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Effects of Oxygen Deprivation on Pilot Performance and Cognitive Processing Skills: A Pilot Study

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EFFECTS OF OXYGEN DEPRIVATION ON PILOT PERFORMANCE AND COGNITIVE PROCESSING SKILLS: A PILOT STUDY

by

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A Thesis Submitted to the college of Aviation Department of Applied Aviation Sciences
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This thesis was prepared under the direction of the candidate's Thesis Review Committee Chair, Dr. Guy M. Smith, Ed.D., Associate Professor, Daytona Beach Campus, and Thesis Committee Member, Dr. John French, Ph.D., Professor, Daytona Beach Campus, and has been approved by the Thesis Review Committee. It was submitted to the Department of Applied Aviation Sciences in partial fulfillment of the requirements for the degree of Master of Science in Aeronautics.

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Abstract

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According to Federal Aviation Administration (FAA) regulations, pilots flying above 14,000 ft. are required to use supplemental oxygen. The purpose of this study was to examine how oxygen deprivation below 14,000 ft. affects pilot performance using the Frasca Mentor Advanced Aviation Training Device (AATD), and cognitive processing skills using the Automated Neuropsychological Assessment Metrics (ANAM™) cognitive test. The study was conducted in a Normobaric High Altitude Laboratory at simulated altitudes of 5,000 ft. and 14,000 ft. In this pilot study, only five participants were tested; non-significant results of the analysis were anticipated; however, as oxygen levels decreased and time of exposure increased, cognitive processing skills decreased and pilot performance degenerated. The conclusion from this pilot study was that further research is warranted.

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Chapter I

Introduction

The Federal Aviation Administration (FAA) has regulations specifying aircraft pilots' use of supplemental oxygen above 14,000 ft. This study was designed to examine whether there is a deterioration of pilot performance and cognitive processing skills as a result of low-altitude hypoxia below 14,000 ft. The study was conducted in a High Altitude Lab (HAL) at simulated altitudes of 5,000 ft. and 14,000 ft.

Significance of the Study

FAA (2003) has defined hypoxia as "a lack of sufficient oxygen in the body cells or tissues caused by an inadequate supply of oxygen, inadequate transportation of oxygen, or inability of the body tissues to use oxygen" (p. 9). The National Transportation Safety Board (NTSB) has documented evidence of numerous aircraft accidents caused by hypoxia ("Extreme Training," 2009). On October 25, 1999, a Learjet Model 35 crashed near Aberdeen, South Dakota. The airplane departed Orlando, Florida, for Dallas, Texas, with the captain, first officer, and four passengers. Radio contact with the flight was lost north of Gainesville, Florida, after air traffic control (ATC) had cleared the airplane to flight level (FL) 390 (NTSB, 1999). The military pilots who had responded and observed the airplane in flight at close range stated that the forward windshields of the Learjet appeared to be frosted or covered with condensation. Their radio calls to the aircraft went unanswered, and 4 hours later, the airplane spiraled to the ground and impacted in an open field. All of the airplane's occupants were killed, and the aircraft was destroyed. The NTSB determined that this accident would not have occurred without both the loss of cabin pressure and the failure of the flight crew to use supplemental oxygen. The NTSB considered both explanations as likely factors in the cause of the accident. Following the depressurization of the aircraft, the pilots had not used supplemental oxygen in sufficient time and/or in an adequate concentration to avoid hypoxia and their subsequent incapacitation. However, the NTSB was unable to determine why the flight crew could not or did not use supplemental oxygen in sufficient time and/or adequate concentration to avoid their incapacitation and the resulting fatal accident (NTSB, 1999).

A new concern has arisen concerning the growing number of affluent general aviation pilots who purchase jet aircraft and then fly at high altitudes for which they have had little to no training to deal with a loss of cabin pressurization ("Extreme Training," 2009). Without such training, pilots, unaware of the detrimental and insidious effects of hypoxia on brain function and the corrective measures required as soon as the effects of hypoxia are experienced, have unwittingly exposed themselves to significant risk when flying at high altitudes without supplemental oxygen. However, the aviation literature is not consistent in defining the altitude at which supplemental oxygen should be required in an unpressurized aircraft.

The FAA's Civil Aerospace Medical Institute has performed studies that have shown that pilots in unpressurized aircraft without supplemental oxygen, flying as low as 8,000 ft., make more procedural errors than pilots who are well oxygenated (Furgang, n.d.). Personal reports by experienced commercial pilots flying unpressurized aircraft at 8,000 ft. reflect judgment errors, such as entering a holding pattern and turning the wrong direction; and, in spite of receiving a warning horn and ignoring the sound, running out of fuel on landing because the pilots forgot to change the fuel tanks from auxiliary to main

(Thorn, 1995). The altitude at which supplemental oxygen is required depends on several factors, such as the weather conditions, day or night, if the pilot is a smoker or non-smoker, male or female, overall physical condition, stress level, and piloting experience.

Statement of the Problem

The altitude threshold at which hypoxia occurs in general aviation pilots, untrained in physiologic effects of oxygen deprivation, has not been determined. The Federal Aviation Regulation (FAR) (FAA, 2010a) that applies to general aviation operation in unpressurized aircraft states:

> (a) General. No person may operate a civil aircraft of U.S. registry—(1) At cabin pressure altitudes above 12,500 ft. Mean Sea Level (MSL) up to and including 14,000 ft. (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. (p. 737)

FAA (2010b), that applies to operators holding an air carrier certificate and operating aircraft with reciprocating engines, states:

> (b) Crewmembers. (1) At cabin pressure altitudes above 10,000 ft. up to and including 12,000 ft., oxygen must be provided for, and used by, each member of the flight crew on flight deck duty, and must be provided for other crewmembers, for that part of the flight at those altitudes that is of more than 30 minute duration. (2) At cabin pressure altitudes above 12,000 ft., oxygen must be provided for, and used by, each member of the flight crew on flight deck duty, and must be provided for other crewmembers, during the entire flight time at those altitudes. (pp. 115-116)

FAA (2010c), that applies to commuter or on-demand operation in unpressurized aircraft, states:

> (a) Unpressurized aircraft. Each pilot of an unpressurized aircraft shall use oxygen continuously when flying—
>
> (1) At altitudes above 10,000 ft. through 12,000 ft. MSL for that part of the flight at those altitudes that is of more than 30 minutes duration; and
>
> (2) Above 12,000 ft. MSL (para. 1).

Purpose Statement

This study sought to measure the pilot performance and cognitive processing skills of pilots while enclosed in a High Altitude Lab (HAL), simulating oxygen conditions at 5,000 and 14,000 ft. The HAL facility located at Embry-Riddle Aeronautical University (ERAU) was designed for the purpose of high-altitude hypoxia awareness training. The lab can accommodate up to ten people per training session, including an instructor. The lab uses normobaric technology which reduces oxygen content, rather than the military's hyperbaric chamber technology which reduces air pressure ("Extreme Training," 2009).

Hypotheses

H1: There is a difference in instrument flight skills at different altitudes up to and including 14,000 ft. Mean Sea Level (MSL) for instrument-rated pilots.

H2: There is a difference in cognitive processing skills at different altitudes up to and including 14,000 ft. MSL for instrument-rated pilots.

Delimitations

The study was limited in its scope. It would be most interesting for the sample size of study participants to represent the spectrum of instrument certificated pilots in age, gender, and experience; but, based on availability of participants and the HAL, this was not realistic. The study was also limited to non-smokers; including smokers would introduce an additional variable for which the study was not designed to consider.

Limitations and Assumptions

The study environment imposed limitations because depressurization while flying in an aircraft was not replicated for both practical as well as safety reasons. The HAL is a laboratory that uses normobaric technology to reduce the oxygen level content of breathing air as opposed to reducing the atmospheric pressure and partial pressure of breathing air as is the case with hyperbaric chambers. When increasing in altitude in a hyperbaric chamber, the barometric pressure decreases and oxygen levels also decrease, in accordance with Dalton's law (Law & Bukwirwa, 1999). This research studied the effects of only one variable, the decrease in oxygen content.

