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Effects of Mild Hypoxia on Pilot Performances at General Aviation Altitudes

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16. Abstract

General aviation pilots may fly continuously at altitudes up to 12,500 ft. without the use of supplemental oxygen. However, hypoxia is a condition that can develop at altitudes under 12,500 ft. Research has shown highly variable tolerance and performance of individuals during low altitude laboratory exposures with simple and complex tasking. This study evaluated the physiological and subjective responses, as well as the simulated flight performance of general aviation pilots during a cross-country flight scenario.

Ten pilots of a mild hypoxia group were compared with 10 pilots of a normoxic control group. Measurements of flight performance from the Basic General Aviation Research Simulator (BGARS) and of flight-following procedures were gathered during a 3-day, 2 hr. per day, cross-country flight scenario. Determined by group membership and terrain elevation during the cross-country flight, subjects breathed either oxygen mixtures simulating sea level, 8,000 ft., 10,000 ft., and 12,500 ft. altitudes or compressed air, throughout.

The physiological measures of oxygen and carbon dioxide partial pressures ($P_{tc}O_2$ and $P_{tc}CO_2$), heart rate (HR), and blood oxygen saturation (SaO_2), provided significant results differentiating the 2 pilot groups and the 4 altitude conditions of the hypoxia group. No significant deviations from assigned altitude, VOR radials, or heading were found during cruise flight. However, significantly more procedural errors were committed by the hypoxia group during cruise flight at 10,000 ft. and during the descent and approach phases of flight from 10,000 ft. on Day 3 and during descent from 12,500 ft. on Day 4. Subjective measures of symptoms, workload, and stress provided limited evidence of hypoxic effects, although the hypoxia group reported significantly greater demands on their time during flight, compared to the control group. Also, significant group differences were found in flight following procedural errors, particularly during the descent and approach phases of flight. Recommendations are made to encourage GA pilots to plan their descents from flights above 10,000 ft. to allow sufficient recovery time as a routine precaution to the often undetectable effects of mild hypoxia.

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FOREWORD

This study was conducted as a part of the FAA Civil Aeromedical Institute (CAMI) general aviation (GA) human factors research program whose efforts support the mission to:

> Conduct applied human factors research in the laboratory and in the field on carefully selected GA problems, to obtain objective, scientifically derived data which will aid in identifying affordable options for reducing the risk exposure, and number of incidents and accidents in the general aviation community, and which will serve to enhance GA pilot performance under non-routine flying conditions.

The CAMI General Aviation Human Factors Research Program is consistent with the FAA policy statement on general aviation, promulgated by the Administrator in 1993, and the goals of the Flight Standards General Aviation Action Plan, distributed in 1992. Development of the program was coordinated with AFS-800, AFS-200, AIR-3, ACE-100 and with guidance by the General Aviation Coalition, accident prevention, and pilot training working groups. FAA human factors program management coordination was provided by AAR-100.

This report resulted from a FY95-96 effort considering the issue of hypoxia during flights in unpressurized general aviation aircraft below the altitude requiring use of supplemental oxygen (i.e., 12,500 ft. and under). Sponsorship for the study was provided by the Office of Aviation Medicine (OAM), and the Aviation Flight Safety Program Branch (AFS-810). Also, through continued coordination of hypoxia research with CAMI's Aeromedical Research Division (AAM-600), this study provided information pertaining to regulatory questions in partial fulfillment of efforts originating in a research project initiative with Aircraft Certification (ACE-100) in 1992.

ACKNOWLEDGMENTS

Several individuals contributed significantly to this research project and should be recognized for their support. Dr. Dennis Beringer (AAM-510) made an assortment of modifications to the Basic General Aviation Research Simulator (BGARS) to meet our specialized requirements and also, assisted in the fine-tuning of the flight scenario. Dr. Scott Mills (AAM-510) developed the Automated Air Traffic Control (Auto ATC) system for the study, which has since been extremely useful in several other projects. He also developed the software interface for the physiological measurement system for data acquisition and real-time monitoring of our subjects during their reduced oxygen exposures. Delbert Marsh, II (OMNI Corp.) was extremely helpful in assisting Dr. Wreggit (AAM-510) in the development of the flight scenario and the ATC scripts employed in the study. He also supported the data acquisition phase of the study by familiarizing many of our pilot subjects to the simulation environment during Day 1 and manning the BGARS experimental work station during Days 2-4.

Charles Chittum (AAM-630) designed and wired the solenoid valve system and remote switching mechanism used in this study to control the simulated altitude/breathing gas administration system. Dr. Robert Garner, Joseph Mandella, and Richard Murphy (AAM-623) performed all of the pulmonary function testing (PFT) sessions with our pilot subjects. Dr. Garner also assisted in interpretation of the PFT and physiologic data of the study. Dr. R.E. Blanchard (AAM-510), managed the CAMI GA Human Factors Research Program and contributed to all phases of this project.

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INTRODUCTION

Federal Aviation Regulation (FAR) 91.211 states:

(a) *General.* No person may operate a civil aircraft of US registry — (1) At cabin pressure altitudes above 12,500 feet (MSL) up to and including 14,000 feet (MSL) unless the required minimum flight crew is provided with and uses supplemental oxygen for that part of the flight at those altitudes that is of more than 30 minutes duration...

However, hypoxia is a condition that can occur during flights at 12,500 ft. (Mean Sea Level) and below, exposing general aviation (GA) pilots to differing degrees of hypoxia that could compromise flight safety as they fly continuously up to that ceiling altitude without supplemental oxygen.

Background

Hypoxia is a state of oxygen deficiency in the blood, cells, or tissues of the body sufficient to cause an impairment of function. In aviation, a reduction in total atmospheric pressure occurs with increasing altitude. This change produces a reduction of oxygen partial pressure (P_{O2}) and hence, a reduction of alveolar oxygen pressure *and* the pressure gradient between the alveoli and mixed venous blood in the pulmonary capillaries. By breathing the "ambient air" of a reduced pressure environment, less oxygen diffuses across the alveolar-capillary membranes into the blood stream and to the tissues of the body.

Among the various tissues of the body, neural tissue is particularly sensitive to reduced oxygen tension. Normal brain functioning requires a relatively constant and high supply of oxygen. The brain consumes almost one-fifth of the total oxygen uptake of the body at rest, even though it comprises only 2% of the body's weight (Ernsting, 1988). Lipton and Whittingham (1982) stated that a low oxygen tension condition profoundly disturbs cerebral functioning. Their work concentrated on certain aspects of neuronal transmission and neurotransmitter metabolism in the brain during hypoxic exposures. They reported on neurological dysfunctioning at pressure-altitude equivalents comparable to the range of GA altitudes of interest in this study.

The human body is quite effective in compensating for the hypoxic condition experienced in aviation, but only up to a certain point (Ward, Milledge, and West, 1995; Van Liere and Stickney, 1963). Physiological compensation occurs in the body to optimize the amount of oxygen available for the tissues by modulating respiration and circulation. Breathing faster and deeper raises the availability of oxygen for diffusion into the circulatory system that also increases in flow rate and volume. Hyperventilation, however, causes a loss of too much carbon dioxide from the body and creates other problems that can also impair a pilot's performance. According to Ernsting, Sharp, and Harding (in Ernsting and King, 1988), the body's ability to compensate for hypoxia during flights above the altitude range of 8,000 and 10,000 ft. (MSL) is compromised by the antagonistic effects of the reduced oxygen tension and hyperventilation.

Factors such as the rate of ascent, the maximum altitude attained, and the duration of flight at that altitude interact with personal factors, such as physical fitness and activity, mental health, and the use of medications and drugs to influence a pilot's tolerance to hypoxia (USAF Physiological Training Pamphlet, 1976). After the pilot reaches higher altitudes, however, the body's ability to compensate for the hypoxia condition is eventually exceeded, and significant physiological disruption occurs. The higher altitudes are also where significant subjective symptoms and behavioral effects occur.

The minimum altitude at which cognitive and psychomotor performance becomes significantly impaired has been, and remains, a controversial issue with important implications for flight safety. Tune

(1964), in a review of the hypoxia literature between 1950 and 1963, concluded that 10,000 ft. was the minimum altitude at which significantly degraded perceptual-motor performance occurred. Denison, Ledwith, and Poulton (1966) found that decremental performance occurred in their study at 5,000 and 8,000 ft., though later, it was believed that the performance effects were due to such factors as the novelty of the Manikin task they used, combined with the physical exertion of pedaling an ergometer at a low workload level of 27 watts. Fiorica, Burr, and Moses (1971), in a study of simple vigilance performance, found no differences between a well-oxygenated group and a group performing the task for 4 hrs. at 11,500 ft. in a hypobaric chamber. Other research has been rather equivocal in identifying hypoxia-related performance task impairment at GA altitudes under 12,000 ft. (Crow and Kelman, 1971, 1973; Green and Morgan, 1985; Kelman and Crow, 1969; Kelman, Crow, and Bursill, 1969).

Fowler, Paul, Porlier, Elcombe, and Taylor (1985) re-evaluated the question concerning the minimum altitude at which hypoxia-related performance decrements could be found. In experiment 1 of their study, they found no slowing of reaction times to a spatial transformation task during the simulated 8,000 ft. condition. However, in experiment 2, they found slower reaction times of the spatial transformation task and attributed them to an accompanying decrease in blood oxygen saturation (SaO_2) values. They explained the decrease in SaO_2 to a combination of hypoxia, exercise, and hypoventilation caused by the breathing resistance of their simulated altitude system. In another study, Fowler, Elcombe, Kelso, and Porlier (1987) modulated the breathing mixtures of subjects to reduce their SaO_2 values in 2% steps between 86% to 76% and found that response times slowed in a step-dependent manner. Their results identified an SaO_2 threshold, an equivalent altitude estimate of 9750 ft., for which performance decrements were found and influenced by a disruption of vision.

A recent study evaluating perceptual-motor performance during hypobaric chamber exposures at pressure-altitude equivalents of 7,000 and 12,000 ft. found that significantly slower response times occurred during both altitudes, compared with a sea-level control, and a significant difference in stimulus discrimination accuracy was found in performance during the 12,000 ft. condition, compared to the sea level condition (McCarthy, Corban, Legg, and Faris, 1995). Comparisons of the discrimination accuracy for the 4 stimulus types showed that subjects had difficulty with digits and ellipses during the 12,000 ft. condition compared to the sea level and 7,000 ft. conditions. Research conducted by the FAA's Civil Aeromedical Institute found that complex task performance was significantly affected by exposures to a simulated altitude condition equivalent to 12,500 ft. (Mertens and Collins, 1986, 1985; Mertens, Higgins and McKenzie, 1983; and Higgins, Mertens, McKenzie, Funkhouser, White and Milburn, 1982).

Other studies that have incorporated complex or multiple, time-shared tasks or simulated flight activities in their designs (Denison et al., 1966; Frisby et al., 1973; Gold & Kulak, 1972; Ledwith & Denison, 1964) produced equivocal results at the altitudes between 8,000 and 12,500 ft. In explanation of this ambiguity of results, Fulco and Cymerman (1987) have suggested that many different factors can influence the performance results of studies on hypoxia, including the interindividual variability of personality traits, motivation, and attentiveness. If these factors are not well controlled for during experimentation, consistent results are not often found.

Purpose

FAR 91.211 clearly states that supplemental oxygen is required for use by pilots in general aviation above 12,500 ft. MSL. Hypoxia, however, occurs during flights below the pressure altitude of 12,500 ft. Research shows that a significant physiological threshold is reached between 8,000 and 10,000 ft., whereby the body's ability to compensate for the condition is diminished and that neurological functioning may be compromised. Individual tolerance to hypoxia is extremely variable and influenced by multiple environmental and personal factors. This interaction of environmental/personal factors with widely variable individual tolerances to hypoxia can either attenuate or accentuate performance degradation. Many research studies of hypoxia have used simple performance tasks and testing procedures. Other research studies have employed more complex tasks and procedures. However, results from studies evaluating the range of altitudes under 12,500 ft., are rather ambiguous and inconclusive about performance degradation. Flight safety remains a significant matter of concern during any flight producing hypoxia, particularly at altitudes between 10,000 and 12,500 ft. MSL.

