

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

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Objectives: We examine the time course of performance recovery from gravity-induced loss of consciousness (GLOC) and evaluate the utility of exposing participants to repeated bouts of GLOC in promoting recovery time. **Background:** A substantial number of accidents among fighter pilots have resulted from episodes of GLOC. U.S. Air Force doctrine holds that when pilots experience GLOC, impairment lasts for 24 s, in which there are 12 s of complete unconsciousness and 12 s of confusion. However, there is reason to suspect that performance efficiency associated with GLOC is degraded well before unconsciousness sets in and that more than 24 s are required for performance efficiency to return to baseline levels. Additionally, there is a belief that repeated exposure to GLOC will reduce recovery time. **Method:** Centrifuge simulators were used to induce GLOC in U.S. Air Force personnel with math and tracking tasks employed to emulate flight performance. Participants were tested once per week for 4 consecutive weeks. **Results:** On average, performance deficits appeared 7.44 s prior to the onset of unconsciousness and persisted for 55.6 s following the GLOC event. Repeated exposure failed to moderate these results. **Conclusion:** The temporal course of performance deficits produced by GLOC far exceeds prior estimates. The problem is more serious than previously envisioned and it is not alleviated by repeated exposure to GLOC. **Application:** U.S. Air Force doctrine regarding the severity of GLOC and the utility of repeated exposure to this problem needs to be revised and these data incorporated into future aircraft auto recovery systems.

INTRODUCTION

The evolution of high-performance combat aircraft has resulted in the imposition on pilots of an ever-increasing amount of physiological stress stemming from noise, vibration, thermal extremes, spatial disorientation, and gravity-induced loss of consciousness (GLOC). The most dangerous of these stressors are disorientation and GLOC (Albery & Van Patten, 1991). The latter is the focus of this investigation. Gravity-induced loss of consciousness has been implicated in a substantial number of mishaps involving losses of pilots and their aircraft (Deaton & Mitchell, 2000). These results underscore the need to learn more about the effects of GLOC on pilot performance and to discover practical and cost-effective countermea-

asures that may reduce the mishap rate attributable to GLOC.

The principal physiological basis for GLOC is the reduction of cerebral perfusion resulting from a differential blood pressure gradient that exists between the heart and the brain within the +Gz head to foot acceleration. As the level of +Gz increases, blood supply to the brain is decreased, leading to unconsciousness (Burton & Whinnery, 1996). In a landmark study, Whinnery, Burton, Boll, and Eddy (1987) noted that GLOC involves not only 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 pilot 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 pilot regained control of the aircraft as indexed by the ability to respond to a warning tone. In their characterization of GLOC, Whinnery et al. (1987) suggested that each of the two phases lasts for about 12 s, resulting in a 24-s period of total 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 miles per hour (mph; Burton, 1988), Whinnery et al.'s (1987) estimate of the duration of a GLOC event means that these aircraft could cover 3.3 miles while the pilot is totally incapacitated. The probability of a serious mishap under such conditions is obvious.

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 24-s incapacitation period. There is reason to believe, however, that this assumption may be incorrect and that they may have underestimated the duration of the GLOC-based window of disrupted flight performance and the severity of the GLOC hazard. Using an arithmetic computation task to represent pilots' cognitive functions in a centrifuge-based simulated +Gz environment, Houghton et al. (1985) found that 3 min were required for performance on the task to return to pre-GLOC levels. This recovery period together with the 24-s total incapacitation time of the GLOC episode itself means that a plane flying at 500 mph could cover a distance of 28.3 miles while the pilot's cognition is impaired.

Although the experiment by Houghton et al. (1985) provides a potentially serious challenge to Whinnery et al.'s (1987) estimate of the total period of performance disruption following GLOC, their study is troubled by a problem with the +Gz onset rates that they employed. In either an aircraft or a centrifuge, the rate of acceleration used to reach the critical +Gz level needed to produce unconsciousness can be gradual (gradual +Gz onset rate, or GOR) or rapid (rapid +Gz onset rate, or ROR). Because of an extended period in the presence of excessive +G, GORs produce greater ischemic effects and, therefore, greater levels of

hypoxia than do RORs (Burton & Whinnery, 1996). 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, Houghton et al. (1985) combined rapid and gradual onset rates in their analysis of GLOC recovery, so it is not possible to discern the relative contributions of GORs and RORs to the time course of performance disruption in their study. 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, particularly 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 +Gz onset rate.

In their experiment, Houghton et al. (1985) employed a tracking task along with a math task. They found that only the math task required a considerable period of time to recover from GLOC. A result of this sort suggests that cognitive but not motor functions are subject to impairment after a GLOC episode. Houghton et al. (1985) assessed performance in relatively long (1-min) intervals. It is possible that post-GLOC tracking performance is impaired but that recovery occurs quickly (Wickens & Hollands, 2000) 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 this investigation was to examine post-GLOC math and tracking performance in a more temporally detailed manner. Toward that end, performance efficiency was assessed in 1-s rather than 1-min intervals.