Another limitation was the use of purposive sampling that resulted in participants being college students, predominantly between the ages of 18 and 25 years old. Furthermore, although some participants had accumulated hundreds of flight hours; compared to the population of instrument-rated pilots, the study participants were not as experienced as airline or military pilots. The physical limitations of this study were the requirements not to exceed 14,000 ft. and to restrict time in the HAL to 30 minutes.

Although the Advanced Aviation Training Device (AATD) used in this study had a full instrument panel and flight control devices capable of simulating flight in a

Cessna 172 airplane, the simulator lacked haptic fidelity. Similarly, the visual screen that displayed various airport approaches could not replicate the multidimensional panoramic view seen from an aircraft window, although this limitation was of no consequence to this study.

It was assumed that the HAL would be functioning properly to provide consistently reliable data. It was also assumed that the participants were in good physical health and had received adequate rest just before their exposure to the HAL. In addition, it was assumed that the ANAM™ test and the flying tasks would have consistent administration and data interpretation.

Definitions of Terms

Advanced Aviation Training Device (AATD): The device used for this experiment was a Frasca Model Mentor 100 with simulated cockpit controls to replicate regular and instrument flight (Frasca, 2010).

Automated Neuropsychological Assessment Metrics (ANAM™): A proven computer-based tool designed to detect speed and accuracy of attention, memory, and thinking ability (Defense & Veterans Brain Injury Center [DVBIC], n.d.). The test battery used in this study was the Switching Test Battery which included three tests – arithmetic reasoning, kinesthetic perception, and switching between the tasks (DVBIC, n.d.).

High Altitude Lab (HAL): Normobaric Lab at ERAU that simulates altitude conditions by decreasing the oxygen content in air. The Lab was used to expose participants to the symptoms of hypoxia (“Extreme Training,” 2009).

Normobaric: The technology of removing the oxygen content from air while maintaining normal atmospheric pressure (“Extreme Training,” 2009).

List of Acronyms

AATD	Advanced Aviation Training Device
AIM	Aeronautical Information Manual
ANAM™	Automated Neuropsychological Assessment Metrics
ANOVA	Analysis of Variance
ATC	Air Traffic Control
ATP	Air Transport Pilot
BATD	Basic Aviation Training Device
CDI	Course Deviation Indicator
CFR	Code of Federal Regulations
CSV	Comma-Separated Value
DCS	Decompression Sickness
DH	Decision Height
DoC	Department of Commerce
DoD	Department of Defense
DoT	Department of Transportation
DVBIC	Defense & Veterans Brain Injury Center
ERAU	Embry-Riddle Aeronautical University
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations
FL	Flight Level
HAL	High Altitude Lab
HSI	Horizontal Situation Indicator

IFR	Instrument Flight Rules
ILS	Instrument Landing System
MSL	Mean Sea Level
NASA	National Aeronautics and Space Administration
NTSB	National Transportation Safety Board
SPSS	Statistical Package for the Social Sciences
USC	United States Code
VFR	Visual Flight Rules

Chapter II

Review of the Relevant Literature

This study sought to extend on a previous study conducted by McMillan (2010) in November 2009 at ERAU. McMillan sought to validate the FAA requirements relative to prescribed oxygen requirements when participants were exposed to altitudes from sea level up to and including 14,000 ft.

Federal Aviation Administration

The FAA is one of the 12 regulatory agencies that make up the United States Department of Transportation (DoT). It is responsible:

> For insuring the safe, efficient, and secure use of the Nation's air space, by military as well as civil aviation, for promoting safety in air commerce, for encouraging and developing civil aeronautics, including new aviation technology, and for supporting the requirements of national defense. (FAA, 2010d, para. 1)

This responsibility is met by setting standards and issuing regulations for all facets of operations and behavior of personnel that are included in Title 14 of the Code of Federal Regulations (CFRs).

Code of Federal Regulations

The CFRs are sets of regulations that establish minimum standards of behavior for persons and entities operating within the U.S., with each set identified by titles. Title 14 pertains to aeronautics and space, and four parts are under FAA oversight: Parts 67, 91, 121, and 135. All of the rules specified in Title 14 are also called Federal Aviation Regulations (FARs). Within each part, there are sections that are of particular relevance to this study.

This study examined supplemental oxygen requirements for general aviation pilots (and crewmembers) of non-pressurized aircraft with reciprocating-engine-powered airplanes. The parts and sections of interest were 61, 67, 91.211, 121.327, 135.89, and 141. Part 67 pertains to medical standards and certification; Parts 61 and 141 regulate flight training; and Parts 91.211, 121.327, and 135.89 apply to oxygen requirements during flight.

Title 14 CFR Part 67, *Medical Standards and Certification*, was relevant to this study because it specifies the required medical conditions a person must meet in order to be a certified pilot (National Archives and Records Administration, 2009a). This regulation has specified the requirements to both obtain and hold a pilot's license.

Title 14 CFR 121.327, *Operating Requirements Domestic, Flag and Supplemental*, was relevant to this study because it relates to commercial passenger or freight aircraft. The section specifies that if a flight crew was exposed to a cabin pressure altitude greater than 10,000 ft. up to and including 12,000 ft. for more than 30 mins, the pilot would be required to breathe supplemental oxygen. When cabin pressure has exceeded 12,000 ft., the pilot would be required to breathe supplemental oxygen the entire time above this altitude (National Archives and Records Administration, 2009b, pp. 115-116).

Title 14 CFR 91.211, *Supplemental Oxygen*, was relevant to this study because it covers general aviation pilots who fly at higher altitudes above 12,500 ft. It has allowed pilots to fly without supplemental oxygen at higher altitudes than either Title 14 CFR 121.327 or CFR 135.89. The section specifies that if a flight crew was exposed to a cabin pressure altitude greater than 12,500 ft. up to and including 14,000 ft. for more than 30 mins, the pilot would be required to breathe supplemental oxygen. When cabin pressure has exceeded 14,000 ft., the pilot would be required to breathe supplemental oxygen the entire time above this altitude. When cabin pressure exceeds 15,000 ft., all occupants must be provided with supplemental oxygen (National Archives and Records Administration, 2009d, p. 737).

The FAA's primary focus has been safety. Its mission statement has declared "Our continuing mission is to provide the safest most efficient aerospace system in the world" (FAA, 2010e, p.1). The first line of its vision statement has proclaimed "We strive to reach the next level of safety . . ." (FAA, 2010e, p.1). Its value statement has proclaimed "Safety is our passion. We work so all air and space travelers arrive safely at their destination" (FAA, 2010e, p.1).

Aeronautical Information Manual

The *Aeronautical Information Manual* (AIM) (FAA, 2010d), a publication issued by the FAA and commonly referred to as the *Official Guide to Basic Flight Information and ATC Procedures,* was relevant to this study because it contains health and safety information of interest to pilots. Of specific interest to this study was the health information and medical facts, factors affecting flight safety, a pilot/controller glossary of terms used in the ATC System, and information on safety, accident, and hazard reporting. Although not regulatory in nature, parts of the AIM have re-stated and amplified some of the FARs, making it of greater interest to this study. Moreover, if a pilot failed to follow procedures set out in the AIM, such failure could be used in enforcement actions, were the pilot charged with careless or reckless aircraft operations (FAA, 2010d).

National Transportation Safety Board (NTSB)

In 1926, the U.S. Congress assigned the Department of Commerce (DoC) the responsibility of investigating and identifying the cause of aircraft accidents (NTSB, n.d.). In 1940, the Civil Aeronautics Board was established and assigned this responsibility (NTSB, n.d.). The DoT was created in 1967, and all transportation agencies were consolidated into this new agency (NTSB, n.d.). The NTSB was also included in this reorganization from an administrative perspective but with independence for investigative powers. In 1974, the NTSB was established as a completely independent organization outside the purview of any other organization (NTSB, n.d.). The reason was that an investigative organization could not properly assess accountability unless it was completely independent from every other organization. As an independent organization, the NTSB has been "assigned by Congress to investigate every civil aviation accident in the United States and significant accidents in other forms of transportation- highway, marine, pipeline, and railroad - and to issue safety objective recommendations to prevent future accidents" (NTSB, n.d., para. 1). Title 49 Chapter 11 of the United States Code (USC) established the structure for the NTSB. The NTSB has relevance to this study because it investigates all aviation accidents, including those in which hypoxia was a probable or a contributing cause.