This study was developed because research has indicated significant physiological evidence of hypoxia during exposures to altitudes between 8,000 and 12,500 ft. but ambiguous evidence of task performance impairment at similar altitudes. The study was designed to evaluate complex pilot performance during simulated flight because comparatively less research has been conducted on hypoxia in a flight simulation environment. Simulated flight in this study required GA piloting skills during a 3-day cross-country scenario. Flight at altitudes of 8,000, 10,000, and 12,500 ft. was required in the scenario by the changing terrain elevation enroute. Differential effects on performance were anticipated for the hypoxia and control groups of subjects.

METHODS

Subjects

Twenty private pilot subjects (17 males, 3 females) were recruited as paid volunteers from a local Part 141 flight training school with national and international clientele. The subjects varied in age from 19-32 (*M*= 22.5, *SD* = 3.5); with an average of 186 total flight hrs.; during the last 90 days they averaged 91 hrs. All subjects performed a pulmonary function test (PFT) to determine normal lung functioning. Ten subjects were randomly assigned to either a hypoxia group or a control group. The hypoxia group breathed altitude-equivalent oxygen mixtures to simulate environmental flight conditions in the research simulator. The control subjects breathed compressed air throughout the experiment.

Simulated Altitudes

Various reduced oxygen breathing mixtures (Primary Standard purity, ± .05 %) were used to simulate the following altitudes:

- sea level (SL) = 21% oxygen, balance nitrogen (Grade E Compressed Air)
- 8,000 ft. (2438 m) = 15.5% oxygen, balance nitrogen
- 10,000 ft. (3048 m) = 14.3% oxygen, balance nitrogen
- 12,500 ft. (3810 m) = 13.0% oxygen, balance nitrogen.

The use of premixed reduced oxygen breathing gas has been found to be an acceptable simulation of altitude (Baumgardner, Ernsting, Holden, and Storm, 1980; Baumgardner and Storm, 1980), and was the only method logistically possible in our flight simulation environment.

Each breathing gas was administered to the subject from high pressure cylinders. Regulator valves (2 Matheson Model 9-580, 2 Victor Equipment Company Model VTS 450 D) reduced cylinder pressures to the inlet 60-100 psi required of the USAF CRU-68/A demand, oxygen breathing regulator (ARO Corp.) that was set in the nondilution mode to deliver 100% of the source gas. Subjects breathed the oxygen conditions via a Scott Aviation Model 358-1540V quick-don, pressure-demand oxygen mask assembly. Selection of each oxygen condition was controlled by a manual remote switch box that electronically actuated 1 of 4 (ASCO® normally closed) solenoid valves. High-pressure lines connected each of the oxygen cylinders to the 4 solenoid valves. High pressure outlet lines connected the 4 valves to a single line to the CRU-68A breathing regulator. The 4 solenoid valves were secured to a metal box placed within an acoustical attenuation enclosure. An internal fan provided cooling for the valves. The cylinder pallet and the valve system were located adjacent to the BGARS behind acoustical panels and out of sight and sound of the pilot subject. The CRU-68A breathing regulator was located to the left of the pilot's seat. Remote switching from one valve, and hence oxygen mixture, to another by the experimenter was unnoticed by the subject.

Measures

Physiological variables. Four physiological variables were measured:

1) oxygen partial pressure ($P_{tc}O_2$) (Radiometer TCM-3)
2) carbon dioxide partial pressure ($P_{tc}CO_2$) (Radiometer TCM-3)
3) heart rate (beats per minute) (Nelcor Pulse Oximeter Model 200)
4) blood oxygen saturation (SaO_2) (Nelcor Pulse Oximeter Model 200)

These 4 measures were displayed on a CRT for near-real time monitoring of each subject and stored on a 486 personal computer (PC). Data were stored as ASCII files for post-study analysis.

Pulmonary Function Testing (PFT) was conducted prior to the training session for each subject in the study. This testing was conducted by the Environmental Physiology Laboratory staff (AAM-623) with a spirometer (Sensormedics Model 922). Increased risk, associated with the reduced oxygen conditions of our study, prohibited subjects with significantly out-of-range PFT results from participating in the study.

Flight performance. This study used a flight simulator that was modular by design with simulation software emulating flight instrumentation and a popular single engine general aviation aero-model. The Basic General Aviation Research Simulator (BGARS) employed use of high-fidelity analog controls with damped self-centering yoke and throttle quadrant, gear, flap, and trim controls, as well as navigation radios and frequency select controls. Combined with a large front projection screen for the forward view (50° of visual angle) and 2 19" CRT monitors for 45° and 90° left views of the outside world, the BGARS was considered operationally realistic and required complex piloting tasks during flight. Additional information concerning the BGARS is found in Beringer (1996).

Sixteen flight performance variables were collected at 0.2 Hz. with an aero-model emulating a Beech Sundowner aircraft. The sixteen variables included:

1. Sample number
2. Longitude
3. Latitude
4. Altitude
5. Airspeed
7. Magnetic Variation
8. Gear
9. Flaps
10. Airway marker
11. Outer marker
12. Middle marker
13. Glide slope altitude
14. DME
15. Localizer error
16. Event marker

Two hours of flight data were recorded for each day of the cross-country scenario. Videotape recordings of the cockpit environment (including audio), indexed to DME, were made for each day. Digital audiotape (DAT) recordings were also made of all communications for post processing. The DAT-based pilot voice wave profiles will be analyzed for evidence of altitude/hypoxia effects at Brown University (Lieberman, Protopapas, and Kanki, 1995; Lieberman, Protopapas, Reed, Youngs, and Kanki, 1994).

Scenarios and procedural errors. Figure 1 represents a scenario timeline and altitude profile of the 4-day study. Each day's flight required ascent to the targeted altitudes of the study due to changing ground elevations. Cruise flight segments of approximately 45 min. duration were designed for each targeted altitude as a minimum exposure necessary to produce hypoxic effects on performance. Twenty-knot winds were designed into each day's flight in a manner that provided a similar, but opposite, crosswind component. The scenario checklist and Air Traffic Control (ATC) scripts for each day are provided in Appendix A and a summary of the scenario timeline and altitude profile depicted in Figure 1 is as follows:

Day 1: Study overview, signed consent, PFT, 1.5 hr. mask assembly adaptation and BGARS familiarization flight with sea level breathing conditions.

Day 2: Ryan Field to Phoenix Sky Harbor Airport. Under ATC flight following, subjects were instructed to fly the first cruise segment at 4,000 ft. (while breathing compressed air). Midway, subjects were instructed to climb to 8,000 ft. (switched to breathing 15.5% O_2).

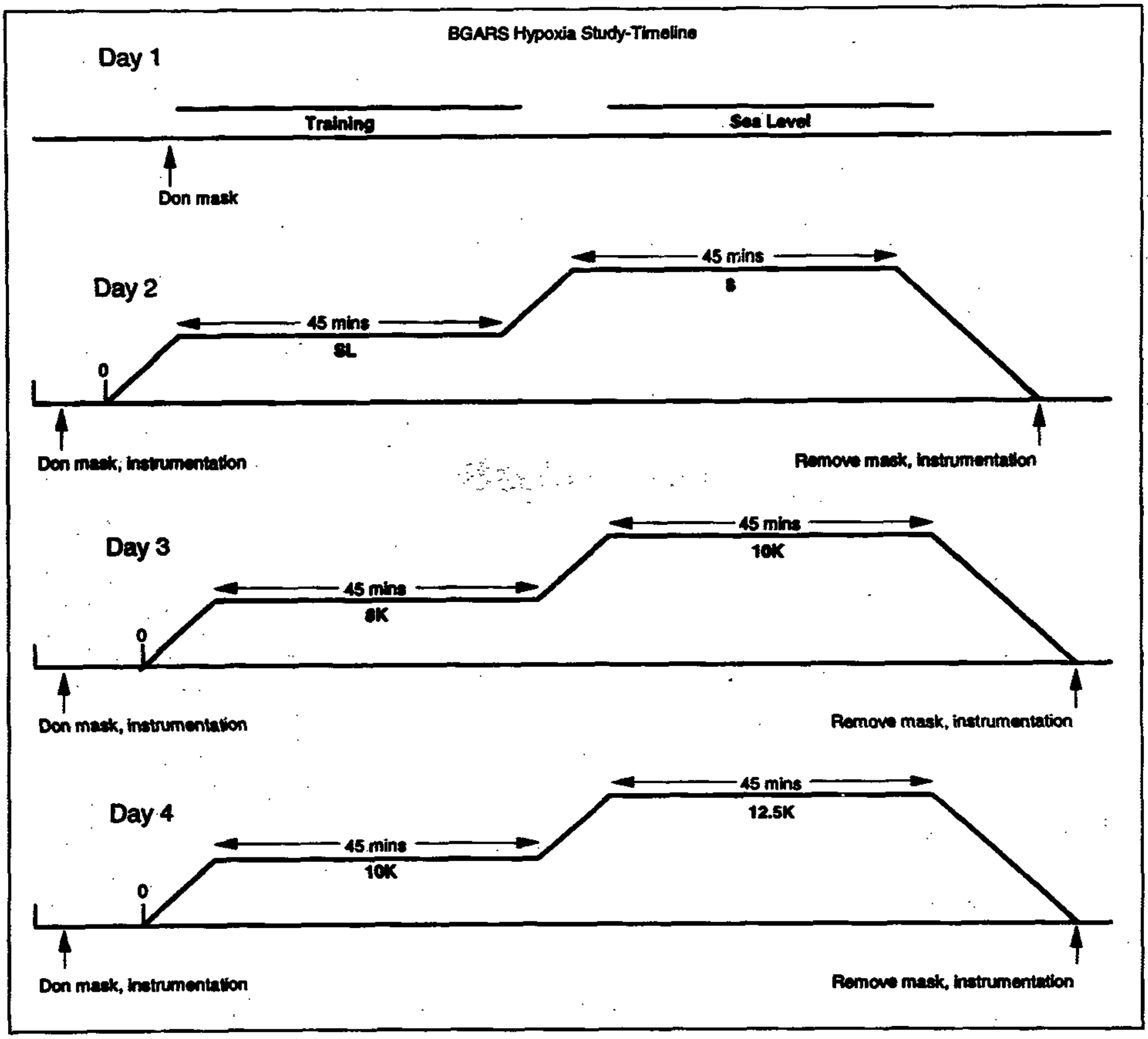

Figure 1: BGARS hypoxia study scenario timeline and altitude profile.

Day 3: Phoenix Sky Harbor to Gallup Airport (New Mexico). Flight following instructed subjects to fly at 8,000 ft. during the first cruise segment (breathing 15.5% O_2). Midway, subjects were instructed to climb to 10,000 ft. (switched to breathing 14.3% O_2).

Day 4: Gallup Airport to San Luis Regional Airport (Colorado). Subjects flew the first cruise segment at 10,000 ft. (while breathing 14.3% O_2), as directed by ATC under flight following conditions. Midway, subjects were instructed to climb to 12,500 ft. (switched to breathing 13.0% O_2).

All subjects were under ATC flight following rules and were provided with instructions via a pre-scripted automated ATC voice system. This system was designed to provide the same scenario script for all subjects with different voices for each different controller as the flight progressed from ground communications to departure, enroute, and tower on approach when available. Instructions were provided for pilots to change headings, change radio frequencies, change transponder frequencies, intercept very high frequency omnidirectional range (VOR) system radials, report heading and altitude information, and to report intercepts and other flight relevant information. Because of these numerous requests, opportunities for pilots to commit "procedural errors" were frequent and available for measurement during the cross-country flight. The procedural errors were important additional measures of pilot performance during the 4-day study.