In addition to the rapid recovery assumption in their characterization of the GLOC episode, Whinnery et al. (1987) also assumed that a 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 in the case of their post-GLOC assumption, there is reason to believe that their pre-GLOC assumption may also be incorrect. Gillingham and Fosdick (1988) and Wood (1990) have shown that pilots exposed to

+Gz forces sufficient to produce a rapid drop in cerebral blood pressure have about 5 to 7 s when they can perform their flight tasks before brain tissue oxygen reserves become depleted to the point at which unconsciousness sets in. Research has indicated that observers undergoing hypoxia are subject to mental blocks, a general slowing of reaction time, and a deterioration of psychomotor functions (Chelette, Albery, Esken, & Tripp, 1998; Lindeis, Nathoo, & Fowler, 1996; 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) as well as studies indicating that the types of performance tasks to be employed herein, arithmetic and complex tracking, are severely impaired by hypoxia (Sausen et al., 2001; Vaernes, Owe, & Myking 1984). Consequently, it is conceivable that the flight skills to be simulated in this study will deteriorate during the 5- to 7-s period before unconsciousness occurs in a GLOC episode, a result that would exacerbate the GLOC hazard. A third goal for this investigation was to explore that possibility.

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). To date, a combination of approaches involving muscle tension and assisted breathing, anti-G suits, and pilot positioning has been employed for that purpose with only moderate success (Fong, 1992). While viewing tapes of GLOC episodes, Whinnery and Burton (1987) and Whinnery and Jones (1987) noted that the period of relative incapacitation tended to grow shorter with repeated GLOC exposure. Therefore, they recommended that pilots may learn with experience to overcome the confusion and disorientation associated with a GLOC episode and shorten the time that they are incapacitated. To date, however, no systematic experimental effort has been devoted to that possibility. Accordingly, a final goal for this study was to provide that effort.

METHOD

Participants

Thirteen active duty members of the U.S. Air Force (5 women and 8 men) volunteered to par-

ticipate in the study. They ranged in age from 25 to 36 years, with a mean of 29 years, and had no prior experience with GLOC. Military ranks ranging from airman to major were represented in the sample. All participants were members of the sustained acceleration stress panels at Brooks City-Base, Texas, and Wright-Patterson Air Force Base, Ohio. They were required to meet U.S. Air Force Flying Class III medical standards and to have no history of neurological pathology. All participants were determined by a flight surgeon to be in excellent health.

Facilities

The study was conducted at the Air Force Research Laboratory's centrifuge facilities at Brooks City-Base and Wright-Patterson Air Force Base. Seven participants were tested at Wright-Patterson, the remainder at Brooks. The centrifuges employed featured 19-foot (5.79-m) radius arms and permitted the generation of identical acceleration profiles with 3 G/s onset rates. Participants were secured in an F-16-like ACES II ejection seat reclined at 30° from vertical. An emergency abort switch enabled participants to stop the centrifuge at any time during testing. Participants wore a standard U.S. Air Force issue Nomex® flight suit and a Gentex (Carbondale, PA) HGU-55/P flight helmet without a visor during all GLOC runs. The absence of a visor maximized the ability of the investigator and flight surgeon to observe participants' facial activity during GLOC, as described later. Participants were instrumented with electrodes during testing to measure electrocardiographic (ECG) activity.

Centrifuges were outfitted with a simulated fighter cockpit incorporating 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. A viewing screen (70° × 40° 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. Continuous real-time surveillance of participants was afforded during each run by two closed-circuit infrared television cameras. Video projection systems were used to present the stimuli for the performance tasks and an image needed for assessing visual field loss, as described later. Identical computer

systems at each facility orchestrated stimulus presentations and stored participants' responses.

Acceleration Profiles

Computer control systems were used to generate two acceleration profiles in the sessions in which participants experienced GLOC. The first was a gradual +Gz onset rate (GOR) of 0.1 +Gz/s. This profile established the participant's relaxed +Gz level. Participants were asked to view a solid red circle as it appeared on a uniform white background. They aborted the acceleration profile when their central vision was reduced to an angle $<10^\circ$ (i.e., when only the red circle was visible). The +Gz level at which this occurred was termed GOR_{max} . This value was used to enable the induction of GLOC at the lowest possible +Gz level (Forster & Cammarota, 1993).

The second +Gz profile, which was run after the determination of GOR_{max} , featured a rapid +Gz onset rate (ROR) of +3 Gz/s to a preestablished 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} . The G levels required to induce GLOC ranged from 5.5 +Gz to 8.5 +Gz with a mean of 6.7 +Gz ($SD = 0.91$ +Gz). To maximize the likelihood of inducing unconsciousness at the lowest possible (and therefore the safest) +Gz level, participants were not equipped with G suits and were instructed to refrain from performing anti-G straining maneuvers (AGSMs). The principal investigator aborted the ROR profile when real-time images and ECG tracings indicated that a participant was executing an AGSM. The real-time images also permitted the principal investigator to terminate the ROR profile when GLOC occurred. The presence of GLOC was determined using the Whinnery et al. (1987) criteria: (a) dual eye closure, (b) slumping of the head and upper body, and (c) 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.