Advanced Aviation Training Devices (AATD)

In the early 1970s, with the introduction of the desktop computer, basic aircraft simulation programs were developed. As computer memory capacity expanded and graphics improved, computer game programmers created complex instrument flight simulators. Instrument flying involves several complex disciplines. The AATD allows the pilot to remain in a controlled environment on the ground, free of the fear of making a critical error that could be fatal in a real aircraft.

Flying an airplane requires being proficient in many skills. Using the AATD, a flight student can be taught one skill at a time, and then practice the combined skills before ever flying a real aircraft. The benefits of using the AATD include instruction that is more efficient because the system can be paused so the instructor can provide immediate coaching, an individual skill can be practiced multiple times, and flight performance can be saved for later review or for repetition (Frasca, 2010). However, for an AATD to be recognized as a certified training device, it must be first approved by the FAA. *Advisory Circular 61.136* (FAA, 2008) defines AATDs and specifies the requirements for a device to become approved. The requirements include meeting or exceeding the specified equipment and conditions and a training program related to ground and flight performance tasks leading to various flight certificates and ratings per Title 14 of CFR Parts 61 and 141. The equipment specified for Appendix 2 is primarily related to those functions needed to fly an airplane. The equipment specified for Appendix 3 is primarily related to providing a more realistic aircraft/cockpit environment including an instrument panel, a visual system that provides acceptable cues in both day and night visual flight rules (VFR) and instrument flight rules (IFR) meteorological conditions to enhance a pilot's visual orientation in the vicinity of an airport; and a separate instructor station to permit effective interaction without interrupting the flight in overseeing the pilot's horizontal and vertical flight profiles in real time and space.

The AATD owned and operated by ERAU and used in this study is called the Mentor 100, built by Frasca International. The Mentor 100 is a new high-quality compact simulator device with integrated avionics systems that has been approved by the FAA as an AATD (FAA, 2008).

High Altitude Lab (HAL)

Turner and Huntley (1991) have stated “Some National Transportation Safety Board staff members have expressed a concern that high-altitude flight physiology training for civilian flight personnel should receive greater emphasis than it currently does" (p.1). Boshers (2010), a member of the FAA Civil Aeromedical Institute’s Airman Education Program, has claimed that there is a tremendous need for initial training in high-altitude physiology for all civilian pilots. He has claimed there is a large number of general aviation pilots who are not aware of the physiological problems that can occur during flight. He has recommended that pilots be trained in an altitude chamber to give them an opportunity to experience symptoms of hypoxia in a safe environment.

There had been several methods used to expose pilots to high altitude conditions. In some cases, trainers were taken up in an aircraft and then their oxygen supply equipment was removed. This tactic had been used by both the U.S. and British militaries (Gradwell, 2000).

The preferred method of high altitude training has been the use of a hyperbaric chamber because it most closely replicates the real situation of an increasing altitude by reducing air pressure (Colorado Altitude Training, n.d.). However, such chambers have had the drawback of being very expensive to both build and operate. Furthermore, they have carried the risk for decompression sickness (DCS), a life threatening medical condition caused by the development of inert gas bubbles in the blood when the chamber’s atmospheric pressure is decreased too quickly. This condition has been more commonly associated with underwater divers surfacing too quickly after breathing compressed air underwater (Colorado Altitude Training, n.d.). Another drawback and risk has been the need to wait for some time before ascending to altitude after a hyperbaric exposure (e.g., flying or driving in the mountains) to avoid DCS. Therefore, because of their significant expense and the associated risks from exposure, there have been very few available, and pilots have not been receiving the recommended hypoxic training (Colorado Altitude Training, n.d.).

A relatively recent technological development has been the “normobaric” lab, also known as a High Altitude Lab (HAL), in which there is no reduction in ambient pressure; only the oxygen concentration from breathing air content is removed (“Physiological Equivalence,” 2010). Exposures in the HAL have enabled pilots to experience hypoxia without the risks of DCS. Designed with a dual lock, HAL has an outer door and an inner door. This type of design has allowed occupants to enter and leave the inner chamber without the need to change the atmospheric pressure inside so it is equal to the pressure outside the chamber. The reported benefits for the HAL have been their lower construction and operation costs, improved safety, more convenient, and improved design flexibility (“Physiological Equivalence,” 2010). Furthermore, and perhaps most important with regards to return on investment, because the risk of DCS has been removed, individuals can be subjected to multiple exposures in one day (“Physiological Equivalence,” 2010). There have only been two HALs built in the US; one is owned and operated by ERAU in Daytona Beach, Florida and the other one is owned and operated by the FAA in Oklahoma (Colorado Altitude Training, n.d.).

Hypoxia

Hypoxia is a Greek word meaning, “less than the normal amount of oxygen” (Klausen, 1969). Many conditions and situations can cause hypoxia from oxygen deficiency, such as, breathing air at reduced atmospheric pressure, malfunctioning oxygen equipment, drowning, pneumonia, and carbon monoxide poisoning (Ernsting, 1973). Atmospheric pressure is defined as the measure of a column of air directly over any spot. Standard atmospheric pressure is 760 mm Hg or 15 lbs per square inch (Law & Bukwirwa, 1999). The weight and height of a column of air is greatest at sea level and as a person climbs to higher elevations, the height and weight of the column of air is reduced. In this situation, atmospheric pressure decreases, the amount of air is less, and the number of molecules of gas per liter of air diminishes. Air content is made up of 21% oxygen, 78% nitrogen, and small quantities of carbon dioxide, argon, and helium. Dalton’s Law states, “The total pressure of a mixture of gases equals the sum of the pressures that each would exert if it were present alone” (Law & Bukwirwa, 1999, p. 1). The equation for Dalton’s Law is: $P_{total} = P_1 + P_2 + P_3 + \ldots P_n$ (Law & Bukwirwa, 1999).

Since oxygen is the primary gas to support human life, using Dalton’s Law, the pressure of oxygen (PO_2) of dry air at sea level can be determined as follows: 21/100 x 760 = 159 mm Hg (Powers & Howley, 2008).

Once air is warmed and humidified by the upper respiratory track and reaches the trachea, water vapor is subtracted which exerts a pressure of 47 mm Hg. After the oxygen goes through the trachea, the PO_2 is recalculated as follows: 21/100 x (760 – 47) = 150 mm Hg (Powers & Howley, 2008).

Air passes through the trachea and enters the lung through the bronchus as depicted in Figure 1.

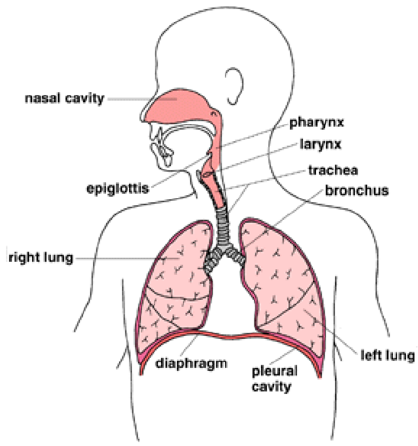

Figure 1. Respiratory diagram. Retrieved from “Human Physiology” (n.d).

Gas exchange of O_2 and CO_2 connecting the external environment and the cells of the body occurs in the lung. This exchange occurs in the 300 million alveoli sacks located in the lung (“Human Physiology,” n.d.).

Blood returning to the heart is carried by pulmonary arteries which form pulmonary capillaries and surround the alveoli. The delivery of the blood to the alveoli is called perfusion. The delivery of air to the alveoli is called ventilation. The exchange of gases, O_2 and CO_2 occurs in the alveoli by diffusion across the blood-gas barrier. If everything was perfect, a matching of ventilation and blood flow is required. If, however, the alveoli is well ventilated but the blood flow is not adequate, or if the blood flow is adequate but the alveoli is not well ventilated, there is not a match, and normal gas exchange does not occur. The importance of this exchange was first discovered by Dr. John B. West in the 1950s. He developed the ventilation/perfusion (V/Q) ratio which measures the effectiveness of the exchange. A perfect V/Q is when there is a one-to-one relationship between ventilation and blood flow and reflects a ratio of 1. A ratio of .5 is generally sufficient to meet most oxygen demands when the subject is at rest (“Human Physiology,” n.d.).