Subjective questionnaires. Several standardized mood and subjective state questionnaires were utilized to identify changes perceived by the subject over the course of each session. Pre- and post-flight measures included: Mood II scale, the Stanford Sleepiness Scale (SSS), and the Environmental Symptoms Questionnaire (ESQ-III). The NASA TLX survey measured perceived workload and was presented only during the post-flight questionnaire session. Brief descriptions of these measures are provided in Appendix B.

Training Procedure

The first day was devoted to providing subjects with information concerning the experiment and equipment, reading and completing the informed consent form (as directed by the CAMI Institutional Review Board), conducting the PFT, and a familiarization/training flight with BGARS (refer to Appendix A for details). The introductory flight required the pilot to perform simple and basic flight maneuvers, both without and with a 20-knot wind (e.g., standard rate turns and pattern work), operate navigation and communications radios, intercept VOR radials, and become familiar with the automated ATC system used for all air traffic transmissions and scenario flight following procedures. Also during the training flight, subjects became accustomed to using the oxygen mask assembly, Peltor headphones, and simulated altitude delivery system. Subjects wore the quick-don oxygen mask and breathed room air throughout the 1.5 hr. training flight to become accustomed to the breathing resistance and the general distractions imposed by the system. Upon conclusion of the training day, subjects landed at Ryan field in Arizona and were briefed in preparation for the continuous 3-day cross-country flight across Arizona, New Mexico, and into Colorado.

Experimental Procedure

Upon arrival for each experimental session, subjects completed a daily health and sleep survey and the pre-flight subjective symptom and mood questionnaires. A short pre-flight briefing was provided before the subject reviewed the chart(s) and general course for the day. Subjects recorded all NAV/COM frequencies and other information that they believed pertinent for the flight. Each session involved approximately 2 hrs. of continuous flight; therefore, subjects were given a short break before electrode application and donning of the mask and headphones. Following equipment setup, subjects breathed compressed air until a required change in altitude occurred.

Once the physiological measures stabilized, pilots provided a read-back of selected letters of the phonetic alphabet for the daily baseline DAT recording. The flight scenario began with the pilots listening to Automated Terminal Information System (ATIS), contacting ATC for instructions and/or announcing their intentions on the traffic advisory frequency, when applicable, before take-off. Once airborne, subjects requested flight following to their destination airport or field. The experimenter followed a daily scenario script to activate data markers and trigger specified

Auto-ATC voice files for proper sequencing of communications (detailed in Appendix A). After pilots were instructed to climb or descend to different altitudes, the experimenter manually switched a remote controller to introduce the appropriate breathing gas condition as the subject passed through an altitude of 1000 ft. below, when climbing and above, when descending to each targeted altitude.

ANALYSIS AND RESULTS

Analyses for this study were conducted using the Statistical Analysis System (SAS) General Linear Model (GLM) procedures for the parametric data and the Statistical Package for the Social Sciences (SPSS) for all nonparametric analyses.

Data reduction and calculation of means, standard deviations, and Root Mean Square Error (RMSE) were completed using Microsoft Excel V6.0. Event markers were inserted into both the BGARS and physiological data at times when subjects were asked to climb, descend, complete particular tasks, and when the breathing mixture was switched by the experimenter. Insertion of the markers allowed for precise partitioning of the data during the reduction process. Because stabilization of the subject's physiology was important in evaluating the effects of hypoxia on performance, only data corresponding to the approximately 45 min. cruise-altitude segments for both the physiological and BGARS data were analyzed.

The between-subjects factor was Group (hypoxia or control). The within-subjects factors were Cruise segment (1-6) for the initial series of analyses and Altitude condition (SL, 8K, 10K, 12.5K ft.) for the final series. Initial analysis procedures evaluated the 6 cruise-altitude segments for evidence of sequential trial effects and/or evidence of time-on-task effects, particularly the early vs. late conditions of the 8,000 ft. and 10,000 ft. altitudes. No such effects were found in the results of this series of analyses, so, the early session/late session altitude data were combined and a final series of analyses were performed. The results of these analyses are presented in the following sections for the physiological, BGARS, procedural error, and subjective survey data.

Physiological Data

Means and standard deviations of the 4 physiological measures are shown in Table 1 for the hypoxia group and control group for each altitude condition. The 8,000 ft. and 10,000 ft. columns in the table labeled 8K and 10K, represent mean values of the two cruise altitude exposures for those conditions, respectively (refer to Figure 1).

Table 1: Means and standard deviations of the 4 physiological variables.

Variable	Group	SL	8K	10K	12.5K
$P_{tc}O_2$	Hypoxia	73.36	42.51	32.64	23.15
		(13.60)	(10.12)	(9.56)	(8.96)
	Control	71.60	69.91	70.37	68.72
		(12.00)	(14.65)	(19.32)	(25.42)
SaO_2	Hypoxia	99.00	95.53	92.78	89.01
		(0.68)	(2.53)	(2.54)	(4.78)
	Control	97.24	98.00	98.70	96.96
		(2.59)	(2.24)	(0.87)	(0.82)
$P_{tc}CO_2$	Hypoxia	46.14	45.22	44.28	42.43
		(1.92)	(2.19)	(2.31)	(2.19)
	Control	43.27	42.94	43.45	43.44
		(3.94)	(3.90)	(4.14)	(4.68)
Heart Rate	Hypoxia	80.39	86.72	88.82	89.60
		(7.55)	(8.93)	(9.72)	(9.87)
	Control	88.56	85.44	83.35	83.35
		(14.15)	(14.03)	(11.49)	(10.67)

Significant results of the analyses of the oxygen partial pressure measure ($P_{tc}O_2$) included a between group effect, $F(1,18) = 25.14$, $p<.0001$, an altitude effect, $F(3,54) = 24.08$, $p<.0001$, and a group by altitude interaction effect, $F(3,54) = 20.12$, $p<.0001$. These effects were anticipated and Ryan-Einot-Gabriel-Welsch (REGW) Multiple Range Tests showed that the oxygen level in the tissues was different between the experimental hypoxia group and the control group and that the tissue oxygen level decreased as altitude increased.

One-way ANOVAs were conducted to analyze further the interaction effect and revealed that tissue oxygen for the hypoxia group changed significantly with increasing altitude but remained the same for the subjects of the control group. Figure 2 presents means and standard errors of the $P_{tc}O_2$ variable for each group across the altitude conditions.

Analyses of the blood oxygen saturation measure (SaO_2) yielded results quite similar to those of $P_{tc}O_2$, as we expected. The results demonstrated a between group effect, $F(1,18) = 27.57$, $p<.0001$, an altitude effect $F(3,54) = 16.33$, $p<.0001$, and a group by altitude interaction effect $F(3,54) = 34.02$, $p<.0001$. Post-hoc testing showed that SaO_2 for the hypoxia group decreased in value with increasing altitude but remained the same for the control group because they breathed compressed air throughout the experiment. Figure 3 presents the SaO_2 means and standard errors for each group across the altitude conditions.

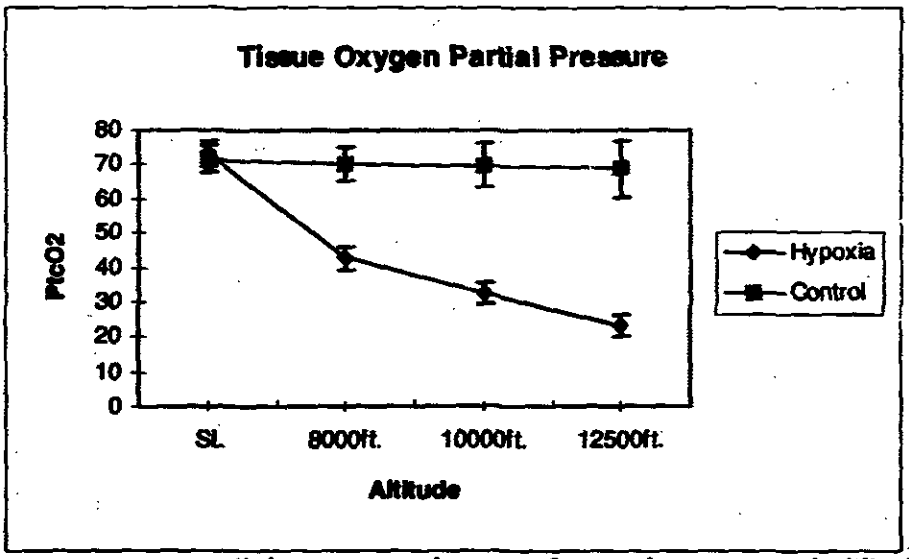

Figure 2: Tissue oxygen partial pressure changes for each group and altitude condition.

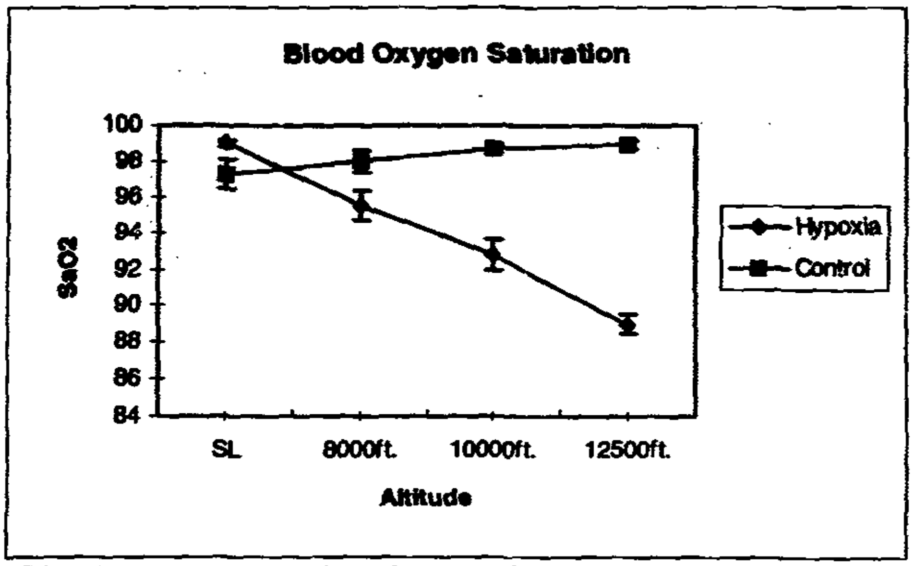

Figure 3: Blood oxygen saturation changes for each group and altitude condition.

Analyses of the carbon dioxide partial pressure measure ($P_{tc}CO_2$) yielded an altitude effect $F(3,54) = 6.57, p<.0007$, as well as a group by altitude interaction effect $F(3,54) = 10.09, p<.0001$. ANOVA simple effects analyses for the interaction terms showed that $P_{tc}CO_2$ for the hypoxia group decreased across altitudes, whereas the control group showed no change. Means and standard errors of the $P_{tc}CO_2$ data are shown in Figure 4.

Results of the analysis of the heart rate data showed a group by altitude interaction effect $F(3,54) = 9.95, p<.0001$. No significant effects were found in the one-way ANOVAs conducted for simple effects. Heart rate means and standard errors are portrayed in Figure 5.

Flight and Performance Data

Sixteen measures were collected with BGARS to assess pilot performance and capture flight information. Data for each variable were measured and recorded every 5 seconds during the data collection flight. For this study, only the altitude and heading measures and VOR tracking error were deemed relevant and reduced for analysis. Event markers were used to signify various points in the data when subjects climbed, descended, or completed particular tasks, and when the breathing mixture was changed by the experimenter. Means and standard deviations are shown in Table 2 for the 3 BGARS measures for each group across the altitude conditions.