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's and flight surgeon's decision that the participant had returned to consciousness. During the relative incapacitation phase, participants were confused and disoriented and unable to engage the performance tasks that were assigned to them. Based on 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, which composed one aspect of the performance battery and is described next. The signs of loss of consciousness and recovery of consciousness and the signs of tracking recovery based on real-time images of the flight stick data were so evident that the principal investigator's call was never challenged by the flight surgeon and there was no variability introduced by requiring two people to reach agreement in real time.

Performance Tasks

A 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 1.

Participants performed the tracking task by using the flight stick to align the intersection of a moving reticle composed of white horizontal (72.5 cm long \times 0.4 cm thick) and vertical (51.5 cm long \times 0.4 cm thick) crosshairs with the center point of a fixed target composed of crossing horizontal and vertical arms. Movement of the reticle was directly proportional to the applied force on the flight stick (i.e., zero-order control). The elements constituting the target were four elongated open rectangles arrayed about a smaller open rectangle, all formed by 0.4-cm green lines. The two rectangles constituting 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 3 cm tall) by 1.5 cm. Thus the entire horizontal or x axis of the target was 72.5 cm. The two rectangles constituting the vertical arms of the target (22.75 cm long and 1 cm thick) were also separated from the centering rectangle by

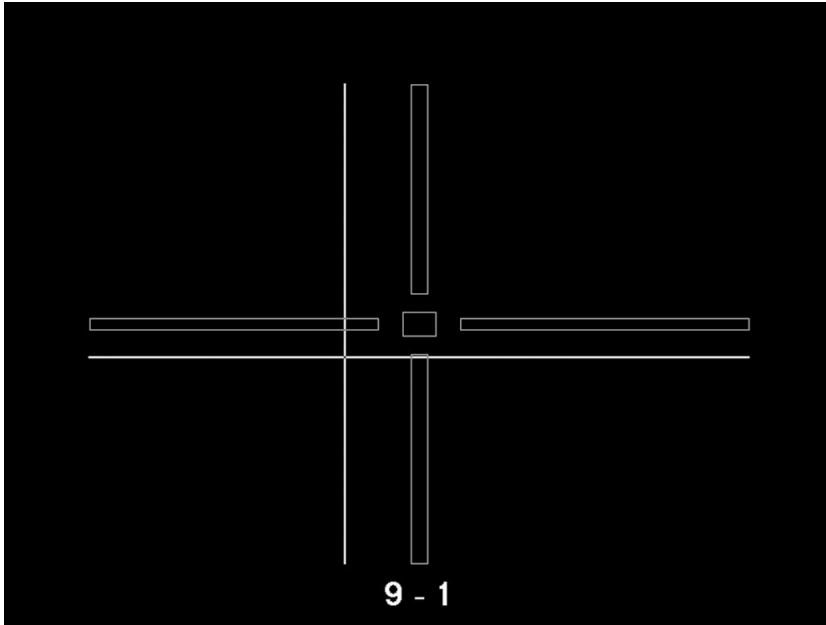


Figure 1. Compensatory tracking and math tasks.

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, and 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 vertical and horizontal forcing functions, each composed of three sine waves (1/3, 1/7, and 1/11 Hz), the phases of which were chosen at random and the amplitudes of which were equal. The maximum possible displacements of the horizontal component of the moving reticle, because of its forcing function alone, were the top and bottom edges of the upper and lower arms of the target, respectively. The maximum possible displacements of the vertical component of the moving reticle, because of its forcing function alone, were the farthest left edge of the left and right arms of the target, respectively. Maximum displacements of the moving crosshairs were a function of the input signals themselves and were independent of participants' responses. Acceleration G forces were directed through the center of the flight stick, making the difficulty of tracking equal on both axes. A detailed

description of the tracking task can be found in Houghton et al. (1985).

We also required participants 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 (0.7×2.1 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 >5 and down if the solution was <5 . Problems were displayed until the participant responded or until a 2.5-s 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 at random for each participant during all phases of the experiment.

As illustrated in Figure 1, the stimuli for the computation task were presented at the bottom 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 at 16 Hz over a 5-min interval. Like the tracking task, the arithmetic computation task employed in this study was identical to that featured in Houghton et al. (1985).

Prior to engaging in the GLOC phase of study, participants at each facility were trained on the performance tasks using the dual-task conditions that they would later encounter during that phase. At each facility, training was conducted in the gondola in a static +1-Gz environment. Ten-minute training sessions were conducted twice weekly until the participant met the following preestablished dual-performance criteria: (a) the standard deviations of the root mean square (RMS) tracking scores over the 10 min (600 s) of training (based on the Euclidean distance between the crosshairs and the center of the fixed reticle) were within 10% of each other on 2 consecutive days and (b) the percentage of correct math responses across the 10 min of training equaled or exceeded 90% of a minimum number of 240 problems attempted on the same 2 consecutive days.

