, Clovis, CA) was used to generate a composite picture of the two views of the participant along with the time, date, and +Gz acceleration in a given run. At both facilities, video data were stored on 1/2 inch VHS videotape for later analysis; TELEX (Minneapolis MN) model P1000 video projection systems were used to present the stimuli for the performance tasks and the image for assessing visual field loss. Identical computer systems at each facility (developed by the Air Force Research Laboratory) orchestrated stimulus presentations and stored the participants' responses to the performance tasks.

Acceleration Profiles

Computer control systems at each facility were used to generate two acceleration profiles in the sessions in which participants experienced GLOC. The first was a gradual G-onset rate (GOR) of 0.1 +Gz/sec or an increase in +G of +1Gz every 10 seconds. This profile was employed to establish the participant's relaxed +G-tolerance level (the +G-level at which eye-level blood pressure could no longer be maintained) on a given test day. As the centrifuge was slowly accelerated, participants were asked to view the solid red circle as it appeared on a uniform white background. They were instructed to execute an AGSM when the visual field blackened out and all that could be seen was the circle, i.e., central light loss (CLL) occurred. The test director aborted the acceleration profile upon observing the participant executing the AGSM, using the real-time images of the participant in the centrifuge. 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 +3Gz/sec or an increase of +3Gz every second to a pre-established target level at which the participant was rendered unconscious. That level was set *individually* for each participant on *each* testing day. It was reached by adding 1 +Gz to the GOR_{max} . To maximize the likelihood of inducing unconsciousness, participants were not equipped with G-suits and were instructed to refrain from performing the anti-G straining maneuver. Using the real-time images of the participant, the principal investigator terminated the ROR profile when GLOC occurred. The presence of GLOC was determined using the Whinnery et al. (1987) criteria that include the following signs: (1) dual eye closure, (2) slumping of the head and upper body, (3) jaw muscle relaxation evidenced by a gaping mouth. *All three signs* needed to be present in the real-time surveillance images of the participant in order to determine that the participant had gone into

GLOC and the principal investigator and the flight surgeon had to be in *total agreement* in order to make the call. Figure 7 shows a participant undergoing the absolute incapacitation period of a GLOC episode. Notice that the participant has released his grip on the flight stick (right hand) while in the unconscious phase.

Figure 7. A participant exhibiting the signs of unconsciousness during GLOC including eye closure, slumping of the head and upper-body, and jaw muscles relaxed.

Following the protocol developed by Whinnery et al. (1987), participants were considered to have regained consciousness when they reopened their eyes. The principal investigator in *complete agreement* with the flight surgeon judged the point in time when this occurred using real-time observation of the participant. Again following the Whinnery et al. (1987) protocol, participants were considered to have entered the relative incapacitation phase immediately upon the principal investigator/flight surgeon's decision that they had returned to consciousness. During the relative incapacitation phase, participants were typically confused and disoriented and unable to engage the performance tasks that were assigned to them. Based upon

the real-time surveillance images, the principal investigator *in complete agreement* with the flight surgeon determined that the relative incapacitation phase of a GLOC event had ended when a participant was able to use the flight stick to jointly manipulate *both* axes of the tracking task that composed one aspect of the performance battery (see below).

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. The task is illustrated in Figure 8.

Figure 8. Compensatory tracking and math tasks.

Participants performed the tracking task by using the flight stick to align the *intersection* of a moving reticle composed of white horizontal (72.5cm long x 0.4 cm thick) and vertical (51.5cm long x 0.4 cm thick) crosshairs with the *center point* of a *fixed* target composed of crossing horizontal and vertical arms. The elements comprising the target were four elongated open rectangles arrayed about a smaller open rectangle all formed by 0.4 cm green lines. The two rectangles comprising the horizontal arms of the target (32.25 cm long and 1 cm thick) were each

separated from the centering rectangle (5 cm wide and 3cm tall) by 1.5 cm. Thus, the entire horizontal or x-axis of the target was 72.5 cm. The two rectangles comprising the vertical arms of the target (22.75 cm long and 1 cm thick) were also separated from the centering rectangle by 1.5 cm. Thus, the entire vertical or y-axis of the target was 53.5 cm.

The target was centered in the middle of an otherwise black projection screen. The horizontal component of the moving reticle was positioned up and down along the y-axis of the target, while the vertical component of the moving reticle was positioned to the left and right along the x-axis of the target. Positioning of the moving lines was accomplished by three independent force functions composed of three sine waves (1/3, 1/7, and 1/11 Hz). The maximum displacements of the horizontal component of the moving reticle were the top and bottom edges of the upper and lower arms of the target, respectively, while the maximum displacements of the vertical component of the moving reticle were the furthest left edge and the furthest right edge of the left and right arms of the target, respectively. The dual forcing functions made the tracking task difficult.