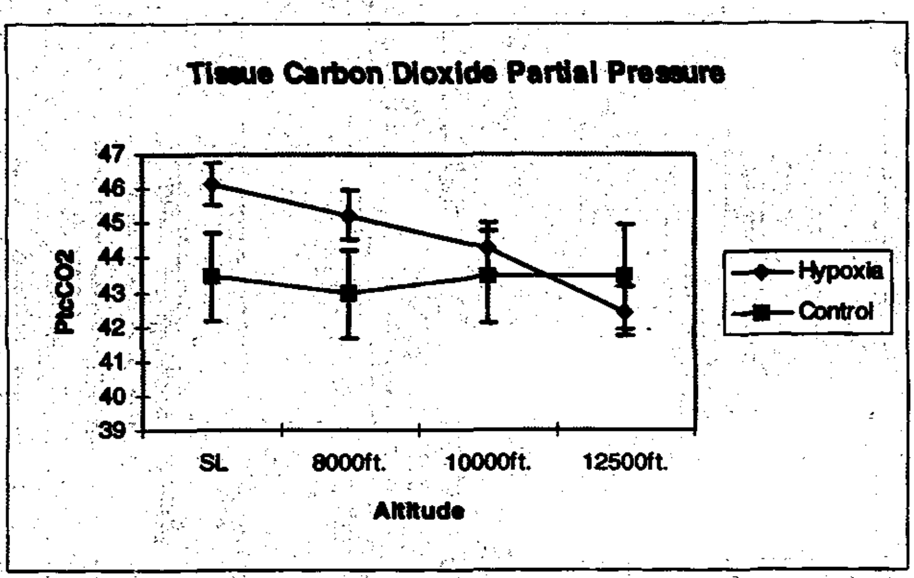

Figure 4: Tissue carbon dioxide partial pressure changes for each group and altitude condition.

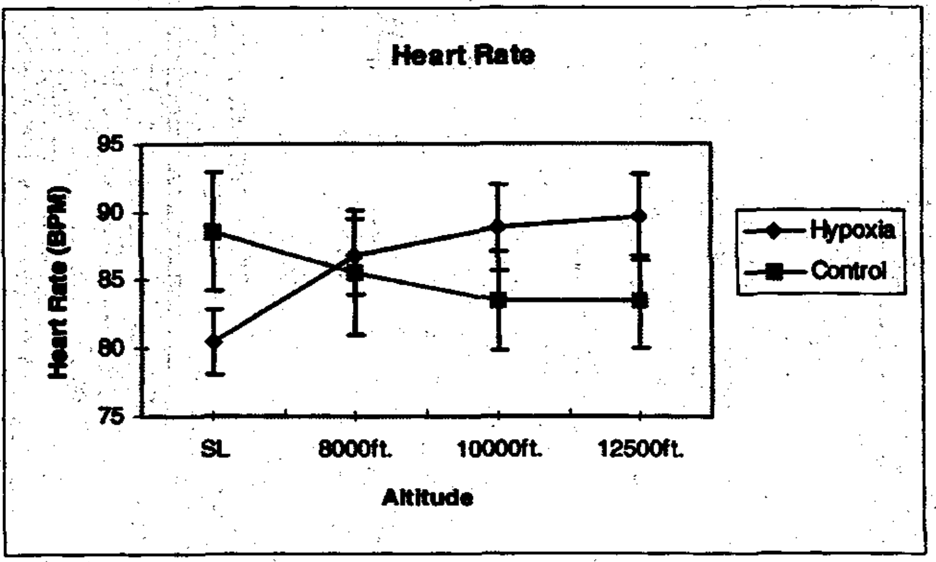

Figure 5: Heart rate changes for each group and altitude condition.

Table 2: Means and standard deviations for the BGARS variables.

Variable	Group	SL	8K	10K	12.5K
ALT RMSE	Hypoxia	37.41	33.06	30.70	25.98
		(16.63)	(12.28)	(16.46)	(14.32)
	Control	53.87	36.51	32.39	32.84
		(48.59)	(14.72)	(13.51)	(13.56)
VOR RMSE	Hypoxia	1146.46	1801.91	1554.18	1288.38
		(543.92)	(1597.52)	(1376.26)	(1179.85)
	Control	1652.24	1503.27	1710.07	1498.61
		(1479.16)	(1140.32)	(1471.89)	(1004.42)
HEADING RMSE	Hypoxia	5.34	5.97	5.53	3.90
		(2.03)	(6.37)	(0.99)	(0.69)
	Control	5.98	12.53	5.95	4.72
		(2.73)	(9.09)	(1.33)	(1.63)

Altitude Data. Aircraft altitude measures were sampled once every 5 seconds with the BGARS. Only data following the event marker, when subjects reported being level at assigned cruise altitudes, were used for comparisons. If the aircraft was ascending or descending, these data were parsed from the cruise segments and not used in the analysis. Root Mean Square Error (RMSE) was calculated for each cruise-altitude segment for each day. RMSE was obtained by using the following formula for each subject on each day:

$$\sqrt{\frac{\sum(X_i - criterion_i)^2}{(n)}}$$

Where *i* is the sample, *criterion* is the assigned altitude, and *n* is the total number of samples for a given segment.

Results of the analysis of altitude RMSE found an altitude effect, $F(3,54) = 4.49$, $p<.007$. No other effects were found. Ryan-Einot-Gabriel-Welsch (REGW) Multiple Range Tests found mean altitude RMSE to be greater during the SL altitude condition, compared to all other conditions. Further investigation found an outlier value in the control group data that dramatically affected the mean value for the analysis.

VOR Tracking Error. VOR tracking error was reduced and RMSE was calculated for each assigned radial during each cruise altitude. More attention was needed to reduce these data because some cruise segments required both intercepting and flight over more than 1 VOR radial. To investigate accurately the effects of the altitude conditions on tracking error, only data from the cruise segments when subjects were level at a particular altitude and were flying a particular radial, were used. Segments of flight when the aircraft was ascending, descending, or turning to intercept another radial, were omitted. This allowed for a proper between-group comparison of performance for each altitude condition.

The BGARS calculates tracking error data (in feet) from the radial vector that is dialed in on the navigational radio no. 1 (NAV1; subjects were instructed to use this radio as their primary navigational radio). The tracking error output was equivalent to having already computed the value of the above RMSE calculation; therefore, the error scores were squared and summed, then divided by *n* to complete the computation. The results of the analysis for the VOR RMSE measure found no significant effects.

Heading Data. Wind conditions were designed into the BGARS flight scenarios so that each day there would be some degree of dynamic perturbation and challenge for performance. As configured, winds of 20 knots were selected to produce differential crosswind effects for the cruise segments each day. Because of the variability in the direction of the winds and flight, different crab angles were required to maintain accurate flight along each radial vector. The degree of wind correction (or crab angle) necessary to maintain a given radial varied between +5° and -9°. Wind correction angle was calculated using a Jeppesen model CR3 computer for analysis.

Heading RMSE was calculated for each requested cruise heading. These calculations were computed using the same formula for RMSE as was used with the altitude data. Cruise segments for heading error were broken down by altitude in the same manner as the Localizer Error data. The analysis of heading RMSE yielded no significant results.

Procedural Error Data

Pilot procedural errors and other pilot behaviors were recorded during each session by the experimenters. These data were not explicitly captured by the BGARS measures but were collected as additional indices of pilot performance. These measures were classified into 12 error categories and were based mostly on scripted opportunities related to ATC flight following procedures, requested activities, and routine and unexpected events, including:

1. Misdialed Frequency or Transponder Codes
2. Failed to use Reciprocal value when setting OBS for the *inbound* Radial
3. Failed to report radial intercept, level at altitude, etc., as previously instructed by ATC
4. Deviated from course by inattention or distraction (e.g., reading chart, dropping chart)
5. Failed to follow ATC instruction
6. Landed downwind
7. Crashed on landing attempt
8. Failed to recognize airport (even after reporting "in sight")
9. Missed approach (did not land on initial attempt, had to go around)
10. Premature maneuver or radio contact
11. Landed in wrong location
12. Dialed incorrect OBS setting (unrelated to inbound reciprocal)

The procedural error records were reviewed and categorized by the experimenters. The approach used to evaluate the error data was to parse the data by (1) error category, (2) altitude, (3) cruise segment, and (4) phase of flight; then, with a nonparametric test, the data were analyzed for group differences. First, the data were summed over subjects by group for each error category. This characterized the errors committed by each group, as shown in Figure 6. A Mann-Whitney nonparametric test of error category resulted in significant group differences for the *Did not see/ recognize airport* category, U(1,19) = 30, $p = .03$, and the *Failed to use reciprocal* category, U(1,19) = 29.5, $p = .05$. Visual inspection of all the data suggested general group differences.

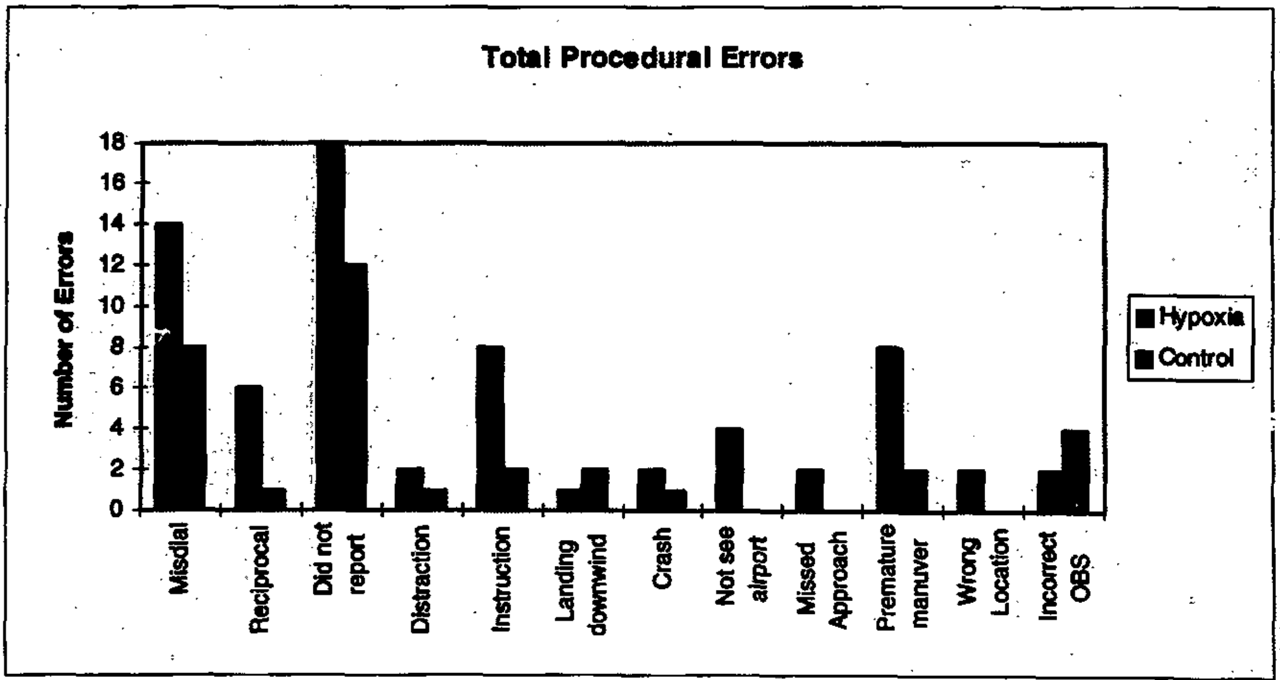

Figure 6: Total number of procedural errors for each group by error category.

Next, the approach was to sum and average errors across altitude condition for each group. These data are presented in Figure 7. Visual inspection, again, suggested group differences. The Mann-Whitney nonparametric test results, however, were not found to be statistically significant at the 0.05 level.

Errors were summed across subjects within each group for each cruise-altitude segment and are presented in Figure 8. A Mann-Whitney nonparametric test for cruise-altitude segment was again computed and indicated significant group differences at 10,000 ft. during the first cruise segment at that altitude, $U(1,19)=18$, $p=.010$.