GLOC Testing

Participants experienced GLOC on 1 day per week over a period of 4 successive weeks. While seated in the immobile centrifuge, they 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 basis. Following the baseline period, participants' GOR_{max} level was determined, 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 s at this +Gz level, the ROR profile commenced and remained in force until GLOC became visible, which, on average, occurred 10.86 s ($SD = 0.92$ s) after commencement of the ROR profile. The centrifuge was stopped when participants went into GLOC. Unloading the +Gz force in this way is similar to what a pilot might experience when releasing the flight stick during an in-flight GLOC event. Participants were instructed to reengage the performance tasks as soon as possible after the relative incapacitation

period during a GLOC event. They were required to perform the tracking and math tasks in a static environment for an additional 5 min following recovery from GLOC.

RESULTS

Phase Durations

A 2 (phase) \times 4 (days) repeated measures analysis of variance (ANOVA) was used to assess the effects of repeated exposure on the durations of the GLOC episodes. No significant effects were found in that analysis, $p > .05$ in all cases. Thus the durations of the absolute ($M = 11.44$ s, $SE = 0.87$ s) and the relative ($M = 12.76$ s, $SE = 1.00$ s) incapacitation phases of the GLOC events observed in this study were similar to each other and to the 12-s value described by Whinnery and Whinnery (1990). Moreover, although there was a tendency for the mean overall GLOC duration to decline across days (for Days 1–4, respectively, $M = 27.39$ s, $SE = 2.86$ s; $M = 25.39$ s, $SE = 1.67$ s; $M = 21.69$ s, $SE = 1.82$ s; and $M = 22.31$ s, $SE = 1.67$ s), that tendency was not statistically significant. This and all subsequent ANOVAs utilized the Box correction when appropriate to compensate for violations of the sphericity assumption (Maxwell & Delaney, 2004).

Given that the effect of repeated exposure on the duration of GLOC episodes was a central aspect of this study, the effect was explored more closely on an individual participant basis. Plots of the durations of the relative and absolute incapacitation phases across days for each participant are provided in Figure 2. Only 2 of the participants (S5, S12) showed a shortening of time spent in the relative incapacitation phase over the 4 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 did not have a beneficial effect on the durations of the phases of the GLOC events in this study.

Post-GLOC Performance

The moving window strategy. The two performance tasks used in this study reflected fine motor control and higher order cognitive functions. Consequently, scoring was necessarily different for each task. However, in order to provide a direct fine-grained comparison of the time needed to

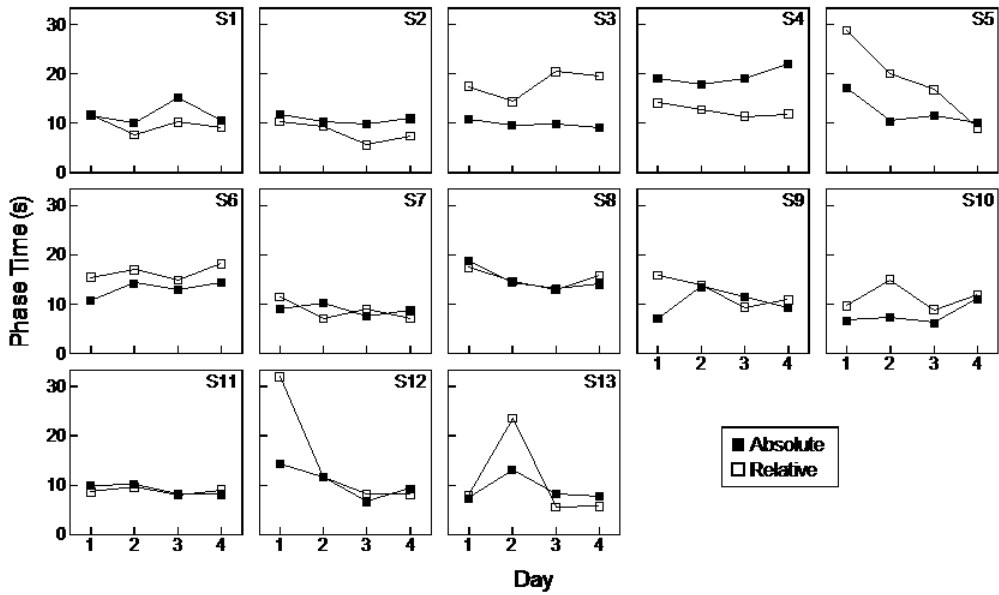


Figure 2. Mean absolute and relative incapacitation phases over 4 test days.

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 seconds 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 (i.e., was no more than 10% larger than 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-s intervals of the final 4 min 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. To compare a participant’s post-GLOC performance against these daily standards, the geometric mean was initially determined for the 30-s window from 1 to 30 s after GLOC on a given test day. If (a) this value fit within the 110% upper bound of the baseline standard for that day and (b) if the RMS error for the first 1-s 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 s after GLOC. If either of those criteria was not met, the time window from 2 to 31 s after GLOC was then examined; this procedure was iterated serially (i.e., 3–32 s, 4–33 s, 5–34 s, ..., 271–300 s) until a 30-s 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 (2 s in the 2–31 s window, 3 s in the 3–32 s window, 4 s in the 4–33 s window, etc.). The 30-s window was designed to ensure the integrity of the tracking and math performance indices by reducing the possibility that motor movements caused by limb flailing during GLOC recovery could influence them.