In addition to the tracking task, participants were required to perform a computation task designed by Shingledecker (1984) to tap the higher-order cognitive skills needed by fighter pilots to navigate their aircraft. The task involved a series of addition and subtraction problems featuring paired white digits (0.7 cm x 2.1 cm) from 1 to 9 (e.g. 3 + 5; 8-1). Duplicate pairings (e.g., 3+3; 8-8) were included. 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 118 problems, 77 summations and 41 subtractions. Problems were exposed until the participant responded or until a 2.5 sec solution

window elapsed. A new problem appeared *immediately* after each response and/or after the closing of a solution window. Participants were instructed to respond as quickly and as accurately as possible. The order in which participants experienced the computational problems was determined on the basis of a process that iterated the presentation of all of the problems within the ensemble at random without replacement over continuous sets of 118 presentations throughout any given session. For each participant, different random orders were used with all sets in a session. Moreover, the orders differed across all participants throughout all phases of the experiment. The phases encompassed training and pre-GLOC (baseline) and post-GLOC (recovery) testing.

As illustrated in Figure 8, the stimuli for the computation task were presented at the center of the viewing screen 2.6 cm below the bottom edge of the lower arm of the tracking target. 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.

In all phases of the study, tracking performance was sampled *16 times per sec* (16 Hz) *over a 5-min interval*. For each sample, the difference in the locations of the intersection of the moving reticule and the center point of the fixed target was expressed in terms of a vector error, V ,² according to the formula:

$$V^2 = (X)^2 + (Y)^2 \quad [1]$$

where X^2 was the square of the *difference in pixel units* between the location of the intersection of the moving reticule and the center point of the of the target in terms of the x-axis of the target, and Y^2 was the square the *difference in pixel units* between the location of the intersection of the moving reticule and the center point of the target in terms of the y-axis of the target. The overall

error in tracking (Schmidt & Lee, 1999) was expressed in terms of the root mean square of the vector errors determined for successive *1-sec* segments of tracking performance during the 5-min testing interval by the formula:

$$\text{RMS}_{v^2 \text{ 1-sec}} = \sqrt{\frac{\sum V^2}{N}} \quad [2]$$

Where $\sum V^2$ is the sum of the vector errors across the 16 samples of a given 1-sec time interval and $N = 16$. The RMS error values in this study could range from 0 to 566 pixel units.

Performance on the math task was also sampled in *5-min* intervals during all phases of the study. The percentage of correct responses per interval was determined by the formula:

$$\text{PC}_{5\text{min}} = \text{TC}/\text{TA} \times 100 \quad [3]$$

where TC was the total number of problems solved correctly during the interval and TA was the total number of problems attempted. Note that with a 2.5 sec solution window, the *minimum* number of problems presented per 5-min was 120.

Training Procedure

Participants at each facility were trained on the performance tasks prior to engaging in the GLOC phase of study using the dual-task conditions that they would later encounter during that phase. At each facility, training was conducted in the gondola of the centrifuge while it was immobile, i.e., training was accomplished under static conditions. Participants were not required to wear flight gear during training. Training sessions were conducted for 10 min per day (two successive 5 min intervals) twice weekly until the participant met the following pre-established dual performance criteria: (1) the standard deviations of the RMS tracking scores over the 10 min (600 sec) of training were within 10% of each other on *two consecutive days* and (2) the percentage of correct responses across the 10-min of training equaled or exceeded 90% of a minimum number of 240 problems attempted on the same two consecutive days. The number of

training days required by the participants to meet this training criterion ranged from 4 to 10 with a mean of 4.7 days. Upon completing training, participants were given an opportunity to engage in the tasks for 30 sec in ROR +4Gz and ROR +5Gz environments to familiarize themselves with performance under high +Gz. Both +Gz levels were experienced in each of two familiarization sessions that took place within the same week. The lower +Gz level was experienced first within each session. During the familiarization sessions, participants were provided with G-suits and encouraged to engage in anti-G straining maneuvers to minimize the possibility of GLOC. No participant was rendered unconscious during the familiarization sessions.

GLOC Testing Procedure

Participants experienced GLOC one day per week over a period of four successive weeks. Upon arrival at the laboratory on a GLOC day, they were given a brief medical examination by the flight surgeon and were fitted with EKG and EEG leads and with cerebral tissue oxygen and arterial oxygen sensors. They were then seated in the gondola of the centrifuge in full flight gear and the operation of the physiological indicators was verified. While seated in the immobile centrifuge, participants performed the dual tracking and math tasks for 5 min to provide *a daily baseline* against which post-GLOC performance could be compared on an individual daily basis for each participant. Following the baseline period, participants' GOR_{max} level was determined (see above) and they were then permitted to rest for 6 min. The GLOC run was initiated immediately after the conclusion of the rest period. It began with participants engaging in the performance tasks while the centrifuge was rotated at 1.4 +Gz. After 15 sec at this +Gz level, the ROR profile commenced (see above) and remained in force until GLOC occurred and the centrifuge was stopped. Participants were instructed to re-engage the

performance tasks *as soon as possible* after returning to consciousness during a GLOC event.

They were also required to perform the tracking and math tasks with the centrifuge immobilized for an additional 5 min after the principal investigator and the flight surgeon had concurred that the relative incapacitation phase of the GLOC event had ended.