The gas and the blood come together in the alveolus where the exchange occurs with oxygen moving into the blood stream and carbon dioxide moving out of the blood stream. Fick’s Law of Diffusion states, "The rate of transfer of a gas through a sheet of tissue is proportional to the tissue area and the difference in gas partial pressure between the 2 sides and inversely proportional to the tissue thickness" (“Fick’s Law,” n.d.). The gas moves from a higher level of pressure across the one micron thick wall of the alveolus wall to replace the gas of lower level of pressure. This concept is shown in Figure 2.

	LUNGS	**TISSUES**
OXYGEN	High pressure	Low pressure
CO_2	Low pressure	High pressure

Figure 2. Blood-gas diffusion. Retrieved from “Human Physiology” (n.d.).

By the time oxygen is in the alveolus and ready for diffusion, PO_2 has dropped to 100 mm Hg, now identified as PAO_2. The pressure drop is a result of balance between the two processes of the removal of oxygen by the pulmonary capillaries and the continual supply by alveolar ventilation (Law & Bukwirwa, 1999). The balance of pressure is derived by a person’s continuous breathing, bringing fresh air with lots of O_2 and little CO_2 into the lungs, as shown in Figure 3.

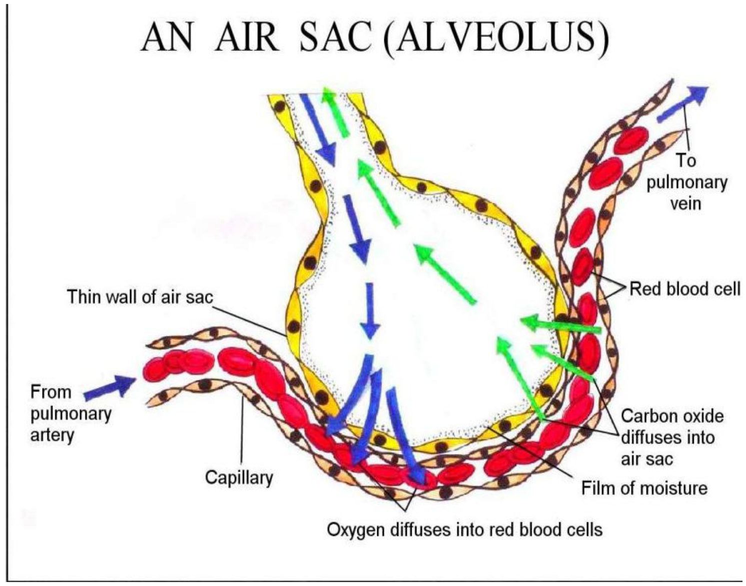

Figure 3. Blood-gas exchange system. Retrieved from "Gas Exchange Systems" (2006).

Oxygen is carried in the blood in two ways: about 1% is dissolved in plasma and 99% is combined with hemoglobin, a protein contained in the red blood cell. Each molecule of hemoglobin can transport four oxygen molecules. This binding is called oxyhemoglobin. The amount of oxygen that can be carried by the blood is dependent on the concentration of hemoglobin. A normal healthy male has a concentration of hemoglobin of 150 grams per liter of blood, while a normal healthy female has a concentration of 130 grams per liter of blood. When the hemoglobin is completely saturated with oxygen, each gram of hemoglobin can transport 1.34 ml of O_2. A normal healthy male can, therefore, carry approximately 200 ml of O_2 while the normal female can carry 174 ml of O_2 (Powers & Howley, 2008). When the oxygen is released to the tissue from the hemoglobin, it is called deoxyhemoglobin. Oxygen is released when the partial pressure of O_2 is low and the partial pressure of CO_2 is high. The high CO_2

changes the shape of the hemoglobin molecule and supports the unloading of oxygen. Other conditions that enhance the unloading of oxygen are high temperature and an increase in acidity (Gregory, n.d.). The percent of hemoglobin saturation at various partial pressures of oxygen are demonstrated in the following Oxygen Dissociation Curve as shown in Figure 4.

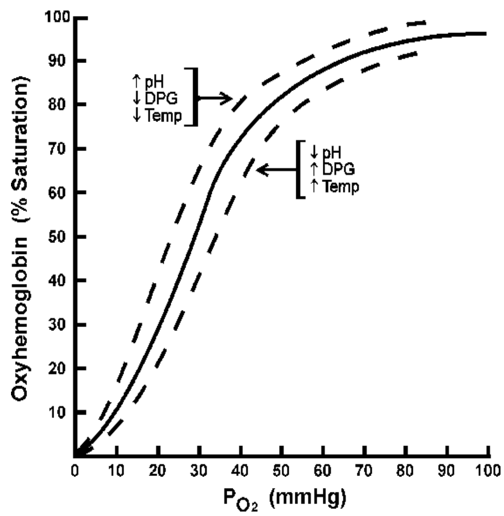

Figure 4. Oxygen dissociation curve. Retrieved from Dickens (1999).

Hemoglobin saturation occurs quickly up to 40 mm Hg where the rate of saturation decreases until it levels off around 90 to 100 mm Hg at which saturation is about 97% (Dickens, 1999). The flat area above 90 mm Hg also reflects a minimal drop in oxyhemoglobin which is extremely important as there is a decline in arterial oxygen during ascent in altitude. The conditions which encourage the unloading of the oxygen cause the curve to move to the right. During heavy exercise, lactic acid is developed in the muscle cell and stimulates the unloading of oxygen to the tissues. Red cells do not contain a nucleus and, therefore, they depend on anaerobic glycolysis for energy needs.

A by-product of anaerobic glycolysis is 2-3 Diphosphoglycerated (DPG) which combines with the hemoglobin and decreases the receptiveness for oxygen. Red blood cells containing concentrations of 2-3 DPG are known to increase during exposure to increased altitude (Powers & Howley, 2008).

In a survey conducted by Smith (2005) involving 53 helicopter pilots and crew members, hypoxia was shown to appear at lower altitudes when there was increased physical exertion. Reports from the participants were submitted recording their personal experiences of hypoxia and the observed hypoxia symptoms in other crew members. Observations of hypoxic symptoms in others were reported more frequently than those recognized in themselves, and crew members performing physical exertion reported symptoms more frequently than those in the flight crew. In a further study by Smith (2007), six participants used a hypobaric chamber to assess the effects of physical exertion on oxygen saturation. Oxygen saturation was measured at rest at sea level, 1,400 ft., 5,000 ft., and 6,200 ft. At sea level, oxygen saturation was normal at 97%. Further altitudes reflected oxygen saturation readings of 96%, 88%, and 85%, respectively. Oxygen saturation was also measured after the introduction of physical activity. Once physical activity was introduced, oxygen saturation began to decrease. At sea level and at 1,400 ft., oxygen saturation reflected only minor decreases of 1% and 2.2%, respectively. At 5,000 ft. and 6,200 ft., the changes were more substantial, resulting in decreases of 4.3% and 5.5%, respectively. When physical activity ceased and the subjects were given 3 mins of rest, oxygen saturation levels returned to within 1% of the original at-rest value. Twenty-one symptoms reflected by the participants were studied for possible hypoxia. Symptoms recorded at 1,400 ft. included breathlessness, tiredness, sweating, weakness and feeling warm. Symptoms shown at 5,000 ft. and 6,200 ft. were neurocognitive and psychomotor impairment.

Carbon dioxide (CO_2) is moved in the blood in three different ways. About 10% of the CO_2 is dissolved in the blood, 20% as carbaminohemoglobin or CO_2 bound to hemoglobin, and 70% as bicarbonate. Powers and Howley (2008) state:

> A high PCO_2 causes CO_2 to combine with water to form carbonic acid. This reaction is catalyzed by the enzyme carbonic anhydrase, which is found in RBCs. After formation, of carbonic acid dissociates into a hydrogen ion and a bicarbonate ion. The hydrogen ion then binds to hemoglobin and the bicarbonate ion diffuses out of the RBC into plasma. (p. 216)

Once the blood reaches the pulmonary capillaries, the CO_2 diffuses out of the blood and across the blood-gas interface (Powers & Howley, 2008).