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% to 100% with a mean of 97%, with no evidence of a speed-accuracy trade-off. Given the clear ceiling effect for accuracy, the speed at 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 4 min 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.

To compare post-GLOC performance against these daily standards, we employed a sliding window approach similar to the one described for the tracking data. The geometric mean of the times to correct responses (within the 30-s window from 1 to 30 s after GLOC) was initially determined for a given test day. If (a) this value fit within the 110% upper bound of the baseline standard and (b) the response time of the first correct response also fit within the upper 110% (or the upper bound) of the central tendency of that participant's performance, the individual's performance was considered to have returned to the baseline level within 1 s after GLOC. If only one (or none) of these criteria was met, the time window from 2 to 31 s after GLOC was examined, and, as in the case of tracking, this procedure was iterated serially until a 30-s 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 baseline performance on the math task.

Recovery time. Mean recovery times in seconds for the tracking task across testing Days 1 through 4 were 47.00 ($SE = 6.88$), 46.31 ($SE = 7.07$), 45.62 ($SE = 11.13$), and 49.62 ($SE = 6.17$), respectively. The corresponding values for the math task were 60.65 ($SE = 9.27$), 56.19 ($SE = 7.31$), 61.51 ($SE = 9.65$), and 77.66 ($SE = 14.84$), respectively. A 2 (task) \times 4 (days) repeated measures ANOVA revealed no significant main effect for task, $p > .05$, and 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 nor the Task \times Day interaction in the ANOVA was statistically significant, $p > .05$ in all cases. However, a one-tailed t test indicated that the average recovery time across tasks, 55.6 s, differed significantly from zero or immediate recovery from the relative incapacity phase, $t(12) = 6.32$, $p < .001$, and therefore that the participants' performance efficiency on both tasks was significantly degraded for nearly 1 min after GLOC.

Pre-GLOC Performance

The issue of pre-GLOC deterioration in performance was addressed in terms of whether partici-

pants ceased to respond to either the tracking or the math task prior to the onset of unconsciousness in a GLOC episode. The absence of response, rather than the relative quality of performance, was used as the dependent variable in this case because response absence represents the most severe and potentially the most deadly aspect of a pilot's failure to control the aircraft with the onset of GLOC. For the tracking task, response absence was operationally defined as a pre-GLOC point in time (in seconds) in the acceleration G plateau at which RMS error reached its maximal limit and remained at that limit for the ensuing 1-s intervals until the participant was judged to be unconsciousness. For the math task, response absence was indexed as the point in time (in seconds) in the acceleration G plateau at which, prior to GLOC, a string of nonresponses (timed-out problems) began and continued until the participant was judged to be unconscious. Response absences were noted for all participants in both tasks on all testing days.

Mean response cessation times in seconds prior to the onset of GLOC for the tracking task across testing Days 1 through 4 were -4.02 ($SE = 0.64$), -2.60 ($SE = 0.79$), -3.05 ($SE = 0.96$), and -3.13 ($SE = 0.66$), respectively. Corresponding values for the math task were -7.56 ($SE = 0.93$), -8.01 ($SE = 0.91$), -7.60 ($SE = 0.91$), and -6.59 ($SE = 0.66$), respectively. The overall mean for the tracking task was -3.20 s, whereas that for the math task was -7.44 s. Both of these overall means were significantly below zero (or coincident with the onset of GLOC), indicating that in each case, response cessation significantly predated the onset of unconsciousness, $t_{\text{one-tail}}(12) > 7.25$, $p_{\text{Bonferroni corrected}} < .05$ in each case. A 2 (task) \times 4 (days) repeated measures ANOVA of the response cessation data confirmed that cessations occurred significantly earlier for the math than for the tracking task, $F(1, 12) = 23.63$, $p < .001$. However, neither the main effect for day nor the Task \times Day interaction was statistically significant, $p > .05$ in each case, indicating that repeated exposure to GLOC had no effect on the appearance of pre-GLOC response cessations.

DISCUSSION

Although the results of the present study confirm Whinnery et al.'s (1987) estimate of the

amount of time taken up by loss of consciousness and confusion during GLOC (approximately 12 s each), they indicate that the temporal envelope during which pilots lose control of their aircraft in a GLOC episode extends well beyond Whinnery et al.'s (1987) proposed limits and also predates 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 s envisioned by Whinnery et al. (1987).

This study was prompted by the need to re-examine the findings of Houghton et al. (1985) that performance recovery from GLOC requires at least 3 min, that it is restricted to cognitive tasks, and that psychomotor performance recovers immediately after the termination of the relative incapacity phase. Toward that end, the present study featured a rapid onset +Gz profile that reflected the acceleration profiles encountered in modern fighter aircraft. The earlier study by Houghton et al. (1985) confounded such profiles with gradual onset profiles. In addition, the present study featured a more fine-grained temporal analysis than the gross 1-min intervals utilized in the earlier study. The results indicated that both math and tracking performance require at least 55.6 s to return to their baseline levels following a rapid +Gz onset. The delay in recovery noted here is considerably less than the 3 min reported by Houghton et al. (1985). However, it is in no way trivial, given that modern fighter aircraft flying at 500 mph (733 feet/s) can cover 40,682 feet – 7.7 miles – in that time.