A post-GLOC medical exam was given to participants by the flight surgeon immediately following each test run and the participants completed a post-GLOC questionnaire regarding any physical symptoms that they might have experienced as a result of the GLOC event. In addition, they were required to return to the laboratory within 24 hours after a run to engage the performance battery for 10 min in a static centrifuge. No untoward events were uncovered by the post-GLOC medical exam and/or the post-GLOC symptom questionnaire or by performance assessment in any of the participants in the study.

CHAPTER 3

Results

Preliminary inspection of the data from the two testing sites indicated that the results from both sites were similar in regard to the durations of the GLOC phases and scores on the tracking and math tasks. Therefore, site was not used as a between sample factor for any analyses. Technical difficulties prevented two participants, one from each site, from completing one of the test runs to which they were exposed. Due to restrictions established by the Institutional Review Board of the Air Force Surgeon General's Office in the number of GLOC episodes that participants could experience in this experiment (limit = 4), missing test runs could not be made up. Accordingly, all of the data analyses are based upon a total of 13 participants.

GLOC Phase Durations

The mean amount of time in which participants were in the absolute incapacitation (unconscious) and the relative incapacitation (awake but confused) phases of GLOC are plotted as a function of testing days in Figure 9.

Figure 9. Absolute and relative incapacitation phases over the four test days. Error bars are standard errors.

It is evident in the figure that repeated exposure to GLOC had little effect upon the length of the absolute incapacitation phase; the duration of that phase remained stable across the four testing days with a mean of 11.44 sec. While the average length across days of the relative incapacitation portion of GLOC was similar to that of the absolute incapacitation phase, $M=12.76$ sec, the figure suggests that the amount of time in which participants were relatively incapacitated tended initially to be longer than the time that they were absolutely incapacitated and that the duration of relative incapacitation tended to shorten with successive exposures to GLOC over the first three testing days.

These impressions, however, were not confirmed by an analysis of variance (ANOVA) of the GLOC-duration data. The analysis indicated that the two GLOC phases did not differ significantly in overall duration, $F(1, 12) = 1.39, p > .05$, that there was no overall effect of repeated GLOC exposures, $F(2, 25) = 2.45, p > .05$ and that the Phase x Day interaction was not statistically significant, $F(2, 27) = 2.74, p > .05$. Complete summaries of this and all subsequent ANOVA's are presented in Appendix A. In all analyses, Box's epsilon was employed when appropriate to correct for violations of the sphericity assumption with repeated measures (Maxwell & Delaney, 1990).

Given that the effect of repeated GLOC exposure was a central aspect of this study, the global tendency revealed in Figure 9 for a reduction in the duration of the relative incapacitation phase over testing days was explored more closely on an individual participant basis. Figure 10 presents plots of the duration of relative incapacitation over days for each of the participants in the study. Only two of them (S5, S12) showed a shortening of time spent in the relative incapacitation phase over the four testing days. For the majority of participants, the durations of both phases of

the GLOC episodes were stable over days. All in all, it seems clear that repeated exposure to GLOC had no effect upon the durations of the phases of the GLOC episodes in this study.

Figure 10. Absolute and relative incapacitation times for each participant on each test day.

Post-GLOC Performance

The Moving Window Strategy. The two performance tasks used in this study reflected fine motor control and higher-order cognitive function. Consequently, scoring was necessarily different for each task. However, in order to provide a direct fine-grained comparison of the time needed to recover performance efficiency following GLOC on these tasks, it was necessary to convert the scores on the two tasks to a common scale. Toward that end, a “moving window” strategy was employed to determine the time in *sec*, after the termination of the relative incapacity phase of GLOC, when a participant’s performance efficiency on each task returned to a level that was within the upper 110% (or the “upper bound”) of the central tendency of that participant’s performance on the tasks during the baseline period on a given testing day.

The Tracking Task Window. For the tracking task, the geometric mean of the participant's RMS error scores across the 240 1-sec intervals of the final four minutes of the baseline period of each test day was used as the performance standard for *that* day. The geometric mean was employed to normalize the data, which were positively skewed. For representational purposes, the means and standard deviations (in parentheses) of these baseline values across participants (in pixels) for testing days 1 through 4 were 109.72 (50.47), 103.05 (46.4), 101.05 (46.14), and 87.30 (30.76) respectively. To compare a participant's post-GLOC performance against these daily standards, the geometric mean was initially determined for the 30-sec window from 1-30 sec after GLOC on a given test day. If (a) this value fit within the 110% upper bound of the baseline standard for that day (the upper limit to which participants were trained), and (b) if the RMS error for the first 1-sec interval within the window *also* fit within the 110% upper bound of the baseline standard the participant's performance was considered to have returned to the baseline level within 1-sec post GLOC. If any one of these criteria was not met, the time window from 2-31 sec post-GLOC was then examined and this procedure was iterated serially (i.e. 3-32 sec; 4-33 sec; 5-34 sec...271-300 sec) until a 30-sec window was found in which the dual criteria were fulfilled. The initial interval within the qualifying window was considered the time of return to the baseline performance level, i.e., 2 sec in the 2-31 sec window, 3 sec in the 3-32 sec window, 4 sec in the 4-33 sec window, etc.