Generally, the body is able to deliver more oxygen to the cells than what is actually used. An adult at rest will consume about 250 ml of oxygen per minute, which equates to about 25% of the amount of oxygen available. When the body consumes more oxygen, the increased need is normally supplied by an increase in cardiac output. The amount of oxygen available per minute is known as oxygen delivery and is calculated by multiplying cardiac output by arterial oxygen content. If oxygen delivery falls in comparison to oxygen consumption, the tissues will extract more oxygen from the hemoglobin (Carlson, 1998).

The maximum capacity of an individual’s body to transport and use oxygen is identified as VO_2. Maximal cardiac output is a combination of the heart rate multiplied by the output of blood pumped by the heart in one minute, measured in liters/minute.

Studies conducted by Powers and Howley (2008) demonstrated a reduction in VO_2 as altitude increases. In addition, they determined that the heart rate remained the same at altitudes of 7,500 ft., 10,000 ft., and 13,000 ft. and that although there was some variance in the stroke volume, it was not sufficient enough to affect the conclusion that the reduction in VO_2 was due to a difference in oxygen extraction. The Oxygen Dissociation Curve data (Figure 5) demonstrated that at sea level, hemoglobin is about 97% saturated with oxygen (Powers & Howley, 2008). At 12,500 ft. saturation falls to 86%, at 14,000 ft. saturation is 82%, and at 15,000 ft. saturation is 80% and is similar to the reductions in VO_2.

Pressure Altitude (ft)	**Alveolar partial pressure of O_2 (mm Hg)**	**Dissolved O_2 (ml O_2/ 100 ml blood)**	**Hemoglobin saturation (%)**	**O_2 carried by hemoglobin (ml O_2/ 100 ml blood)**	**Total O_2 in blood (ml O_2/ 100 ml blood)**
0	103	0.32	97	20.22	20.54
5000	81	0.25	94	19.60	19.85
10000	61	0.19	90	18.77	18.96
12000	54	0.17	87	18.14	18.31
13000	51	0.16	84	17.51	17.67
14000	48	0.15	82	17.10	17.25
15000	45	0.14	80	16.68	16.82
20000	34	0.11	67	13.97	14.08
30000	30	0.09	57	11.88	11.97

Figure 5. Oxygen dissociation curve data. Retrieved from West (1982). *Note*. Oxygen content of human blood by pressure altitude assumes that alveolar O_2 = arterial O_2, pH 7.40, T = 37°C, 1.39 ml O_2 per gram of saturated hemoglobin (actual physiologic probably approximates 1.31).

Considering that each liter of blood is now carrying less oxygen, more blood is now needed to supply the same amount of oxygen, and the heart rate is increased to compensate. The bodies of individuals remaining at increased altitudes adjust by producing more red blood cells with increased hemoglobin and, therefore, are able to increase oxygen carrying capacity (Powers & Howley, 2008).

Early signs of oxygen starvation are recognized in the function of the eyes. The retina depends on the continual supply of oxygen. The retina consumes oxygen more rapidly than any other tissues, including the brain. The demand for oxygen within the eye is different based upon its function and, as a result, the eye is unique in that it has a dual source of blood supply. Photoreceptors and the predominance of the outer plexiform layer are supplied by one source while the inner retina layers are supplied by branches of the central retina artery. The inner layers that contain the retina rods which are the detectors of low light are the most sensitive to hypoxic challenges, whereas the outer layers are more resistant. The initial effect of hypoxia on the pilot is the instruments look fuzzy and less clear (Kaur, Foulds, & Ling, 2008).

Pilots are at risk from hypoxia. The safest and most effective way to learn about the effects of hypoxia and its dangers is to participate in a formal course in aviation physiology (Ernsting, 1973). The effects of hypoxia can be grouped into four stages by altitude. The first two stages, the indifferent stage and compensatory stage, occurred within this study. The disturbance stage and critical stage occur at altitudes much higher than those addressed in this study. The indifferent stage occurs between sea level and 10,000 ft. Physiological changes include an increased heart and respiratory rate, a decrease in night vision, and a reduction in the ability to perform tasks. The compensation stage occurs between 10,000 ft. and 15,000 ft. More observable symptoms occur in this stage including drowsiness, increased reaction time, and the slowing of mental processes that possibly could affect the ability to perform normal cockpit functions. Although some variability in these altitude benchmarks can occur, based on the individual's physical conditions, historically, the definition of these categories are generally accurate (FAA, 2003).

Low Altitude Hypoxia

Some pilots might accept the fact that symptoms of hypoxia may occur when the altitude exceeds 10,000 ft. This general thinking is supported by the numerous regulations specified by the FAA and similar publications and regulations issued in other countries ("Oxygen," n.d.). Nevertheless, the minimum altitude threshold where cognitive and psychomotor function becomes impaired remains a controversial issue. Many cases of mild hypoxia have been classified during accident investigation as pilot error ("Oxygen," n.d.). Symptoms of hypoxia have been reported as low as 5,000 ft. with decreased night vision. Forced concentration, fatigue, and headaches have been experienced at 8,000 ft. ("Oxygen," n.d.).

In a study conducted by Thorn (1995), learning of tasks at 8,000 ft. was shown to be impaired, and the impairment remained even once the blood oxygen level returned to normal. In contrast, tasks learned at sea level were performed better than those learned at 8,000 ft. Moreover, participants who learned the task at sea level performed better while in a hypoxia condition than those who learned the task at 8,000 ft. Tests that measure the way people make decisions under of conditions of uncertainty, called the Signal Detection Test, have resulted in response times substantially slower at 7,000 ft. than at sea level. As this test and numerous studies have reported, because of the possible onset of hypoxia at altitudes lower than 10,000 ft., the safety concern is legitimate (Thorn, 1995).

A pulse oximeter was developed to measure the oxygen content of the blood. Early pulse oximeters had questionable accuracy plus they were large and difficult to work with. Technology advances have now made the pulse oximeters inexpensive and small enough to be able to be carried around the neck or in a flight bag. Many commercial airlines include the pulse oximeters in their on-board medical kit. The portability provides private pilots the opportunity to carry these with them and substantially reduce their individual risk of hypoxia ("Pulse Oximeter," n.d.).

Cognitive Processing

In the early 1980s, the Department of Defense (DoD) was concerned over the fact that some military personnel were being exposed to the effects of chemical warfare (Reeves, Winter, Bleiberg, & Kane, 2007). A group was established to develop a standardized performance assessment tool to assess cognitive, emotional, perceptual, psychomotor, and physiology functioning (Defense & Veterans Brain Injury Center, n.d.). The test was designed to measure cognitive functioning, and it was to provide information regarding possible treatment of brain injuries. The program involved the division of military jobs into critical tasks which further related to behavioral constructs that were measured by cognitive and psychomotor tests. As a result of the development of smaller computer technology, scientists were able to construct and run the computer tests during medical and field operations on a personal computer quickly and process the results quickly (Reeves et al., 2007). The DoD was supporting computerized test development with extra attention being paid to those with repeated measures paradigms, generation of alternate forms, and the ability to assess changes in performance overtime.

These computerized test systems met research and clinical objectives and led to the development of the Automated Neuropsychological Assessment Metrics (ANAM™) test (Reeves et al., 2007). The development of ANAM™ was the result of input from a combination of preexisting computer test systems, including the *Walter Reed Performance Assessment Battery, the Air Force Criterion Test*, *Navy Performance Evaluation Tests for Environmental Research*, *Naval Medical Research Institute Performance Assessment Battery*, and the *North Atlantic Treaty Organization Standardized Tests for Research with Environmental Stressors Battery*. The significance of the selection of these historic tests was that it immediately established the validity of the ANAM™ (Reeves et al., 2007).