The delayed performance recovery time noted in this study is consistent with a report by Arnold, Tripp, and McCloskey (1995) that at least 90 s are required after exposure to hypoxia for arterial blood saturation to return to a prehypoxic baseline. The finding of a much shorter recovery time for math performance in this study, in comparison with the 3-min estimated by Houghton et al. (1985), may also be related to hypoxia, given that the severity of hypoxia is proportional to the amount of time in high +Gz (Burton & Whinnery, 1996), and the gradual acceleration profiles used in the Houghton et al. (1985) study increased the amount of time participants were exposed to a high-Gz environment.

This study was also prompted by findings indicating 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 (Gillingham & Fosdick, 1988; Wood, 1990). Because hypoxia can severely impair performance on arithmetic and complex tracking tasks (Sausen et al., 2001; Vaernes et al., 1984), it is conceivable that the flight skills emulated in this study would deteriorate before unconsciousness appeared in a GLOC episode. Such a result would challenge Whinnery et al.'s (1987) assumption that flight performance is not perturbed prior to the onset of unconsciousness. Consistent with our expectation, such deficits were indeed evident in the data; participants abandoned the math task 7.44 s and ceased tracking 3.20 s prior to falling unconscious. Both of these values significantly predate the onset of unconsciousness.

In sum, the results of this study indicate that by focusing on overt symptoms of loss of consciousness and mental confusion and by ignoring subtle nuances of performance degradation that might predate and follow these symptoms, Whinnery et al. (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 s, a period that is more than three times longer than the 24 s 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 summarized in Figure 3. It is important to note that the degraded performance interval observed in this study represents but one set of conditions and that the interval may possibly vary as a function of several other factors, such as dynamic changes in the onset profile that a pilot might endure (Houghton et al., 1985; Morrison, et al., 1994) or the use of anti-G protection.

The asymmetry in the performance deficits prior to and after GLOC noted in this study requires consideration. In the period preceding the onset of unconsciousness, participants ceased performing the math task significantly before they

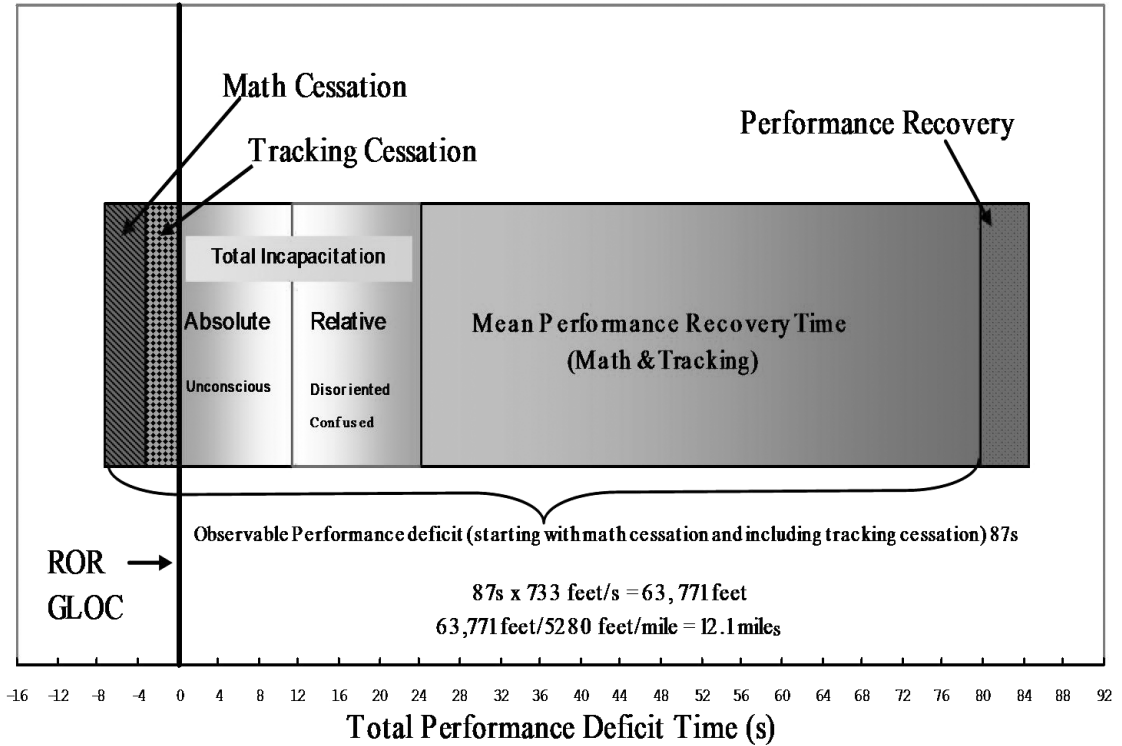


Figure 3. Summary of performance deficit duration under rapid G onset rate (ROR.)

abandoned the tracking task, but post-GLOC recovery times for both tasks were similar. Along this line, it is worth noting that although the *Ns* involved in both comparisons were the same, the effect size for the difference preceding the onset of unconsciousness was quite large ($\omega^2 = .36$), whereas that for recovery was quite small ($\omega^2 = .03$; see Keppel, 1991), indicating that there was little association between recovery time and task type.