The Math Task Window. For each participant, the percentages of correct responses on the math task over the 4-min baseline period and the 5-min post-GLOC testing period on each testing day ranged from 92.3% to 100% with a mean of 97.05%. In each case, the observers met a minimum standard of at least 96 problems attempted during the baseline measure (the maximum number of problems that could be performed in 4 min with a 2.5 sec solution window)

and at least 120 problems attempted during post-GLOC testing. Given the clear ceiling effect for accuracy, the *speed* with which participants solved problems correctly was used as the foundation of the performance index on the math task. The geometric mean of the participant's response times to correct solutions for the final four minutes of the baseline period on a given testing day was used as the performance standard for that day. As in the case of the tracking task, the geometric mean was employed to normalize the data, which were positively skewed across participants. For representational purposes, the means and standard deviations (in parentheses) of these baseline values across participants (in sec) for testing days 1 through 4 were 1.13 (0.41), 1.02 (0.28), 0.99 (0.34) and 0.96 (0.28) respectively. To compare post-GLOC performance against these daily standards, the geometric mean of the times to correct responses within the 30 sec window from 1-30 sec after GLOC was initially determined for a given test day. If (a) this value fit within the 110% upper bound of the baseline standard (the upper limit to which participants were trained), and (b) if the response time of the first correct response within the window *also* fit within the 110% upper bound of the baseline standard (the upper limit to which participants were trained), the participant's performance was considered to have returned to the baseline level within 1-sec post-GLOC. If one or none of these criteria were met, the time window from 2-31 sec post-GLOC was then examined, *and as in the case of tracking (see previous page)*, this procedure was iterated serially until a 30-sec window was found in which the dual criteria were fulfilled. As in the tracking task, the initial interval of the qualifying window was considered the time of return to the baseline level of performance on the math task.

Recovery Time. Mean recovery times for the tracking and math tasks are plotted as a function of test days in Figure 11. The figure reveals that performance efficiency on both tasks did not return to baseline levels immediately after participants emerged from the relative

incapacity phase of GLOC. Instead, an average of 47 sec was needed for tracking performance to return to baseline level and an average of 64 sec was needed for the math task. An ANOVA of the data of Figure 11 indicated that these means did not differ significantly from each other, $F(1, 12) = 2.34, p > .05$. However, a one-tailed test of significance indicated that the average recovery time across tasks, 55.5 sec, differed significantly from zero or immediate recovery, $t(12) = 6.32, p < .001$, and therefore, that the participants' performance efficiency on both tasks was significantly degraded for several seconds post-GLOC.

As was the case with the duration of the GLOC event itself, the performance recovery data provided no support for the notion that repeated exposure to GLOC can have beneficial effects for participants; neither the main effect for test day the Task x Day interaction in the ANOVA of the performance recovery data were statistically significant, $F(2, 28) = 0.81$ and $F(2, 19) = 0.78$, respectively, $p > .05$ in both cases.

Figure 11. Mean recovery times for the math and tracking tasks on each test day. Error bars are standard errors.

Pre-GLOC Performance

The issue of pre-GLOC deterioration in performance was addressed in terms of whether participants *ceased to respond* to either the tracking or the math task prior to the onset of unconsciousness in a GLOC episode. Cessation of response rather than the relative quality of performance was used as the dependent variable in this case because response cessation represents the maximum measure of when pilots are not in control of the aircraft. For the tracking task, the possibility of response cessation was probed by examining data collected during the acceleration G-plateau for a pre-GLOC point in time (in sec) at which RMS error reached its maximal limit and remained at that limit for the ensuing 1-sec intervals until the participant was judged to be unconscious. For the math task, the presence of response cessation was indexed by examining data collected during the acceleration G-plateau for a pre-GLOC point in time (in sec) at which a string of non-responses (timed-out problems) began, that continued until the participant was judged to be unconscious. Response cessations were noted for all participants in both tasks on all testing days.

Mean response cessation times for the tracking and math tasks are plotted as a function of testing days in Figure 12. It is evident in the figure that response cessation occurred earlier for the math than for the tracking task. On average, response cessation appeared on the math task 7.44 sec prior to the onset of unconsciousness while the corresponding value for the tracking task was 3.20 sec. Both of these results were tested against a hypothesis of no difference from the onset of unconsciousness by means of one-tail t -tests using an alpha of .05 and the Bonferoni correction. In both cases, response cessation occurred significantly prior to the onset of unconsciousness $t(12) > 7.25$ in each case. The figure also reveals that the task-related differences in performance cessation remained relatively constant over the four testing days. An ANOVA of

the pre-GLOC response cessation data confirmed that response cessations occurred significantly earlier for the math as compared to the tracking task, $F(1,12) = 23.63$, $p < .001$. Neither the main effect for day nor the Task x Day interaction were statistically significant, $F(3, 31) = 0.54$ and

Figure 12. Mean response cessation times for the math and tracking tasks on each test day. Zero represents the point of unconsciousness. Error bars are standard error.

$F(2, 20) = 1.65$, respectively, $p > .05$ in each case, indicating that repeated exposure to GLOC had no effect upon the appearance of pre-GLOC response cessations.