The last step in the analyses of the procedural error data was to evaluate the errors summed across subjects within each group for each phase of flight. These data are presented in Figure 9. A Mann-Whitney nonparametric test was conducted to determine whether group differences were present during certain phases of flight. A significant difference between groups was found for the first 10,000 ft. cruise segment on Day 3 ($U(1,19)=25$, $p=.03$), confirming the previous analysis. Also, significant differences were found between groups on the descent phases of flight for both Days 3 and 4 ($U(1,19)=30$, $p=.03$ and $U(1,19)=30$, $p=.029$) and a trend for Day 2. The descent phase of flight for

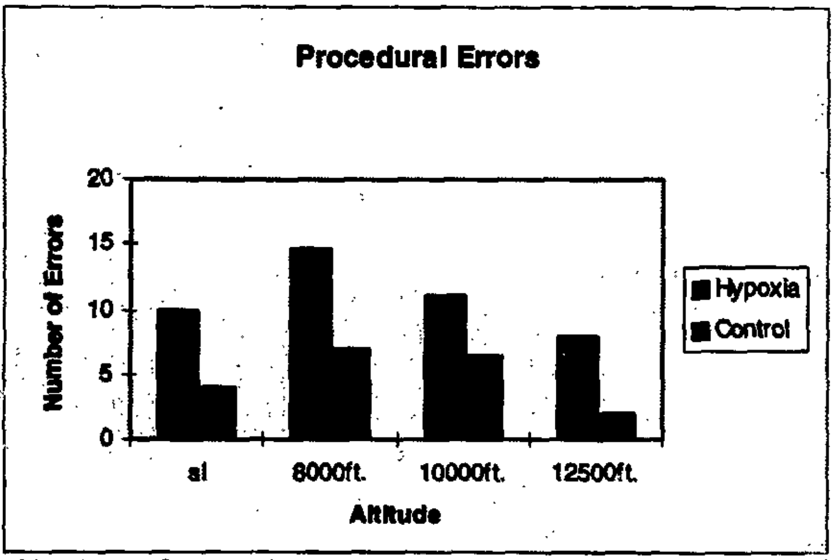

Figure 7: Number of procedural errors for each group and altitude condition.

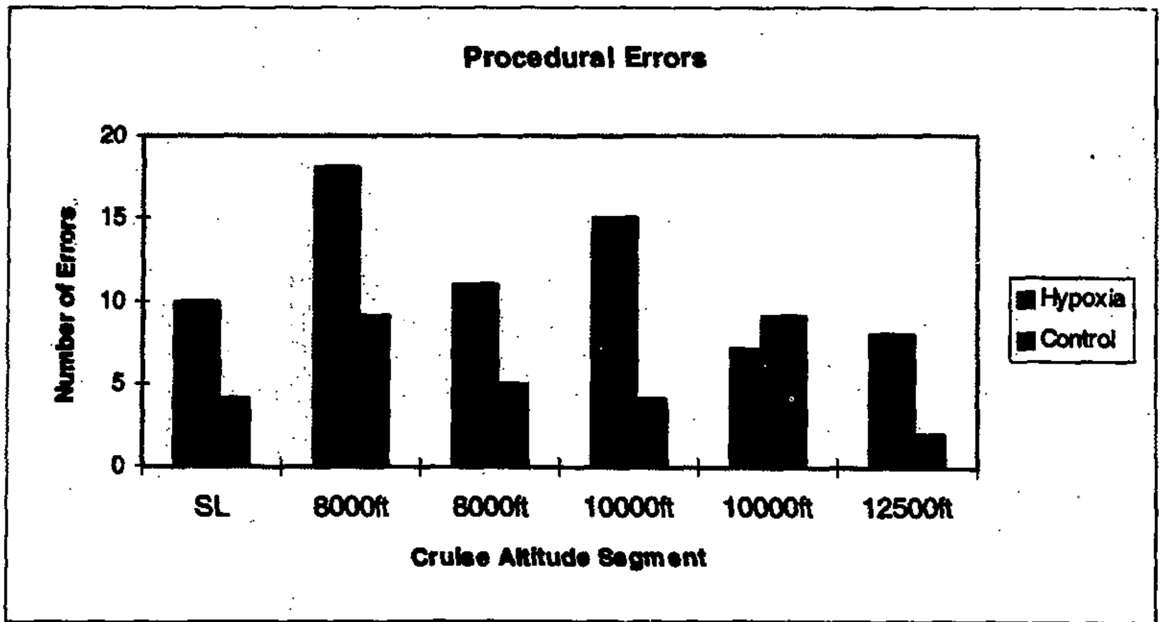

Figure 8: Number of procedural errors for each group and cruise altitude segment.

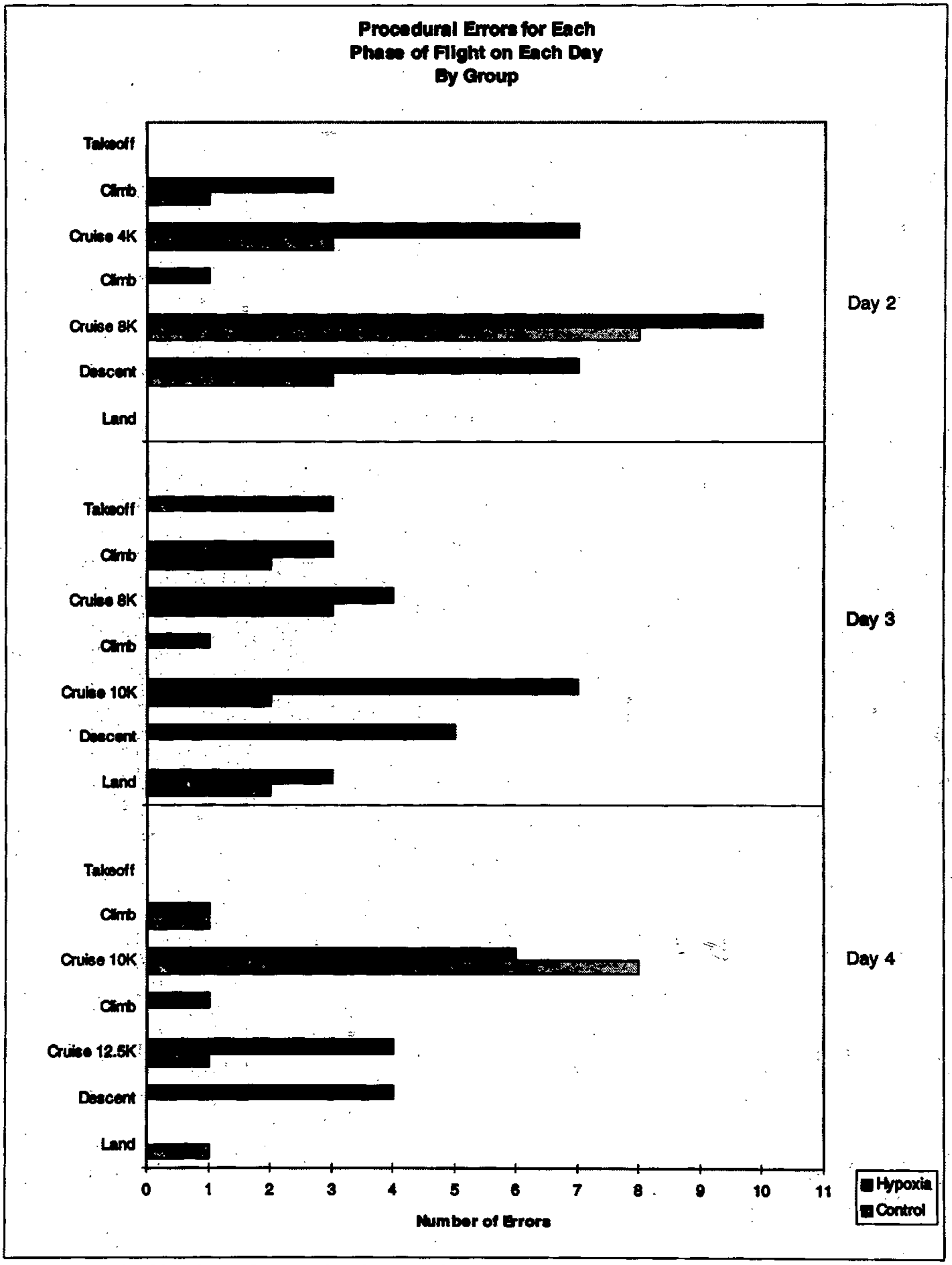

Figure 9: Number of procedural errors for each phase of flight on each day by group.

this study also included the approach to landing segment of flight. The results of these analyses indicated that the hypoxia group committed significantly more procedural errors, compared to the control group, during descent to landing.

Questionnaire Data

The subjective questionnaire data were collected during pre- and post-flight sessions on each of the 3 experimental days. No statistically significant effects were found to differentiate the hypoxia group from the control group for the 9 factors of the Environmental Symptoms Questionnaire (ESQ-III), the 6 subscales of the Mood II questionnaire, or for the Stanford Sleepiness Scale.

The NASA TLX workload scale was completed only during the post-flight session each day. The results of the analysis found a group by day interaction effect and significant differences between the hypoxia group and the control group for the temporal stress subscale. Figure 10 depicts the mean TLX score for each subscale by group. The results show that the hypoxia group provided ratings of greater temporal stress than did the control group; they felt a greater demand on their time while completing the required tasks during the flight.

DISCUSSION

An experimental group of 10 pilots, breathing reduced oxygen concentrations to simulate GA altitude flight conditions, was compared with a control group of 10 pilots breathing a sea level concentration of oxygen (i.e., 21% O_2). The premise tested was that differential changes in physiologic, subjective, and performance measurements proportional to the simulated altitude conditions, would occur with the hypoxia group, whereas the control group would show no significant changes.

Analysis of the physiological data clearly demonstrated the predicted differential effects of the simulated altitude conditions. Group by altitude interaction effects were found for all 4 physiologic measures, indicating that the simulated altitude conditions of the study were consistently achieved for the hypoxia group and significantly different for the control group. Limited supporting evidence of perceived hypoxic changes for the experimental group was provided by the subjective questionnaire results. Though the critical respiratory index factor of the ESQ III demonstrated a unique trend for the hypoxia group; these subjects appeared to have experienced greater respiratory distress, compared to the control group. Also,

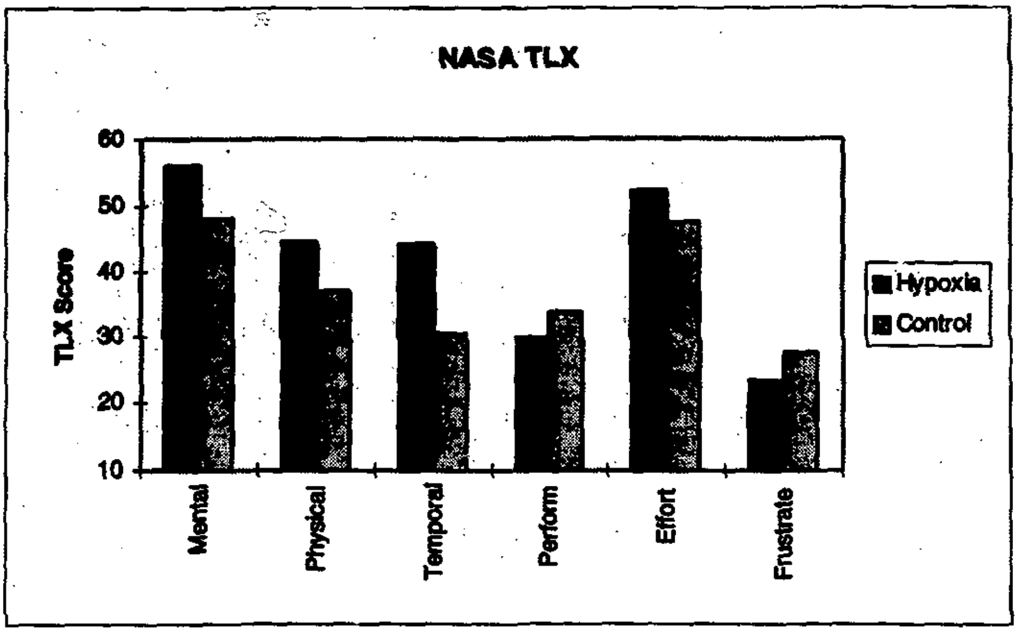

Figure 10: NASA TLX workload subscales by group.

anecdotal reports given by the hypoxia group during the final debriefing session indicated that they had noticed subtle changes that were consistent with hypoxia but had not realized their importance until after leaving the laboratory.