A result of this sort with regard to task abandonment and recovery may also be physiologically mediated by hemodynamics within the brain. When a high +Gz force is encountered, blood is withdrawn from the brain in a graded fashion, with ischemia being more pronounced in the cortical than in the lower centers (Fong, 1992; Whinnery, 1989). 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 brain-imaging studies have led to the belief that arithmetic operations are determined primarily at the cortical lev-

el (Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999; Rickard et al., 2000). In contrast, motor control functions, which underlie tracking performance, involve a complex interaction between cortical and subcortical centers (Gazzaniga, Ivry, & Magun, 2002; Kandel, Schwartz, & Jessell, 2000). Thus it is conceivable that because of the lowered level of blood loss in the subcortical components, tracking performance was able to resist the degrading effects of mounting +Gz-induced ischemia for a longer period than was math performance, whereas the balance in cortical and subcortical tissue perfusion following GLOC may have enabled both tasks to recover at the same rate.

A final goal for this study was to determine whether or not perceptual adaptation resulting from repeated exposure to GLOC could minimize the negative consequences of that flight hazard, as suggested by Whinnery and Burton (1987) and Whinnery and Jones (1987). The results of this investigation, however, provided no support for the perceptual adaptation approach. After participants had four exposures to GLOC, one per day over a span of 4 weeks, there was no evidence of

reduction in the periods of unconsciousness/confusion or 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 (see Lackner & DiZio, 1993; Nelson et al., 1998; Welch, 1986). It is noteworthy that the videotapes of repeated GLOC episodes that led Whinnery and Burton (1987) and Whinnery and Jones (1987) to suggest the adaptation strategy featured participants 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 reexamined with massed practice, one should recognize the possible dangers of exposing participants to repeated periods of unconsciousness, 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 (see Lackner & DiZio, 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; Whinnery, 1989; 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.

One might argue that providing participants such as those in the present study with anti-G protection (anti-G suits and anti-G straining maneuvers) might aid them in learning to combat the negative effects of GLOC. However, operational pilots who experience GLOC in flight do so while employing anti-G protection, and their learning through repeated experience to combat GLOC with such protection would still be subject to the

limiting effects of hypoxia and retrograde amnesia. Evidently, approaches other than adaptation need to be developed to overcome the GLOC hazard. One recent approach is the use of an in-flight aircraft autorecovery system that employs physiological data and aircraft-state information to determine that a pilot has experienced a GLOC episode and takes over control of the aircraft until the pilot is able to resume that task (Forster, 1998).

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REFERENCES

- Albery, W. B., & Van Patten, R. E. (1991). Non-invasive sensing systems for acceleration-induced physiologic changes. *IEEE, Engineering in Medicine and Biology*, 10, 52–55.
- Arnold, A., Tripp, L. D., & McCloskey, K. K. (1995). *Human performance effects of decreased cerebral tissue oxygen saturation induced by various levels of mixed oxygen/nitrogen* (Tech. Rep. No. AL/CF-TR-1995-0039; NTIS No. AD-A315 960/51NZ). Wright-Patterson Air Force Base, OH: U.S. Air Force.
- Burton, R. R. (1988). G-induced loss of consciousness: Definition, history, and current status. *Aviation, Space, and Environmental Medicine*, 59, 2–5.
- Burton, R. R., & Whinnery, J. E. (1996). Biodynamics: Sustained acceleration. In R. L. DeHart (Ed.), *Fundamentals of aerospace medicine* (2nd ed., pp. 201–260). Baltimore, MD: Williams and Wilkins.
- Chelette, T. L., Albery, W. B., Esken, R. L., & Tripp, L. D. (1998). Female exposure to high G: Performance of simulated flight after 24 hours of sleep deprivation. *Aviation, Space, and Environmental Medicine*, 69, 862–868.
- Deaton, J., & Mitchell, T. (2000, June). *Aircrew experience with G-induced loss of consciousness: Problem identification analysis* (Report No. T0000027.S001). Orlando, FL: CHI Systems.
- Dehaene, S., Spelke, E., Pinel, P., Stanescu, R., & Tsivkin, S. (1999). Sources of mathematical thinking: Behavioral and brain-imaging evidence. *Science*, 284, 970–974.
- Fong, K. L. (1992). *Maximizing +Gz tolerance in pilots of high performance combat aircraft* (Rep. No. AL-SR-1993-0001). Wright-Patterson Air Force Base, OH: Armstrong Laboratory.
- Forster, E. M. (1998). Smart aircrew integrated life support system. *Aviation, Space, and Environmental Medicine*, 69, 614–615.
- Forster, E. M., & Cammarota, J. P. (1993). The effect of G-LOC on psychomotor performance and behavior. *Aviation, Space, and Environmental Medicine*, 64, 132–138.
- Gazzaniga, M. S., Ivry, R. B., & Magun, G. R. (2002). *Cognitive neuroscience: The biology of the mind* (2nd ed.). New York: Norton.
- Gillingham, K. K., & Fosdick, J. P. (1988). High-G training for fighter aircrew. *Aviation, Space, and Environmental Medicine*, 59, 12–19.
- Glaister, D. H. (1988). Current and emerging technology in G-LOC detection: Noninvasive monitoring of cerebral microcirculation using near infrared. *Aviation, Space, and Environmental Medicine*, 59, 23–28.
- Houghton, J. O., McBride, D. K., & Hannah, K. (1985). Performance and physiological effects of acceleration-induced (+ Gz) loss of consciousness. *Aviation, Space, and Environmental Medicine*, 56, 956–965.
- Kandel, E. R., Schwartz, J. H., & Jessell, T. M. (2000). *Principles of neural science* (4th ed.) New York: McGraw-Hill.