The output of the ANAM™ test was a consistent series of scores. The scores included percent correct, mean response time for all responses, mean response time for correct responses, standard deviation of the mean response time for all responses, standard deviation of the mean response time for correct responses, median response time for all responses, median response time for correct responses, throughput (responses per min), response omissions, and premature responses. In addition, data could be presented in three different formats. Within ANAM™, there were 31 different test modules and several different methods for recording and extracting the data for research purposes (Reeves et al., 2007). The output of the ANAM™ was then transported via a program used to exchange data between disparate applications called Comma-Separated Value (CSV). This program has become a standard tool throughout the aviation industry with a common interchange format between software packages supporting tabular data such as Microsoft Excel® format (Reeves et al., 2007).

Population

A search of 2008 U.S. census data has revealed there were 592,000 licensed pilots in the United States (Department of Labor, 2009). Worldwide, there were 244,000 private pilots, 116,000 commercial pilots, 145,000 transport pilots, and 87,000 student pilots (Department of Labor, 2009). Of the 592,000 U.S. pilots, only 34,000 were women. In 2008, there were 77,090 pilots employed by scheduled airlines (Department of Labor, 2009). It is projected there will be a 12% growth of airline pilots between 2008 and 2018 (Department of Labor, 2009).

Rose (2001) contends the personality profile of a pilot is that they are, for the most part, bright and socially skilled. Pilots are positive in their approach, diligent in their work effort, interested in what is going on around them but prefer quick overviews of the big picture. They are cooperative on everything except decisions regarding safety.

Summary

The CFR's are sets of regulations that establish the rules of behavior for the functioning of the United States Government. Title 14 established the FAA and the functioning of activities related to air and space travel. The FAA's primary focus is safety. The FAA further established the rules of activity called FARs. The FARs established the need for supplemental oxygen in unpressurized aircraft at cabin pressure altitudes above 10,000 ft., up to and including 12,000 ft. when the exposure is longer than 30 minutes.

The AIM is a publication by the FAA and is referred to as the Official Guide to Basic Flight Information and ATC Procedures. Although the AIMs are not regulatory in nature, failure to follow their procedures could be used in enforcement proceedings.

The NTSB was established under CFR Title 49 as an independent agency to investigate every civil aviation accident and significant accidents of other forms of transportation.

The FAA approves AATDs that meet specific criteria regarding the inclusion of facilities and software support that are capable of providing a realistic flying experience that can be used as a training operation. The AATD, plus the use of a Normobaric Laboratory, can replicate, for training purposes, the effects of hypoxia caused by oxygen deprivation.

The most common occurrences of hypoxia in aviation are pilots flying in non-pressurized aircraft. The symptoms and intensity of hypoxia vary both within and between individuals. Incidents have been recorded that indicate hypoxia and mental impairment occur at lower altitudes than that specified by the FAA.

Chapter III

Methodology

Research Approach

The research was quasi-experimental and involved exposing participants to decreasing amounts of oxygen, representing altitudes of 5,000 ft. and 14,000 ft. Using an AATD to measure pilot performance and the ANAM™ cognitive test to measure processing skills, tasks were assigned to participants at specific time increments and altitude levels. Data were collected on pre-and post-testing and in-processing testing.

Design and procedures. Participants were self-selected from ERAU students who were certificated instrument-rated pilots. Two tests were administered, the ANAM™ and the AATD profile.

ANAM™. Before participating in the study, participants were administered the ANAM™ test 10 times and were required to score 90% or better on the test; this assured that the participants were completely familiar with all aspects of the ANAM™ test. The participants had to be knowledgeable about test methodology and content to assure that test confusion did not become an unrecognized variable. Meaningful data collected was the difference between the pre-study results and those recorded while in the HAL. The participants were not privy to the selected altitude at any time during the session. They were exposed to altitudes of 5,000 ft. and 14,000 ft. The participants were tested in one session at each altitude to test the effects of the decreased oxygen content associated with increased altitudes. In addition, the participants were exposed to only one altitude each day for no more than 30 min. The exposure to one altitude per day assured there was no physical or cognitive overlay impact from one session exposure test to the next. The maximum test altitude of 14,000 ft. for no more than 30 min was consistent with FAR 91.211 (FAA, 2010a).

During each lab session, participants were administered the ANAM™ test at three intervals of exposure to low-oxygen environment: one before entering the lab (at sea level), the next after entering the lab during the first 10 min segment (at altitude), and the last during the last 10 min segment (at altitude). Upon exit, their blood oxygen levels were recorded, and they were released when their blood oxygen levels became normal. Pulse and oxygen levels were also recorded before each participant entered into the lab (at sea level). These measurements were not taken at altitude because they would reveal an approximate altitude to the participants.

Manikin test. The Manikin test assessed three-dimensional spatial rotation ability using pictures of a manikin in various positions showing a person holding an object in one hand. The figure appeared in several different positions, and the task was to identify in which hand, right or left, the object was being held (Reeves et al., 2007).

Mathematical processing task. The math test assessed the cognitive ability of the mind to process mathematical equations. Each equation was a compound addition and subtraction problem, in which the participant had to determine whether the equation was less than or greater than five (Reeves et al., 2007). The test was a processing speed test; answering the problem quickly and correctly scored more points.

Switching task. The Switching task was the test administered in this study and was a combination of the Mathematical Processing Task and the Manikin Test. The purpose of this test was to assess mental flexibility. In this test, both the Mathematical Processing Task and the Manikin Task were shown at the same time, and then there was an arrow pointing to the operation the subject was to complete. The test switched back and forth from one task to another in an unpredictable manner (Center for the Study of Human Operator Performance, n.d.). An example of this test is shown in Figure 6.

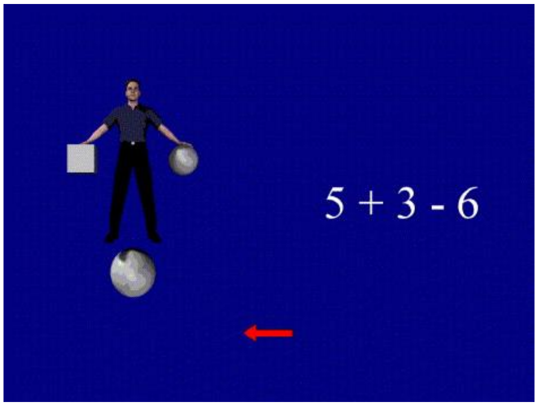

Figure 6. ANAM™ switching test battery screen photograph. Retrieved from Reeves et al. (2007).

AATD test. In conjunction with ANAM™ testing, one participant flew the AATD during the second 10 min segment. This was used to measure the performance of a pilot during an instrument flying task. Each instrument task took approximately 10 to 15 min. This allowed participants to perform the flying task during their rotation through the three stations in the 30-min lab session.

Apparatus and materials. One laptop computer was required for each participant. Software program availability for ANAM™ was required for up to nine laptop computers. For this study, this researcher used a combination of the test modules - Mathematical Processing, Kinesthetic Perception (Manikin Test), and Switching Task (Reeves et al., 2007). The Mathematical Processing test involved performing basic math operations of addition and subtraction. This test assessed computation, concentration, and working memory.

HAL. The HAL was the Normobaric Lab at ERAU that simulated altitude conditions by decreasing the oxygen content in air (Colorado Altitude Training, n.d.). The lab design include a freestanding modular clear room enclosure that can hold up to 10 people. Labs with the capability of simulating altitudes of over 20,000 ft. require an anteroom that was included in the ERAU's lab. It was controlled by a fully automated digital controller with a remote PC hookup with displays showing set-point altitude, current altitude, and CO_2 content. To assure oxygen content accuracy, the environment was monitored by dual sensors with self-correcting capability (Colorado Altitude Training, n.d.).

AATD. An AATD is a computer-based aviation training device that includes the following equipment (Frasca, 2010):

1. Self-centering displacement yoke or control stick that allows continuous adjustment of pitch and bank.
2. Self-centering rudder pedals that allow continuous adjustment of yaw.
3. Throttle lever or power lever that allows continuous movement from idle to full power settings.
4. Controls for the flaps, propeller, mixture, pitch trim, altimeter, transponder, carburetor heat, cowl flaps, gear handle, communication and navigation radio, clock, and microphone with push-to-talk switch.
5. Computer
6. Monitor
7. Simulation software

8. CD drive

9. Sound card with speakers or ear phones

10. CSV software program to transfer the data into a Microsoft Excel format.

Population and Sample

The population that was used in the study was pilots from ERAU. There were 848 pilots enrolled at ERAU's flight program (K. Byrnes, personal communication, March 2, 2011). Instructors and instrument-rated pilots totaled 434 and were eligible to participate in the study. Five participants were self-selected by responding to a flyer that was posted around campus. The flyer sought participants who had a pilot license with a instrument rating, were non-smokers, and were between the ages of 18 to 25.