CHAPTER 4

Discussion

Gravity-induced loss of consciousness (GLOC) is a major psychophysiological threat to pilots of high performance aircraft. It is brought about by a sudden reduction in cerebral blood flow and brain tissue O₂ saturation (rapid hypoxia) as a result of increased +G force (Burton & Whinnery, 1999; Tripp, et al., 1998; Werchan, 1991). GLOC has been responsible for several mishaps involving USAF aircraft with substantial loss of life (Albery & Van Patten, 1991; Lyons, et al., 1992). In what is considered the classic description of GLOC, Whinnery et al. (1987) estimated that a GLOC event lasts on average for 24 sec during which a 12-sec period of complete unconsciousness (absolute incapacitation) is coupled with 12 sec of confusion and disorientation (relative incapacitation). Similar values for the GLOC experience were also observed in the present study -- the average duration of the absolute incapacitation phase was 11.44 sec and that of the relative incapacitation phase 12.76 sec. While the results of the present study confirm Whinnery et al.'s estimate of the amount of time taken up by loss of consciousness and confusion during GLOC, they indicate that the temporal envelope during which pilots lose control of their aircraft in a GLOC episode encompasses periods both fore and aft of the phases of unconsciousness and confusion. Therefore, the present results indicate that the negative effects of GLOC are more serious and cover a much broader time span than the 24 sec envisioned by Whinnery et al. (1987)

The GLOC-Based Window of Disrupted Flight Performance

A central feature of Whinnery et al.'s (1987) characterization of the GLOC event is the assumption that the efficiency of flight performance returns to pre-GLOC levels immediately at the end of the 12-sec relative incapacitation phase that marks the termination of the episode. An

earlier study by Houghton et al. (1985) cast a shadow of doubt on the validity of this assumption by showing that three minutes were required for performance on a simple math task to return to pre-GLOC baseline levels. Unfortunately, the Houghton et al. study confounded gradual and rapid onset acceleration profiles. A situation of this sort makes it difficult to gauge the post-GLOC recovery time needed by pilots facing the rapid onset acceleration profile typical of modern high performance aircraft (Gillingham & Fosdick, 1988) and the acceleration profile on which Whinnery and his associates focused their estimates of GLOC-based loss of flight control. Accordingly, one goal for the present study was to examine math recovery following a GLOC episode brought about by a rapid acceleration profile.

A second goal for this study was to re-examine Houghton et al.'s (1985) claim that delayed recovery following GLOC is restricted to cognitive tasks and that psychomotor performance does indeed recover immediately after the termination of the relative incapacity phase. Toward that end, Houghton et al.'s use of one-minute intervals to assess recovery time was replaced by a more fine-grained analysis in which the time course of recovery was charted on a second-by-second basis. For both goals, math and tracking tasks were utilized that were similar to those employed by Houghton and his associates and were designed to tap the aviation and navigation skills required by pilots flying high performance fighter aircraft.

The results of the study challenge the Whinnery et al. (1987) immediacy assumption and the Houghton, et al. (1985) cognitive restriction outcome by demonstrating that that both math and tracking performance require at least 55.5 sec to return to their baseline levels following a GLOC episode. Evidently, the acceleration profile used in inducing GLOC and the time grain employed to measure recovery are critical factors in determining the duration of performance deficits following the termination of the GLOC event. The 55.5 sec delay in recovery noted here

is considerably less than the three minutes reported by Houghton and his associates. However, it is in no way trivial, given that modern fighter aircraft flying at 500 mph or 733 ft/sec, can cover 40,682 feet or 7.7 miles in that time.

The finding of delayed performance recovery in this study is consistent with the report by Arnold, Tripp, and McCloskey (1995) that a substantial amount of time (90 sec) is required after exposure to hypoxia for arterial blood saturation to return to a pre-hypoxic baseline. The finding of a much shorter recovery time for math performance in this study in comparison to the three minutes estimated by Houghton and his associates may also be related to hypoxia, since the severity of hypoxia is proportional to the amount of time in high +Gz and the gradual acceleration profiles used in the Houghton et al. study increased the amount of time participants were exposed to a high Gz environment (Burton & Whinnery, 1999).

Another crucial feature of Whinnery et al.'s (1987) characterization of the GLOC event is their assumption that flight performance is not perturbed prior to the onset of unconsciousness. However, the hemodynamics of the brain in a high +Gz environment leads one to question the validity of that assumption as well. Gillingham & Fosdick (1988) and Wood (1990) have reported that pilots facing the sudden application of high +Gz forces can operate for several seconds under subnormal levels of cerebral blood pressure until unconsciousness sets in. Since hypoxia can severely impair performance on arithmetic and complex tracking tasks (Vaernes, et al., 1984; Sausen, et al., 2001), it is conceivable that the flight skills emulated in this study would deteriorate before unconsciousness appeared in a GLOC episode. Consequently, a third goal for the present experiment was to provide the initial experimental search for performance deficits prior to unconsciousness during a GLOC event. Consistent with expectation, such deficits were indeed evident in the data; participants abandoned the math task 7.44 secs and ceased tracking

3.20 sec prior to falling unconscious. If, as in the Whinnery et al. (1987) characterization, the onset of unconsciousness is considered as ground zero for the appearance of performance shortfalls during GLOC, both of these values significantly predate that point.