Simulated flight performance with the BGARS showed no statistically significant differences between groups across the altitude conditions in the cruise phase of flight. The BGARS represented a medium fidelity task environment within which it was anticipated that group differences would be found during flight. The most reasonable explanation for not finding significant flight parameter effects, concerned the routine and relatively uneventful cruise phases of flight. While the overall scenario provided the requirement for multiple operations, and the crosswinds provided a challenge for accurate VOR tracking performance, the task loading of each cruise-altitude segment appears to have been insufficient to influence the measures of performance associated with the hypoxia conditions. Only an occasional request to report heading and altitude were made during each cruise segment. The pilot had little else to occupy his/her time during these segments and maintaining straight-and-level flight was relatively easy. However, pilots in the hypoxia group rated greater temporal stress on the NASA TLX workload scale as it applied to their BGARS flight performance. Although this result was not clearly tied to any specific segment of flight, the elevated scores for this group, compared to the control group, reflected a perception of greater demands on their time while performing flight activities.

Another measure of pilot performance in this study revealed hypoxia-related effects. All pilot-subjects were under ATC flight-following procedures throughout the cross-country scenario. These procedures provided control and consistency in the activities of the flight scenarios. Effectively, the procedures determined *what* activities would happen *when* and what responses were expected to occur. Observed details of each pilot's behavior were recorded throughout the 3-day cross-country flight and captured whether or not they responded appropriately to the ATC requests including: changes of frequencies, VOR intercepts, reports of heading and altitude changes, and other scripted (and all unscripted) activities. Opportunities for failing to respond appropriately were, therefore, scheduled and fairly frequent. Since all subjects were exposed to the same requests and flight activities at approximately the same times during the 3-day scenario, procedural errors were considered important measures of performance for comparisons between groups.

Statistically significant group differences were found in the number of errors committed during flight over the 3-day scenario by nonparametric tests. Reduced by phase of flight, significant group differences were found during the cruise phase at 10,000 ft. and during the descent phase from 10,000 ft. on Day 3, and during the descent phase from 12,500 ft. on Day 4. A nonsignificant trend of increased errors also occurred on Day 2 during descent from 8,000 ft. The descents and combined approach phases of the study occurred at the end of the daily flight that were also, at the end of each 2-hr. session. Subjects in the hypoxia group had, therefore, been breathing reduced oxygen for up to 2-hrs. at the time of descent which is an important point, because it is consistent with flights in the "real world". Flights at GA altitudes for any length of time are followed by descent, approach, and landing phases of flight. Some aircraft accident data suggests that, compared to the amount of time spent in various phases of flight, a moderate proportion of consequential events occur during descent and approach (Baker et al., 1996; Boeing, 1994). These data highlight the criticality of committing errors during the end of any flight and demonstrate the need for careful piloting performance.

The results of our data suggest that the duration of the hypoxic (reduced oxygen) exposure and/or the mild hypoxia condition, itself, significantly affected the number of procedural errors committed by the subjects of the experimental group, compared to the control group. The control group (breathing compressed air throughout the flights) committed only 3 errors during descent from 8,000 ft. on Day 2 and no errors during descents from 10,000 ft. on Day 3 or from 12,500 ft. on Day 4.

In a break-down of the types of errors that were committed by the hypoxia group during descent, the following was found:

1. Four different pilots on Day 2 initiated premature flight maneuvers (changing heading and/or altitude before instructed).
2. One different pilot on each day misdialed a radio frequency.
3. One different pilot during Days 2 and 4 failed to follow ATC instructions.
4. Two different pilots flew a missed approach on Days 2 and 4.
5. One pilot crashed while descending on Day 3 (he failed to check ground elevation on the chart).
6. Four different pilots misreported seeing the airport or field on Days 3 and 4 and required additional instructions.

The last error in the above list, was of interest because all subjects were requested to report when the airport was in sight and each of the 4 hypoxia group pilots making the error reported sighting the airport but continued their flights over the field even with the centerline clearly visible in the display. Each of these pilots maintained their headings well beyond the field and eventually requested ATC assistance and vectors back toward the field. None of the control group subjects had difficulty identifying the airports. Some aspect of reduced vision may have been a factor for the hypoxic subjects to overfly the field, or, perhaps a form of behavioral fixedness could have occurred in these subjects to maintain their last given heading.

Regardless, after reviewing the physiological data, subjective reports, procedural error data, and laboratory notes for these subjects, it was concluded that subtle effects of hypoxia were observed in the experimental group. Unsafe and high risk piloting behaviors were recorded during the final phases of flight for many subjects of the hypoxia group, particularly from the 10,000 ft. and 12,500 ft. altitudes. Subjects of the control group, though not error-free over the 3 days, generally exhibited deliberate and cautious behaviors during the last critical phases of flight; often asking for additional weather and field-condition information. Some of the control group pilots were also observed to descend slowly outside of the landing pattern and only entered the pattern after their intentions were announced. Few, if any, of the experimental subjects conducted their descents and approaches in this manner. Hurried and precipitous behavior was often seen during descents for many pilots of the hypoxia group.

Recommendations

In summary, this study did not provide unequivocal evidence of detrimental flight performance due to the mild hypoxia found during the cruise segments at 8,000, 10,000, and 12,500 ft. simulated altitudes. However, observed performance during the descent and approach phases of flight was considered to be generally unsafe with potentially deleterious outcomes. Because of the known individual variablility in tolerance to hypoxia, erring on the side of caution is recommended from the results of this study. Descents from GA flights of greater than 2 hrs. at these commonly flown altitudes should proceed slowly and cautiously. Heightened awareness of the potential risks of making critical errors following flights at these altitudes should foster the routine practice of planning a slow descent with enough time at a nominally lower altitude (e.g., 7,000 ft. or 6,000 ft., when possible) for physiologic recovery before the approach and landing phases of flight are continued. Symptoms of mild hypoxia may not be perceived by pilots at the time of their descent procedures, but this should not suggest to the individual that hypoxia is not present. Even subtle effects can have unanticipated influence on the pilot preparing for approach and landing at uncontrolled fields.

To further research the question of GA pilot performance and the detrimental effects of hypoxia, it is recommended that a more advanced GA research simulator be used, such as the Civil Aeromedical Institute's Advanced General Aviation Research Simulator, which offers higher sampling rates for all flight performance measures, greater visual resolution, and more demanding flight scenarios. Also suggested is an increase in the sample size of pilots, and the use of longer hypoxic exposure durations for each altitude condition studied.

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APPENDIX A

EXPERIMENTER'S CHECKLIST
&
ATC SCRIPT

DAY 1 - PRACTICE

WIND: NONE

AM ☞ *<u>Tucson ATIS</u>: Tucson International, Information Delta, one five zero zero [1500] zulu weather, temperature eight one [81], dew point six six [66], wind two six eight [268] at two zero [20], altimeter two niner niner two [29.92]. Advise on initial contact you have Information Delta.*
(Time = 8:00 a.m.) **[Freq. = 123.8]**

PM ☞ <u>Tucson ATIS</u>: Tucson International, Information Delta, one niner zero zero [1900] zulu weather, temperature eight one [81], dew point six six [66], wind two six eight [268] at tw zero [20], altimeter two niner niner two [29.92]. Advise on initial contact you have Information Delta.
(Time = 12:00 p.m.) **[Freq. = 123.8]**

✈ *Aircraft ready on Runway 29L (Tucson International)* **Runway Altitude 2641**

- Aircraft Cruise = 2450 RPM / Rotation Speed = 60K / Approach Speed = 65-70K / Climb Speed = 70
- Take off from Tucson and fly two LEFT-turn patterns at 3500'.

☞ Second pattern to full stop. **(Land on Runway *29L*)**

- <u>Experimenter</u>: Go over OBS and VOR NAV Radio use with the subject.
  Discuss Outbound vs. Inbound (inbound is reciprocal).

<u>**BEGIN FLIGHT**</u>

- Take off from Tucson International. ***(Check Flaps)***
- Fly out on the **TUS 308** Radial Outbound **[*Frequency = 116.0*] (*Alt = 4000*)**.

☞ At 13.0 miles NW of TUS VOR Avra Valley will come into view.

- Review Common Traffic Advisory (CTAF) use. Report downwind, base, and final legs of pattern.
  Example "*Alameda traffic, Piper 5280 Tango, entering downwind for runway one seven full stop, Alameda.*"
- At 18.0 miles from TUS VOR turn right heading 330 to clear Avra Valley traffic.
- At 21.5 miles from TUS VOR (past airfield turn left heading 300 entering into left upwind for Avra Valley
- Descend 3200' for approach pattern - ***Pilot calls in downwind, base, and final leg on CTAF 123.0***
- Land at Avra Valley **(*Land on Runway 30*) [Runway Alt. = 2415]**.

SET WIND: 20 knots, 268° *(where the "W" on the compass card is)*

PRESS M (start data collection)

- Instruct pilot to listen to Tuscon ATIS on 123.8
- Pilot calls CTAF on 123.0 with departure intentions ***(Check Flaps)***
- Take off from Avra Valley maintaining heading of 290 until level at 4,000.
- Instruct Pilot to performs **left** and **right** standard rate turns.
- Instruct Pilot to intercept the Stanfield One Two Zero [117] radial inbound ***(Freq = 114.8, Heading = 297)***

AUTOMATED ATC TAKES OVER

Q *Pilot calls Albuquerque Center on 123.5 for FLIGHT FOLLOWING to RYAN AIRPORT*

hypd1001 Albuquerque Ctr: Beech One Niner Two Golf Bravo, Albuquerque Center. **Squawk two one one five** [2115] - IDENT.

Q *Pilot IDENTs*

hypd1002 Albuquerque Ctr: Two Golf Bravo, radar contact, intercept the Tucson Three Zero Eight [308] radial inbound. Report when established (heading = 128).

Q *Pilot reports established on the 308 inbound*

hypd1003 Albuquerque Ctr: Two Golf Bravo, maintain present track

Q *Pilot responds*

At 28 miles to TUS

hypd100B Albuquerque Ctr: Two Golf Bravo, report heading and altitude.

Q *Pilot reports heading and altitude*

hypd100D Albuquerque Ctr: Roger Two Golf Bravo, contact Tucson Approach on one two five point one [125.1]
when two zero [20] miles from the Tucson VOR.

At 20 miles to TUS

Q *Pilot contacts Tucson Approach on 125.1* hypd1004 Tucson Approach: One Niner Two Golf Bravo, expect heading for Ryan Airport.

Q *Pilot responds*

At 15 miles to TUS

hypd1005 Tucson Approach: Two Golf Bravo, turn right immediately heading one eight eight [188]. Expect Ryan Airport in niner [9] miles. Contact Ryan Tower on one two five point eight [125.8].

Q *Pilot responds*

Q *Pilot calls Ryan Tower on 125.8*

hypd1006 Ryan Tower: One Niner Two Golf Bravo, wind two six eight [268] at two zero [20], altimeter two niner niner two [29.92], cleared for landing on Runway Two Four [24].