- Keppel, G. (1991). *Design and analysis: A researcher's handbook* (3rd ed.) Upper Saddle River, NJ: Prentice Hall.
- Lackner, J. R., & DiZio, P. (1993). Multisensory, cognitive, and motor influences on human spatial orientation in weightlessness. *Journal of Vestibular Research*, 3, 361–372.
- Lindeis, A. E., Nathoo, A., & Fowler, B. (1996). An AFM investigation of the effects of acute hypoxia on mental rotation. *Ergonomics*, 39, 278–284.
- Maxwell, S. E., & Delaney, H. D. (2004). *Designing experiments and analyzing data: A model comparison perspective* (2nd ed.). Belmont, CA: Wadsworth.
- Morrison, J. G., Forster, E., Hitchcock, E. A., Barba, C. A., Santarelli, T. P., & Scerbo, M. W. (1994). Cumulative effects of +Gz on cognitive performance. In *Proceedings of the Human Factors Society 38th Annual Meeting* (pp. 46–50). Santa Monica, CA: Human Factors and Ergonomics Society.
- Nelson, W. T., Hettinger, L. T., Haas, M. W., Warm, J. S., Dember, W. N., & Stoffregen, T. A. (1998). Compensation for the effects of time delay in a virtual environment. In R. R. Hoffman, M. E. Sherrick, & J. S. Warm (Eds.), *Viewing psychology as a whole: The integrative science of William N. Dember* (pp. 579–601). Washington, DC: American Psychological Association.
- Noble, J., Jones, J. G., & Davis, E. J. (1993). Cognitive function during moderate hypoxaemia. *Anesthesia and Intensive Care*, 21, 180–184.
- Rickard, T. C., Romero, S. G., Basso, G., Wharton, C., Flitman, S., & Grafman, J. (2000). The calculating brain: An fMRI study. *Neuropsychologia*, 38, 325–335.
- Sausen, K. P., Wallick, M. T., Slobodnik, B., Chimiak, J. M., Bower, E. A., Stiney, M. E., et al. (2001). The reduced oxygen-breathing paradigm for hypoxia training: Physiological, cognitive, and subjective effects. *Aviation, Space, and Environmental Medicine*, 72, 539–545.
- Sells, S. B., & Berry, C. A. (1961). *Human factors in jet and space travel: A medical-psychological analysis*. New York: Ronald Press.
- Shingledecker, C. A. (1984). *A task battery for applied human performance assessment research* (Rep. No. AARAML-TR-84-071). Wright-Patterson Air Force Base, OH: Air Force Aerospace Medical Research Laboratory.
- Vaernes, R. J., Owe, J. O., & Myking, O. (1984). Central nervous reactions to a 6.5-hour altitude exposure at 3048 meters. *Aviation, Space, and Environmental Medicine*, 55, 921–926.
- Welch, R. B. (1986). Adaptation of space perception. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance: Vol. 1. Sensory processes and perception* (pp. 24.1–24.45). New York: Wiley.
- Whinnery, J. E. (1989). Observations on the neurophysiologic theory of acceleration (+Gz) induced loss of consciousness. *Aviation, Space, and Environmental Medicine*, 60, 589–593.
- Whinnery, J. E., & Burton, R. R. (1987). +Gz induced loss of consciousness: A case for training exposures to unconsciousness. *Aviation, Space, and Environmental Medicine*, 58, 468–472.
- Whinnery, J. E., Burton, R. R., Boll, P. A., & Eddy, D. R. (1987). Characterization of the resulting incapacitation following unexpected +Gz loss of consciousness. *Aviation, Space, and Environmental Medicine*, 58, 631–636.
- Whinnery, J. E., & Jones D. R. (1987). Recurrent +Gz-induced loss of consciousness. *Aviation, Space, and Environmental Medicine*, 58, 943–947.
- Whinnery, J. E., & Whinnery, A. M. (1990). Acceleration-induced loss of consciousness: A review of 500 episodes. *Archives of Neurology*, 47, 764–776.
- Wickens, C. D., & Hollands, J. G. (2000). *Engineering psychology and human performance* (3rd ed.). Upper Saddle River, NJ: Prentice Hall.
- Wood, E. H. (1990). *Evolution of anti-G suits, their limitations, and alternative methods for avoidance of G-induced loss of consciousness* (Vols. 1 and 2). Arlington, VA: Defense Advanced Research Project Agency, Strategic Technology Office.

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