In sum, the results of this study indicate that by focusing on overt symptoms of loss of consciousness and mental confusion and ignoring the subtle nuances of performance degradation that might pre-date and follow these symptoms, Whinnery and his colleagues (1987) seriously underestimated the duration of the GLOC-based window of disrupted flight performance and the severity of the GLOC hazard. Taking the duration of the total incapacitation period of GLOC (unconsciousness and mental confusion) together with the durations of pre-GLOC performance cessation and post-GLOC recovery time, the present results suggest that the total duration of the shortfall in flight control among pilots who encounter rapid-acceleration induced GLOC is at least 87 sec, a period that is more than three times longer than the 24 sec envisioned by Whinnery et al. (1987). It is also one in which pilots flying at 500 mph can travel 12.1 miles while not in control of their aircraft. These effects are illustrated in Figure 13.

One question that arises about the present results concerns an asymmetry in the performance deficits noted prior to and after GLOC. In the time period preceding the onset of unconsciousness, participants ceased performing the math task significantly before they abandoned the tracking task but post-GLOC recovery times for both tasks were similar. A result of this sort may also be physiologically mediated by hemodynamics in the brain. When a high +Gz force is encountered, blood is withdrawn from the brain in a graded fashion with ischemia (blood loss) being more pronounced in higher as compared to lower centers (Fong, 1992; Whinnery, 1989).

Figure 13. Performance-deficit duration under rapid onset rate (ROR) G-force.

When the +Gz force is removed, however, blood does not return to the brain in a graded fashion. Instead, there is a hyperemic effect in which blood flow to all portions of the brain increases dramatically (Wood, 1990). Recent studies using fMRI and PET procedures have localized arithmetic calculations to the prefrontal and parietal cortices of the brain (Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 2001; Hayashi, Ishii, Kitagaki, & Kazui, 2000; Rickard, et al., 2000; Ruekert, et al., 1996). Motor control functions which underlie tracking performance involve cortical circuitry in the primary and supplementary motor and premotor areas and also subcortical structures in the cerebellum and basal ganglia whose output affects both descending extrapyramidal tracts and structures in the cerebral cortex (Beatty, 2001; Gazzaniga, Ivery, & Magun, 1998; Kandel, Schwartz, & Jessell, 2000). Thus, it is conceivable that, because of the lowered level of blood loss in its subcortical components, tracking performance was able to resist

the degrading effects of mounting +Gz induced ischemia for a longer period of time than math, while the balance in cortical and subcortical tissue perfusion following GLOC may have enabled both tasks to recover at the same rate.

Combating GLOC Through Perceptual Adaptation

As noted earlier, current physiological/engineering solutions to prevent or lessen the GLOC hazard, involving a combination of breathing and straining routines, anti-gravity pressure suits, and pilot positioning, are not completely effective (Burton, Cohen, & Guedry, 1988; Harding & Bomar, 1990; Stauffer, 1949; Tripp, 1990; Von Beckh, 1972; 1981). Accordingly, a final goal for the present study was to determine if perceptual adaptation resulting from repeated exposure to GLOC could serve to minimize the negative consequences of this flight hazard. The adaptation strategy was suggested by Whinnery and his associates (Whinnery & Burton, 1987; Whinnery & Jones, 1987) who noted while viewing tapes of GLOC episodes that the period of relative incapacitation tended to grow shorter with repeated GLOC exposure.

The results of this investigation provided no support for the perceptual adaptation approach. After four exposures to GLOC, one per day over a span of four weeks, there was no evidence of a shortening of either the periods of unconsciousness or confusion, and no evidence of a reduction in the durations of pre- or post-GLOC performance deficits.

The absence of any evidence that participants could adapt to GLOC was surprising given the wide range of perceptual and motor aberrations to which observers have adapted in the past, including those that occur in other flight conditions (cf. Lackner, 1993; Nelson, et al., 1998; Welch, 1986). It is noteworthy that the observations made by Whinnery and his associates (Whinnery & Burton, 1987; Whinnery & Jones, 1987) were based upon only a small number of participants (four), who had experienced four GLOC exposures on a single day rather than on the

once a day schedule used here. Consequently, it is possible that the spacing of GLOC exposures employed in this study was too distributed to be effective. However, before arguing that perceptual adaptation to GLOC should be re-examined with massed practice, the possible dangers of exposing participants to repeated periods of unconsciousness should be recognized (see Appendix B) along with the fact that there is a potentially more compelling explanation than distributed practice for the absence of adaptation effects in this study. Prior investigations of the ability of human observers to adapt to distortions and rearrangements of their perceptual-motor environments (cf. Lackner, 1993; Nelson, et al., 1998; Welch, 1986) did not employ procedures that would impair observers' mental faculties. However, early information-processing and working memory functions are suppressed by the hypoxia inherent in GLOC (Burton, 1988; Howard, 1965; Whinnery, 1987; Whinnery, et al. 1987) and GLOC is often accompanied by retrograde amnesia (Glaister, 1988). These sorts of deficits, rather than inappropriate spacing of GLOC events, may be at the root of participants' apparent inability over successive exposures to develop strategies that could aid them in reducing the negative effects of GLOC.