Pilot Study

A pilot study is a small experiment, designed to test logistics and gather information prior to conducting a larger study. They are also used to improve quality and efficiency for the larger study. "Pilot studies can provide limited data and magnitude of the variation to help knock out the bugs and jump-start the larger study. The data collected may or may not show significance, but may be used in the larger study if the variables and procedures are unchanged" (Lancester, Dodd, & Williamson, 2004 p. 1).

Data Collection Device

Test results from AATD and ANAM™ tests were collected on a flash drive on an individual basis with each participant having his or her own unique flash drive. The data were then transferred from each flash drive into Excel and the Statistical Package for the Social Sciences (SPSS) by the use of CSV format.

ANAM™. ANAM™ has its own data collection device that is accurate to the 1,000th of a second response time (Reeves et al., 2007). The two variables that were recorded were Throughput Manikin and Throughput Math. Throughput Manikin was recorded as the number of correct responses per unit of available time. The mean average was calculated and entered into the data set for each participant and altitude tested. Throughput Math was also recorded as the number of correct responses per unit of available time. The mean average was calculated and also entered into the data set for each participant and altitude tested.

Pilot Performance-AATD. The AATD variables (Appendix B) were as follows:

The Localizer is a part of the ILS system that uses ground directional transmitting system that provides course guidance throughout the descent path to the runway centerline threshold from a distance of 18 nautical miles. Proper off-course indications are provided to the pilot (FAA, 2010d). Localizer Excursion was recorded as horizontal deviation from the localizer course measured in "dots" on the course deviation indicator (CDI). In an ILS approach, one dot of deviation is equal to one-half degree right or left of the localizer course (FAA, 2010d). The Localizer Excursion focused on the descent portion from the final approach fix to the missed approach point.

The Glideslope is the angle that the glide path of an aircraft makes with the horizontal ("Flightsim Aviation Zone," 2012). This is also part of the ILS system that starts at the threshold of the runway and extends out and up toward the final approach fix, normally at a three degree angle. Glideslope Excursion was recorded as vertical deviation from the glideslope measured in feet above or below the glideslope (FAA, 2010d). Glideslope Excursion focused on this portion of the ILS.

Target Speed was a set speed (100 kts) that the pilots were briefed to maintain. Target Speed Excursion was the deviation (in knots) from the target speed of 100 kts.

Decision Height (DH) is a specified altitude or height in a landing approach at which a missed approach must be initiated ("McGraw-Hill Dictionary," 2002). Decision Height Excursion was recorded as deviation in feet from the set point at which the participants were to execute the missed approach procedure. The difficulty associated with data collection was that executing a missed approach above DH is acceptable; whereas descending below DH is a violation of the FARs set by the FAA (FAA, 2010f).

Deviation was the difference between the desired flight track of an aircraft and the actual flight path, expressed in terms of either angular or linear measurement ("McGraw-Hill Dictionary," 2002). All of the collected data were mean excersions from the targets set by the researchers.

Instrument reliability. The ANAM™ tests " have strong correlation with traditional measures of neuropsychological functioning with high test and retest reliability typically in the 0.80 to 0.95 range" (Schlegel, Schlegel, & Gilliland, 2007, slide 11). There is no data on the reliability of the pilot performance data. This study began the process of determining the reliability of pilot performance by relating pilot performance data to the proven ANAM™ data.

Instrument validity. "ANAM™ has high differential stability and a large database of studies providing construct validity" (Schlegel et al., 2007). Validity of the pilot performance data was tested in this study by comparing pilot performance data from the AATD to the proven ANAM™ data.

Treatment of the Data

Descriptive statistics. Pilot performance data from the AATD were scale data, and they were described with a table depicting the mean, standard deviation, minimum, maximum, and number of cases. Cognitive processing data from ANAM™ (Throughput Manikin and Throughput Math) were scale data that were described with a table depicting the mean, standard deviation, minimum, maximum, and number of cases.

Hypothesis testing. ANAM™ variables were run with a one-way Analysis of Variance (ANOVAs) used to determine whether or not the means of several groups are equal, and Friedman's test for small samples to detect differences across multiple test attempts. Pilot performance variables from the AATD were run with paired sample *t*-tests to test if the responses measured on the same unit have any differences among them.

Reliability testing. The ANAM™ variables and the AATD variables were both scale data; however, they have different values. In order to standardize these data on a common scale, Z-scores were generated between pilot performance data from the AATD and cognitive processing data from ANAM™. These data were tested by correlation statistics to test congruency between pilot performance and cognitive processing. These calculations were an attempt to determine the validity and reliability of the pilot performance data as a measure of cognitive processing skills for instrument-rated pilots.

Chapter IV

Results

Pilot Performance - AATD

Descriptive statistics. Descriptive statistics were run to ensure the accuracy of the data and to obtain necessary numbers for the analysis. In this study, there were 150 data points for each of the four variables for each participant, and five participants generated the data. The data were reviewed for minimum and maximum numbers to ensure that they were in the correct range for the type of data. Missing values were assessed and replaced as required.

Localizer excursion. Localizer Excursion was the number of dots left or right on the horizontal situation indicator (HSI) from the localizer centerline. Table 1 describes the variable, Localizer Excursion.

Table 1

Localizer Excursion Descriptive Statistics

	Paired Samples Statistics				
Altitude	Mean	*N*	Std. Deviation	Min	Max
5,000	0.37	5	0.23	0.12	0.64
14,000	2.12	5	3.46	0.23	8.30

Glideslope excursion. Glideslope Excursion was the number of feet above or below the absolute glideslope. Table 2 describes the variable, Glideslope Excursion.

Table 2

Glideslope Excursion Descriptive Statistics

	Paired Samples Statistics				
Altitude	Mean	*N*	Std. Deviation	Min	Max
5,000	35.14	5	25.36	13.79	79.08
14,000	63.92	5	71.08	19.80	189.77

Target speed excursion. Target Speed Excursion was the number of knots above or below the assigned 100-knot approach speed. Table 3 describes the variable, Target Speed Excursion.

Table 3

Target Speed Excursion Descriptive Statistics

	Paired Samples Statistics				
Altitude	Mean	*N*	Std. Deviation	Min	Max
5,000	2.52	5	0.63	1.78	3.29
14,000	5.37	5	6.14	1.72	16.25

Executed MAP altitude. Executed MAP Altitude was the number of feet above or below the published DH where the pilot began the missed approach procedure. Table 4 depicts the actual deviation of the executed MAP from the set DH. The negative values are associated with going below DH, which is a violation of the FARs (FAA, 2010f). Table 5 depicts the participants who went below DH for both HAL altitudes and those participants who stayed above DH for both HAL altitudes. Because this study was only a preliminary investigation, these tables were designed to be utilized for further data collection. Tables 4 and 5 describe the variable, Executed MAP Altitude.

Table 4

Actual Deviation from Decision Height (DH)

Participant	5,000 Ft	14,000 Ft
A	-67.4	3
B	2.9	-24.8
C	109.5	45.8
D	-42.1	27
E	-61.5	11.3

Note. Negative deviation from DH indicates below glideslope.

Table 5

Average Deviation Above or Below Glideslope at Decision Height

		Paired Samples Statistics				
Deviation	Altitude	Mean	*N*	Std. Deviation	Min	Max
Above	5,000	56.2	2	75.37	2.9	109.5
DH	14,000	21.77	4	18.86	3	45.8
Below	5,000	-57	3	13.23	-42.1	-67.4
DH	14,000	-24.8	1	0	-24.8	-24.8

Hypothesis testing.

Localizer excursion. For H1, a *t*-Test was conducted to test the null hypothesis: There was no difference in Localizer Excursion between HAL altitudes of 5,000 ft. and 14,000 ft. Table 6 shows the results.