Q *Pilot responds*

Q *Pilot lands at Ryan ---*

PRESS M (stop data collection)

Training Flight Ends

DAY 2 - "Sea Level" to 8,000
(Taking off from Ryan)

WIND: 20 knots, 119°

AMP *<u>Tucson ATIS</u>: Tucson International, Information Tango, one five zero one [1501] zulu weather, temperature eight zero [80], dew point six six [66], wind one one niner [119] at two zero [20], altimeter two niner niner two [29.92]. Advise on initial contact you have Information Tango.*
(Time = 8:01 a.m.) **[Freq. = 123.8]**

PMP <u>Tucson ATIS</u>: Tucson International, Information Tango, one niner zero one [1901] zulu weather, temperature eight zero [80], dew point six six [66], wind one one niner [119] at two zero [20], altimeter two niner niner two [29.92]. Advise on initial contact you have Information Tango.
(Time = 12:01 p.m.) **[Freq. = 123.8]**

Q *Aircraft ready on Runway 24*
Q *Pilot listens to INFORMATION - TANGO* (Tucson - 123.8)
Q *Pilot calls tower on* 125.8 *and informs tower that INFORMATION -TANGO (Tucson) was heard.*

hypd2001 <u>TOWER</u>: Roger Beech One Niner Two Golf Bravo, Clearance is as follows; Maintain runway heading, climb to four-thousand [4000], departure frequency is one two four point five [124.5], **squawk two five one three** [2513]. (*Initial Squawk*)

Q *Pilot reads back correctly*

hypd2002 <u>TOWER</u>: Roger Two Golf Bravo, cleared for take off runway two four [24].

Q *Pilot Responds*

Aircraft lifts off runway

hypd2003 <u>Pseudo Pilot</u>: Ryan Tower, Cessna Two Seven Six Alpha, ready for takeoff, runway two four [24] left.

hypd2004 <u>TOWER</u>: Cessna Two Seven Six Alpha, cleared for take off, runway two four [24] left. Traffic is a Beech Sundowner departing to the southwest.

hypd2005 <u>Pseudo Pilot</u>: Roger, Two Seven Six Alpha.

hypd2006 <u>TOWER</u>: Two Golf Bravo, contact Tucson Departure on one two four point five [124.5]

Q *Pilot contacts departure*

hypd2007 <u>Departure</u>: Beech Two Golf Bravo, Tucson departure - IDENT.

Q *Pilot IDENTs*

hypd2008 Departure: Two Golf Bravo, radar contact. Climb to four thousand [4000]. Intercept the Stanfield one three zero [130] radial and report when established inbound. *(Frequency = 114.8) [heading = 310]*

Q *Pilot responds*

Q *Pilot reports established*

[redacted]

hypd2009 Departure: Two Golf Bravo maintain inbound track. Contact Albuquerque Center on one two three point five [123.5]

Q *Pilot responds*

Q *Pilot contacts Albuquerque Center*

hypd2010 Albuquerque Ctr: Beech Two Golf Bravo, **squawk two two four six** [2246] - IDENT. *(Early Alt. #1 Squawk)*

Q *Pilot IDENTs*

hypd2011 Albuquerque Ctr: Two Golf Bravo, radar contact. Maintain present track. Report Stanfield Station passage.

Q *Pilot responds*

hypd2012 Pseudo Pilot: **Albuquerque Center, Cessna Two Seven Six [276] Alpha with you at four thousand five hundred.**

hypd2013 Albuquerque Ctr: **Roger, Seven Six [76] Alpha, IDENT (Pause 5 seconds). Seven Six Alpha, radar contact. Turn right zero three zero [030], climb and maintain niner thousand [9000].**

hypd2014 Pseudo Pilot: **Seven Six Alpha turning right zero three zero [030], climb and maintain niner thousand [9000].**

25.0 miles to (sw) Stanfield VOR

hypd200T Albuquerque Ctr: Two Golf Bravo, report heading and altitude.

Q *Pilot responds*

hypd200U Albuquerque Ctr: Double Click

Q *Pilot reports Stanfield Station passage* hypd2015 <u>Albuquerque Ctr</u>: Two Golf Bravo, intercept the Buckeye One Two Zero [120] radial and report when established inbound. (Frequency = 110.6) *[heading = 300]*

[redacted]

Q *Pilot responds*

hypd2016 <u>Albuquerque Ctr</u>: Seven Six Alpha, climb and maintain one zero thousand five hundred [10,500].

hypd2017 <u>*Pseudo Pilot*</u>: *Seven Six Alpha, out of niner thousand [9000] for ten thousand five hundred* [10,500]

hypd2018 <u>Albuquerque Ctr</u>: [Double Click the Mic]

Q *Pilot reports established*

[redacted]

hypd2019 <u>Albuquerque Ctr</u>: Two Golf Bravo, maintain inbound track.

Q *Pilot responds*

23.5 miles to (sw) Buckeye VOR

hypd2020 <u>Albuquerque Ctr</u>: Two Golf Bravo, **squawk two five seven three** [2573] - IDENT. (*Late Alt. #1 Squawk*)

Q *Pilot IDENTs*

hypd2021 <u>Albuquerque Ctr</u>: Two Golf Bravo, radar contact, climb and maintain eight thousand. [8000]. Report level at eight thousand [8000]. Report Buckeye Station passage.

Q *Pilot responds*

[redacted]

Q *Pilot reports level at 8000*

[redacted]

hypd2022 <u>Albuquerque Ctr</u>: [Double click mic]

Q *Pilot reports Buckeye Station passage*

hypd2023 <u>Albuquerque Ctr</u>: Two Golf Bravo, continue outbound track.

Q *Pilot responds*

15 miles from (nw) Buckeye VOR

hypd2024 Albuquerque Ctr: Two Golf Bravo, turn right immediately to intercept the Phoenix Two Seven Zero [270] radial inbound. Report when established. *[heading = 090] (Frequency = 115.6)*

[redacted]

Q *Pilot responds*

Q *Pilot reports established on Phoenix 270 radial inbound*

[redacted]

hypd2025 Albuquerque Ctr: Two Golf Bravo, continue inbound track.

38.0 miles to (west) Phoenix VOR

hypd200v Albuquerque Ctr: Two Golf Bravo, report heading and altitude.

Q *Pilot responds*

hypd200w Albuquerque Ctr: Double Click.

32.0 miles to (west) Phoenix VOR

hypd2026 Albuquerque Ctr: Two Golf Bravo, contact Approach with intentions on one two four point niner [124.9]

Q *Pilot responds*

Q *Pilot contacts Approach on 124.9 and states intentions -- if intentions are stated skip to 2028 -- if no intentions are stated go to 2027*

hypd2027 Approach: **(If no intentions)** Beech One Niner Two Golf Bravo, what are your intentions?

Q *Pilot responds*

hypd2028 Approach: Roger, One Niner Two Golf Bravo, **squawk two two four six** [2246] - IDENT. *(Alt. #2 Squawk - this could be thought of as an "extra")*

Q *Pilot IDENTs*

hypd2029 Approach: Two Golf Bravo, radar contact, turn right heading one zero zero [100].

[redacted]

18 miles to Phoenix

hypd2030 Approach: Two Golf Bravo descend and maintain three thousand [3000] .

[redacted]

Q *Pilot responds*

16.0 miles to Phoenix

hypd2031 Approach: Two Golf Bravo, **squawk two five one three** [2513] - IDENT. (*Late Alt. #2 Squawk*).

Q *Pilot IDENTs*

hypd2032 Approach: Two Golf Bravo radar contact,expect heading to Phoenix Sky Harbor.

When pilot approaches 08 Right ILS extended line (apx. 0.5 miles from line)

hypd2033 Approach: Two Golf Bravo, turn left heading zero eight zero [080]. You are cleared for Runway Zero Eight [08] right approach. Contact tower on one one eight point seven [118.7] at seven [7] miles to Phoenix VOR.

Q *Pilot responds*

Q *Pilot contacts tower at outer marker*

hypd2034 TOWER: Beech One Niner Two Golf Bravo, cleared for landing runway zero eight [08] right.

Q *Pilot lands airplane at Sky Harbor - Phoenix*

Save Data File

DAY 3 - 8,000 to 10,000
(Taking off from Sky Harbor - Phoenix)

WIND: 20 knots, 237°

AMP *Phoenix ATIS: Phoenix Sky Harbor International, Information Papa, one five three zero [1530] zulu weather, temperature seven eight [78], dew point six six [66], wind two three seven [237] at two zero [20], altimeter two niner niner two [29.92]. Advise on initial contact you have Information Papa*
(Time = 8:30 a.m.) **[Freq. = 121.2]**

PMP Phoenix ATIS: Phoenix Sky Harbor International, Information Papa, one niner three zero [1930] zulu weather, temperature seven eight [78], dew point six six [66], wind two three seven [237] at two zero [20], altimeter two niner niner two [29.92]. Advise on initial contact you have Information Papa
(Time = 12:30 p.m.) **[Freq. = 121.2]**

Q *Aircraft ready on Runway 26Right*
Q *Pilot listens to INFORMATION - PAPA* [121.2] *(as per experimenter instruction)*
Q *Pilot calls tower on* 118.7 *and informs tower that INFORMATION -PAPA was heard.*

hypd3001 TOWER: Roger Beech One Niner Two Golf Bravo, Clearance is as follows; Maintain runway heading, climb to four-thousand [4000], departure frequency is one two four point seven [124.7], **squawk two four one three** [2413]. *(Initial Squawk)*

Q *Pilot reads back correctly*

hypd3002 TOWER: Roger Two Golf Bravo, cleared for take off runway two six [26] right.

Q *Pilot Responds*

Aircraft lifts off runway

hypd3003 Pseudo Pilot: Sky Harbor Tower Beech Niner Eight Seven Zulu ready for takeoff, runway two six [26] right.

hypd3004 TOWER: Beech eight seven zulu, cleared for take off, runway two six [26] right. Traffic is a Beech Sundowner departing to the west.

hypd3005 Pseudo Pilot: Roger, Niner Eight Seven Zulu.

hypd3006 TOWER: Beech Two Golf Bravo contact departure on one two four point seven [124.7].

Q *Pilot contacts departure*

hypd3007 Departure: Beech Two Golf Bravo, Phoenix departure - IDENT

Q *Pilot IDENTs*

hypd3008 <u>Departure</u>: Two Golf Bravo, radar contact. Climb and maintain eight thousand [8000]. Expect right turn to intercept Phoenix three five niner [359] radial outbound. *(Frequency = 115.6)*

5.0 miles from (west) of Phoenix VOR

hypd3009 <u>Departure</u>: Two Golf Bravo turn right heading zero three zero [030] to intercept Phoenix three five niner [359] radial outbound. Report when established.

Q *Pilot responds (to departure)*

[redacted]

hypd3010 <u>Pseudo Pilot</u>: Phoenix Departure, Beech Niner Eight Seven Zulu with you at three.

hypd3011 <u>Departure</u>: Roger eight seven zulu, IDENT (PAUSE 5 seconds). Eight seven zulu, radar contact. Turn right heading three four zero [340], climb and maintain five thousand [5000].

hypd3012 <u>Pseudo Pilot</u>: Eight seven zulu turning to three four zero [340], climb and maintain five.

Q *Pilot reports establishing Phoenix 359 radial outbound*

hypd300A <u>Departure</u>: Double Click

[redacted]

20.0 miles from (north) of Phoenix VOR

hypd3013 <u>Departure</u>: Two Golf Bravo contact Albuquerque Center on one two three point five [123.5].

Q *Pilot contacts Albuquerque Center on 123.5*

hypd3014 <u>Albuquerque Ctr</u>: Beech Two Golf Bravo, **Squawk Two Seven Four Zero** [2740] - IDENT *(Early Alt. #1 Squawk)*.

Q *Pilot IDENTs*

hypd3015 <u>Albuquerque Ctr</u>: Two Golf Bravo, radar contact, maintain outbound track, expect Victor Airway Five Six Seven [567] at FERER Intersection.