In-Flight Auto-Recovery System

All in all, it would appear that repeated exposure would not be of effective value in modifying the negative effects of GLOC. Given the seriousness of this hazard for flight safety, other approaches need to be tried. One recent approach is the use of an in-flight aircraft auto recovery system. Current research at the Navel Air Warfare Center (Forster, 1998) focuses on the prospect of physiologically monitoring the pilot using noninvasive electroencephalographic, respiratory, and cerebral oxygen sensors that are integrated into the pilot's flight equipment. These data would then be sent to a central processor that is also receiving aircraft state information about altitude, attitude, airspeed, and G-level. Based on criteria comprised of the

flight status of the aircraft and the physiological condition of the pilot, a determination that the pilot has experienced GLOC would be made and the aircraft would be recovered and flown under computer control. Once the pilot recovers from the unconsciousness and confusion resulting from the GLOC event, he/she could resume control of the aircraft. The present study indicates that it would be inadvisable to return control to the pilot immediately after the 24 sec suggested by Whinnery et al. (1987) and that the plane should remain under computer control for at least 79.5 sec after unconsciousness sets in (the Whinnery et al. total incapacitation interval plus cognitive and motor performance recovery time). The present results also suggest that when pilots are faced with mounting +Gz induced ischemia, the auto recovery system should be prepared to assume flight control at least 7.44 sec prior to the onset of unconsciousness. Thus, in addition to shedding light on previously unrecognized temporal aspects of the GLOC hazard, the results of this study provide potentially useful information for designers of advanced systems aimed at combating that hazard.

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APPENDIX A

Detailed summaries of all ANOVA tables

Table A1.
Analysis of Variance for GLOC-Duration Data

Source	df	df _{adj}	MS	F	P
Within Subjects	91				
Incapacitation (A)	1	1	45.39	1.39	>.05
Day (B)	3	2	67.47	2.45	>.05
AB	3	2	26.05	2.74	>.05
Error (A)	12	12	32.58	-	-
Error (B)	36	25	27.54	-	-
Error (A x B)	36	27	9.49	-	-

Note: df_{adj} = degrees of freedom obtained when Box's η^2 is used to correct for violations of sphericity

Table A2
Analysis of Variance for Math and Tracking Task Recovery Time

Source	df	df _{adj}	MS	F	P
Within Subjects	91				
Task (A)	1	1	7397.83	2.34	>.05
Day (B)	3	2	1011.58	0.81	>.05
AB	3	2	759.16	0.78	>.05
Error (A)	12	12	3162.54	-	-
Error (B)	36	28	1246.24	-	-
Error AB	36	19	968.35	-	-

Note: df_{adj} = degrees of freedom obtained when Box's η^2 is used to correct for violations of sphericity

Table A3
Analysis of Variance for Pre-GLOC Math and Tracking Response Cessation Time

Source	df	df _{adj}	MS	F	P
Within Subjects	91				
Task (A)	1	1	468.18	23.64	<.001
Day (B)	3	3	4.32	0.56	>.05
AB	3	2	9.74	1.65	>.05
Error (A)	12	12	19.80	-	-
Error (B)	36	31	7.69	-	-
Error AB	36	20	5.89	-	-

Note: df_{adj} = degrees of freedom obtained when Box's η^2 is used to correct for violations of sphericity

APPENDIX B

G hazards brief

G- Hazards Briefing for Subjects Participating in NAWC/AD Sponsored Acceleration Research

1. Need for acceleration experimentation

- A. Current and predicted future fighter aircraft performance exceeds the capabilities of their human operators.
- B. Effects of G-stress during aerial combat that lead to decreased mission performance are:
 - 1. loss of vision
 - 2. loss of consciousness
 - 3. fatigue
 - 4. misorientation

The understanding by the US Air Force of the underlying physiological causes and mechanisms of these events is incomplete and research is needed to determine these causes and mechanisms.

- C. Methods of improving G tolerance and enhancing performance during G-stress are needed and are being developed. Evaluation of such methods is required.

2. The physiologic and pathologic effects of G-stress in humans

The physiologic and pathologic effects of G-stress in humans has been studied and documented since World War I. However, investigators continue to find new physiological phenomena and possible injury events from world wide research. The currently known physiological and pathological possibilities are listed below:

- A. Central Nervous System
 - 1. peripheral visual loss or general dimming of vision - "grayout"
 - 2. total visual loss - "blackout"
 - 3. loss of consciousness, mild seizures, myoclonic convulsions (intermittent specific muscle contractions), and amnesia
 - 4. motion sickness, with perspiration, pallor, nausea and vomiting
 - 5. transient psychologic alterations (anxiety, euphoria, confusion, disorientation)
 - 6. benign positional vertigo (dizziness/spinning sensation)
 - 7. injury from reduced blood flow to nervous tissues