48 miles from Phoenix VOR

hypd3016 <u>Albuquerque Ctr</u>: Two Golf Bravo, cleared to Winslow via the Winslow two one zero [210] radial inbound. Report when established. (*Frequency = 112.6 for Winslow* VOR) *[heading = 030]*

[redacted]

Q *Pilot reports established*

[redacted]

hypd3017 <u>Albuquerque Ctr</u>: Two Golf Bravo, Maintain inbound track

45 miles to (sw) Winslow VOR

hypd300Y <u>Albuquerque Ctr</u>: Two Golf Bravo, report heading and altitude.

Q *Pilot responds*

hypd300Z <u>Albuquerque Ctr</u>: (Double Click)

15 miles to (sw) Winslow VOR

hypd3018 <u>Albuquerque Ctr</u>: Two Golf Bravo **Squawk two four seven three** [2473] - IDENT (*Late Alt.*

Q *Pilot IDENTs*

hypd3019 <u>Albuquerque Ctr</u>: Two Golf Bravo, radar contact, climb and maintain one zero thousand [10,000]. Report level at ten thousand [10,000].

Q *Pilot responds*

[redacted]

Q *Pilot reports establishing 10,000 feet*

[redacted]

hypd3020 <u>Albuquerque Ctr</u>: Two Golf Bravo, report Winslow station passage.

Q *Pilot responds*

Q *Pilot reports Winslow station passage*

hypd3021 <u>Albuquerque Ctr</u>: Two Golf Bravo, turn right to intercept the Gallup two four two [242] radi inbound. Report when established. (*Frequency = 115.1 for Gallup VOR*) *[heading = 062]*

[redacted]

Q *Pilot responds*

Q *Pilot reports established on GUP 242 inbound*

[redacted]

hypd3022 Albuquerque Ctr: Two Golf Bravo, maintain inbound track.

50 miles to (sw) Gallup VOR

hypd300C Albuquerque Ctr: Two Golf Bravo, report heading and altitude.

Q *Pilot responds*

hypd300D Albuquerque Ctr: (Double Click)

12 miles to (sw) Gallup VOR

hypd3023 Albuquerque Ctr: Two Golf Bravo, **Squawk two one four zero** [2140] - IDENT. *(Late Alt. #2 Squawk)*

Q *Pilot IDENTs*

hypd3024 Albuquerque Ctr: Two Golf Bravo, radar contact, maintain inbound track.

6.0 miles to (sw) Gallup VOR

hypd3025 Albuquerque Ctr: Two Golf Bravo, Gallup is at your 11 o'clock in ten [10] miles. Advise when airport is in sight.

Q *Pilot reports seeing Gallup Airport*

hypd3026 Albuquerque Ctr: Two Golf Bravo, Albuquerque wind is two three seven [237] at two zero [20], altimeter two niner niner two [29.92]. Gallup traffic advisory is one two two point niner five [122.95]. Flight following is discontinued.

Q *Pilot lands airplane at Gallup Airport -- Runway 24 (upwind)*

Save Data File

DAY 4 - 10,000 to 12,500
(Taking off from Gallup)

WIND: 20 knots, 231°
NO TOWER at Gallup

AMP *<u>ABQ ATIS</u>: Albuquerque Information Bravo, one five two five [1525] zulu weather, temperature seven five [75], dew point six six [66], wind two three one [231] at two zero [20], altimeter two niner niner two [29.92]. Advise on initial contact you have Informatio Bravo.*
(Time = 8:25 a.m.) **[Freq. = 118.0]**

PMP <u>ABQ ATIS</u>: Albuquerque Information Bravo, one niner two five [1925] zulu weather, temperature seven five [75], dew point six six [66], wind two three one [231] at two zero [20], altimeter two niner niner two [29.92]. Advise on initial contact you have Information Bravo.
(Time = 12:25 p.m.) **[Freq. = 118.0]**

Tell pilot before takeoff:
- Q *Aircraft ready on Runway 24*
- Q *Pilot should call ABQ ATIS*
- Q *Pilot should announce intentions on* COM frequency 122.95
- Q *Once aircraft lifts off pilot should contact ABQ Cntr. for FLIGHT FOLLOWING on 123.5*

Aircraft lifts off runway

hypd4001 <u>Pseudo Pilot</u>: Gallup traffic, Beech Four Seven Foxtrot taxiing into position for runway two four [24].

hypd4002 <u>Pseudo Pilot</u>: Four Seven Foxtrot rolling on runway two four, will be departing straight out.

Q *Pilot contacts Albuquerque Center on 123.5 and asks for flight following*

hypd4003 <u>Albuquerque Ctr</u>: Beech One Niner Two Golf Bravo, Albuquerque Center. **Squawk two five one three** [2513] - IDENT (*Initial Squawk*)

Q *Pilot IDENTs*

hypd400A <u>Albuquerque Ctr</u>: Two Golf Bravo, radar contact. Turn right, fly heading zero one zero [010]. Climb and maintain one zero thousand [10,000]. Report level at ten thousand.

- Q *Pilot responds*
- Q *Pilot reports level at 10,000*

[redacted]

hypd4004 Albuquerque Ctr: Two Golf Bravo, turn right, heading zero niner two [092] to intercept Gallup Zero Five Five [055] radial outbound. Report established outbound. (*Frequency = 115.1 for Gallup VOR*).

Q *Pilot responds*

hypd4005 Pseudo Pilot: Albuquerque Center, Beech Four Seven Foxtrot passing through eight thousand, climbing to niner, request flight following.

hypd4006 Albuquerque Ctr: Roger Four Seven Foxtrot, IDENT (PAUSE 5 seconds). Four Seven Foxtrot, radar contact. Turn right heading three five five [355], climb and maintain niner thousand [9000].

hypd4007 Pseudo Pilot: Four Seven Foxtrot is turning to three five five [355], climbing and maintaining niner thousand feet.

Q *Pilot reports establishing Gallup 055 radial outbound*

[redacted]

hypd4008 Albuquerque Ctr: Two Golf Bravo. Maintain outbound track.

Q *Pilot responds*

At 50.0 from (ne) Gallup VOR

hypd4009 Albuquerque Ctr: Two Golf Bravo, **squawk two two four six** [2246] - IDENT. (*Early Alt. #1 Squawk*)

Q *Pilot IDENTs*

hypd4010 Albuquerque Ctr: Two Golf Bravo, radar contact, maintain outbound track.

70.0 miles from (ne) Gallup VOR

hypd400Y Albuquerque Ctr: Two Golf Bravo, report heading and altitude.

Q *Pilot responds*

hypd400E Albuquerque Ctr: Double Click

96.0 miles from (ne) Gallup VOR

hypd4011 Albuquerque Ctr: Two Golf Bravo, turn left to intercept the Alamosa two zero three [203] radial inbound. Report established inbound. (*Frequency = 113.9*) *[heading = 023].*

[redacted]

Q *Pilot responds*

Q *Pilot reports established on two zero three [203] inbound [heading = 023]*

[redacted]

hypd4012 Albuquerque Ctr: Two Golf Bravo climb and maintain one two thousand five hundred [12,500]. Report level at twelve five.

Q *Pilot responds*

[redacted]

Q *Pilot reports establishing 12,500 feet*

[redacted]

hypd4013 Albuquerque Ctr: Two Golf Bravo, contact Denver Center on one two eight point three seven [128.37].

Q *Pilot responds*

Q *Pilot contacts Denver Center on 128.37*

hypd4014 Denver Ctr: Beech Two Golf Bravo, **squawk two five seven three** [2573] - IDENT (*Early Alt. #2 Squawk*)

Q *Pilot IDENTs*

hypd4015 Denver Ctr: Two Golf Bravo, radar contact, we are temporarily rerouting you due to airborne fire fighting activity, turn right to intercept the Taos Two Four Zero [240] radial inbound. Report when established. *[heading = 060]*.

[redacted]

Q *Pilot responds*

Q *Pilot reports established on the Taos 240 radial inbound*

[redacted]

hypd40zz Denver Ctr: Double Click

25.0 miles from (west) Taos VOR

hypd4016 Denver Ctr: Two Golf Bravo, turn to heading three three zero [330] to intercept the Alamosa two zero three [203] radial inbound. Report when established.

[illegible]

Q *Pilot responds*

Q *Pilot reports established on the Alamosa 203 radial inbound*

[illegible]

hypd4017 Denver Ctr: Two Golf Bravo, maintain inbound track.

7.5 miles to (se) Alamosa VOR

hypd4019 Denver Ctr: Two Golf Bravo, **Squawk two two four zero** [2240] - IDENT (*Late Alt. #: Squawk*)

Q *Pilot IDENTs*

6.5 miles to (se) Alamosa VOR

hypd4020 Denver Ctr: Two Golf Bravo, turn to heading three five five [355], airport is in ten [10] miles. Advise when San Luis Regional Airport is in sight.

[illegible]

Q *Pilot reports seeing San Luis Valley Regional Airport*

hypd4021 Denver Ctr: Two Golf Bravo, wind is two three one [231] at two zero [20], altimeter two niner niner two [29.92]. San Luis Valley Regional Airport traffic advisory is one two two point eight [122.8]. Flight following is discontinued.

Q *Pilot responds*

Q *Pilot lands airplane at San Luis Valley Regional Airport -- Runway 20*

Save Data File

APPENDIX B

DESCRIPTIONS OF SUBJECTIVE MEASURES

NASA TLX

Participants were asked to rate subjective workload levels by using the NASA Task Load Index (TLX; Hart & Staveland, 1988). The TLX measures subjective workload by requiring the participant to rate the experience of workload on six subscales: Mental Demand, Physical Demand, Temporal Demand, Performance, Effort, and Frustration. These ratings are averaged to produce a single workload score ranging from 0 (very low) to 100 (very high). The TLX has been used successfully to assess workload in a variety of laboratory and field settings (Hart & Staveland, 1988).

Environmental Symptoms Questionnaire (ESQ-III)

The ESQ was originally designed to measure symptoms in subjects at high altitudes (Kobrick & Sampson, 1979). It has since been modified to assess symptoms occurring during other stressor conditions (ESQ—III; Sampson & Kobrick, 1980). The ESQ-III consists of 68 adjectives. During administration subjects were asked to rate how applicable each term was to how they felt at that moment. Six responses were possible from the lowest, 1: (*Not at All*), to the highest, 6: (*Extremely*). Factor analysis conducted in previous research identified 9 factors describing an intercorrelational pattern that appears to reflect environmental and organismic conditions consistent with exposures to altitude (Sampson, Cymerman, Burse, Maher, & Rock, 1983; Shukitt, Banderet, & Sampson, 1990). The 9 factors included: cerebral Acute Mountain Sickness (AMS); respiratory AMS; Ear, Nose and Throat (ENT); cold stress; distress; alertness; exertion stress; muscular discomfort; and fatigue. Cold stress symptoms were nonexistent during this study and essentially summed to zero. Hence, it was dropped from our analysis. Item weights determined by the previous research were applied to our ESQ data and a severity index score was computed for both the cerebral and respiratory AMS factors as defined in Sampson et al., (1983).

MOOD II

The automated MOOD II scale comprises 36 items from the following six subscales: activity, anger, happiness, fear, depression, and fatigue. As in the ESQ-III, subjects were asked to respond to a list of adjectives as to how well each described their current feeling. Possible responses ranged from 1 (*Yes or Mostly*) to 3 (*No, Not at All*). The MOOD scale was originally developed by Ryman, Biersner, and LaRocco (1973). The automated version used in this study was derived from the Walter Reed Performance Assessment Battery (Thorne et al., 1985).

Stanford Sleepiness Scale

The Stanford Sleepiness Scale consists of 7 statements that describe different levels of sleepiness, ranging from 1 (*Feeling very alert, wide awake, and energetic*) to 7 (*Sleep onset soon, losing struggle to remain awake)*. Subjects were asked to select the statement that best described their current feeling. The scale was originally developed by Hoddes, Zarcone, Smythe, Phillips, and Dement (1973). The automated version used in this study was derived from the Walter Reed Performance Assessment Battery (Thorne et al., 1985).

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