B. Skin and Blood Vessels

1. petechial hemorrhages (rashlike spots on the skin)
2. swelling of feet and ankles
3. scrotal hematoma (ruptured blood vessel in the groin area)
4. blood clots which may travel to the lungs or brain

C. Lungs and Chest Wall

1. difficulty in breathing
2. temporary change in blood flow pattern in lungs
3. possible collapse of lung
4. possible burst lung from pressure breathing
5. fractured ribs/chest pain

D. Heart

1. high heart rate
2. arrhythmia's - "skipped" and "extra" heartbeats
3. transient electrical changes (temporary electrocardiographic changes)

E. Musculoskeletal System

1. muscle soreness, pain and discomfort
2. fracture of vertebra, "hip", or ribs
3. hernia or bulging of abdominal contents outside abdominal cavity
4. neck muscle strain

3. The pathologic effects of high G-stress in animals

The pathologic effects of high G-stress in animals have been studied to the point of injury to determine the ultimate damage that may be expected. While subjects are not likely to be exposed to such stress, subjects need to know that this injury potential exists regardless of the level of stress and the fact that animals, other than humans, were used to determine the injury. The pathological effects are listed below:

Heart

1. subendocardial hemorrhage - bleeding under heart lining
2. reversible and permanent damage of heart muscle cells
3. heart blocks - disruption of normal contraction rhythm

4. Adverse events in fighter aircrew during high-G training

Adverse events in fighter aircrew during high-G training have been noted. The adverse events that were found have been included in this brief. Subjects have been medically screened far in excess of our pilot population to increase the probability that subjects will not be exposed to a stress that cannot, medically speaking, be withstood.

5. This research protocol includes the use of:

- A. The Human Centrifuge
- B. Non-invasive cardiac and neurologic studies
- C. Centrifuge research safety procedures for:
 - 1. medical screening
 - 2. medical monitoring
 - 3. emergency medical facilities

6. Special Risks to Female Subjects

There is no reason to expect any more risk of injury to the female who is not pregnant than there is to the male. It is desirable to include women in acceleration research because of their expanding role in fighter aviation. There are, however, several special risks that may affect women. There is the possibility of an increase in menstrual flow, or bleeding or spotting between periods though no problems of this nature have been reported. Forces experienced during acceleration exposure indicate that breast support must be used. The presence of breast implants will preclude participation in research under this protocol. Oral contraceptive pills (OCPs) are not without hazards even outside of the acceleration environment. If women take OCPs, they should not have any history of inflammation of the veins (phlebitis), or a tendency to form blood clots (thrombosis); both of these things are known risks of taking OCPs but have also been reported to occur in the acceleration environment. If a blood clot forms in the leg (thrombophlebitis) and breaks free it may lodge in the lung (pulmonary embolus) with potentially life threatening results. The additional risks to being on OCPs during acceleration stress are not known. Current OCPs in general have a lower hormone content than those used previously and it would be reasonable to believe that a woman's risk of adverse reactions should decline with a lower level of hormones.

No study has been performed on the effects of sustained acceleration on either the pregnant woman or the fetus. The outcome of an early, undetected pregnancy in the acceleration environment is not known, but the possibility of fetal injury, malformation, or death, or of spontaneous abortion, cannot be ignored. Some early pregnancies end in spontaneous abortion as a matter of course, but it is not known whether or not exposure will change this existing risk. As a precaution, within seven calendar days of each scheduled acceleration exposure women subjects will need to collect a routine urine sample for pregnancy testing. The tests used will normally detect a pregnancy by the 12th day, but no test is 100% accurate. Women who have had a bilateral tubal ligation ("BTL", or "surgical sterilization"), will still submit urine specimens for pregnancy testing because of the known possibility (however remote) of pregnancy. In view of the lack of evidence on this matter, it is very important for subjects to report any suspicion of pregnancy to the medical monitor so that exposure can be avoided. If a subject were to become

pregnant during the course of a research project it will in no way jeopardize their ability to participate in other research in the future nor will it affect their medical benefits under either Workman's Compensation or the military medical care system.

Ovarian abnormalities such as cystic enlargement may occur with or without symptoms. There is a possibility that exposure to sustained acceleration forces could increase the normal risk that such an enlarged cyst may rupture or that the ovary may twist about its support cutting off its blood supply. These situations might require major abdominal surgery to correct. In addition to the usual risks of surgery such as infection, bleeding or even death, there is the possibility of losing the ovary. If the other ovary is intact there should be no impact on fertility. Overall, the risk that a female may be subject to is felt to be no greater than her risk as an operational pilot.

I acknowledge that I have been briefed on the above topics, and I understand the evidence related to the potential injurious and life-threatening dangers associated with G-stress. I understand that the physiological and pathological consequences listed above and presented to me represent the best knowledge at this time and that other unknown physiological and pathological consequences, not listed or discussed, are indeed possible.

_____ Signature	_____ Name	_____ Date
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I was present during the explanation referred to above, as well as during the volunteer's opportunity to ask questions, and hereby witness the signature.

_____ Witness Signature	_____ Name	_____ Date
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_____ Principal Investigator Signature	_____ Name	_____ Date
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