Table 6

Localizer Excursion Paired Samples Test

Altitude	5,000	14,000
Mean	0.38	2.13
Variance	0.06	12.03
Observations	5	5
df	4	
t Stat	-1.21	
P(*T*<=*t*) two-tail	0.29	
t Critical two-tail	2.78	

The results failed to reject the null hypothesis; there was no statistical difference in Localizer Excursion between HAL altitudes of 5,000 ft. and 14,000 ft.

Glideslope excursion. For H1, a *t*-Test was conducted to test the null hypothesis: There was no difference in Glideslope Excursion between HAL altitudes of 5,000 ft. and 14,000 ft. Table 7 shows the results.

Table 7

Glideslope Excursion Paired Samples Test

Altitude	5,000	14,000
Mean	35.14	63.92
Variance	643.21	5053.75
Observations	5	5
df	4	
t Stat	-1.34	
P(*T*<=*t*) two-tail	0.25	
t Critical two-tail	2.77	

The results failed to reject the null hypothesis; there was no statistical difference in Glideslope Excursion between HAL altitudes of 5,000 ft. and 14,000 ft.

Target speed excursion. For H1, a *t*-Test was conducted to test the null hypothesis: There was no difference in Target Speed Excursion between HAL altitudes of 5,000 ft. and 14,000 ft. Table 8 shows the results.

Table 8

Target Speed Excursion Paired Samples Test

Altitude	5,000	14,000
Mean	2.52	5.37
Variance	0.40	37.79
Observations	5	5
df	4	
t Stat	-1.09	
P(*T*<=*t*) two-tail	0.34	
t Critical two-tail	2.78	

The results failed to reject the null hypothesis; there was no statistical difference in Target Speed Excursion between HAL altitudes of 5,000 ft. and 14,000 ft.

Cognitive Processing Skills - ANAM™

Descriptive statistics. Descriptive statistics were run to ensure the accuracy of the data and to obtain necessary numbers for the analysis. In this study, there were 50 data points over two variables for each participant, and five participants generated the data at three different HAL altitudes. The data were reviewed for minimum and maximum numbers to ensure that they were in the correct range for the type of data. Missing values were assessed and replaced as required.

Throughput manikin. The ANAM™ Throughput Manikin variables for the different HAL altitudes of Sea Level, 5,000 ft. MSL, and 14,000 ft. MSL are described in Table 9.

Table 9

Throughput Manikin Descriptive Statistics

Altitude	*N*	Mean	Std. Deviation	Std. Error	Min	Max
Sea Level	5	30.51	5.04	2.25	25.54	38.38
5,000	5	34.92	8.18	3.65	24.98	47.64
14,000	5	30.12	3.63	1.62	25.89	34.71

Throughput math. The ANAM™ Throughput Math variables for different HAL altitudes of Sea Level, 5,000 ft. MSL, and 14,000 ft. MSL are described in Table 10.

Table 10

Throughput Math Descriptive Statistics

Altitude	*N*	Mean	Std. Deviation	Std. Error	Min	Max
Sea Level	5	20.81	5.85	2.61	15.99	29.42
5,000	5	21.06	6.62	2.96	13.17	30.70
14,000	5	18.84	6.54	2.92	13.49	29.92

Hypothesis testing.

Throughput manikin. For H2, a one way ANOVA was run to test the null hypothesis: There were no differences in Throughput Manikin scores among the different altitudes of Sea Level, 5,000 ft., and 14,000 ft. Table 11 depicts the results.

Table 11

Throughput Manikin One-Way ANOVA

	Sum of Squares	*df*	Mean Square	*F*	Sig.
Between Groups	71.08	2	35.54	1.01	.39
Within Groups	422.32	12	35.19		
Total	493.40	14			

The results failed to reject the null hypothesis. There were no statistical differences in Throughput Manikin scores among the different altitudes of Sea Level, 5,000 ft., and 14,000 ft.

For H2, a Freedman's non-parametric test was run to further enhance the results from the ANOVA test for difference in small samples. Table 12 depicts the results.

Table 12

Manikin: Session 1 vs. Session 2 at 14,000 ft

P value	.18
Exact or Approximate *P* value	Exact
P value summary	NS
Are means significant ($p < .05$)	No
Number of groups	3
Freedman static	3.60

The Freedman's test showed non-significant results throughout the three data sets run.

Throughput math. For H2, a one way ANOVA was run to test the null hypothesis: There were no differences in Throughput Math scores among the different HAL altitudes of Sea Level, 5,000 ft., and 14,000 ft. Table 13 depicts the results.

Table 13

Throughput Math One-Way ANOVA

	Sum of Squares	*df*	Mean Square	*F*	Sig.
Between Groups	14.79	2	7.39	.18	.83
Within Groups	484.01	12	40.33		
Total	498.80	14			

The results failed to reject the null hypothesis. There were no differences in Throughput Math scores among the different HAL altitudes of Sea Level, 5,000 ft., and 14,000 ft.

For H2, a Freedman's non-parametric test was run to further enhance the results from the ANOVA test for difference in small samples. Table 14 depicts the results.

Table 14

Math: Session 1 vs. Session 2 at 14,000 ft.

P value	.69
Exact or Approximate *P* value	Exact
P value summary	NS
Are means significant ($p < .05$)	No
Number of groups	3
Freedman static	1.20

The Freedman's test showed non-significant results throughout the three data sets run.

Reliability testing. Correlations were chosen for reliability testing because the researcher wanted to validate the AATD against the proven ANAM™ test battery. *Z*-scores were used to standardize the data sets on the same scale. Pearson *r* correlations were calculated to test the null hypothesis: There were no relationships among pilot performance variables and cognitive processing skills at a HAL altitude of 5,000 ft. Only nine cases out of 10 were used because the last case was more than two times the next highest case and skewed the data. Table 15 depicts the results.

Table 15

Correlations Among Variables at 5,000 ft

	ZThroughput_ MAN	ZThroughput_ Math	ZLocalizer	ZGlideslope	ZTarget _Speed
ZThroughput_ MAN	1				
ZThroughput_ Math	0.15	1			
ZLocalizer	0.50	-0.52	1		
ZGlideslope	-0.35	-0.53	0.40	1	
ZTarget_Speed	0.42	-0.70*	0.43	0.21	1

Note. **p* < .05.

The null hypothesis was rejected for correlation between pilot performance (ZTarget Speed) and cognitive processing skill (ZThroughput Math). The null hypothesis failed to be rejected for all other relationships. There was a relationship between pilot performance and cognitive processing skills for ZThroughput Math and ZTarget Speed at a HAL altitude of 5,000 ft.

A correlation was calculated to test the null hypothesis: There were no relationships among pilot performance variables and cognitive processing skills at a HAL altitude of 14,000 ft. Only nine cases out of 10 were used because the last case was more than two times the next highest case and skewed the data. Table 16 depicts the results.

Table 16

Correlations Among Variables at 14,000 ft

	ZThroughput_ MAN	ZThroughput_ Math	ZLocalizer	ZGlideslope	ZTarget _Speed
ZThroughput_ MAN	1				
ZThroughput_ Math	0.78*	1			
ZLocalizer	-0.62	-0.43	1		
ZGlideslope	-0.66*	-0.53	0.99*	1	
ZTarget_Speed	-0.71*	-0.51	0.99*	0.99*	1

Note. **p* < .05.

The null hypothesis was rejected for pilot performance (ZTarget Speed) and cognitive processing skill (ZThroughput Man) and for pilot performance (ZGlideslope) and cognitive processing skill (ZThroughput Man). The null hypothesis failed to be rejected for all other relationships. There was a relationship in pilot performance and cognitive processing skills between ZThroughput Man and ZTarget Speed and between ZThroughput Man and ZGlideslope at a HAL altitude of 14,000 ft.

A square root transformation was calculated to see how the participants reacted during the lab sessions. Their oxygen levels and heart rates were recorded upon exit from the lab. The oxygen levels and heart rates were then added to the rest of the scores from the participants. The square root of each score was taken to bring the scores to a more manageable variation depiction. Figure 7 depicts the scores.

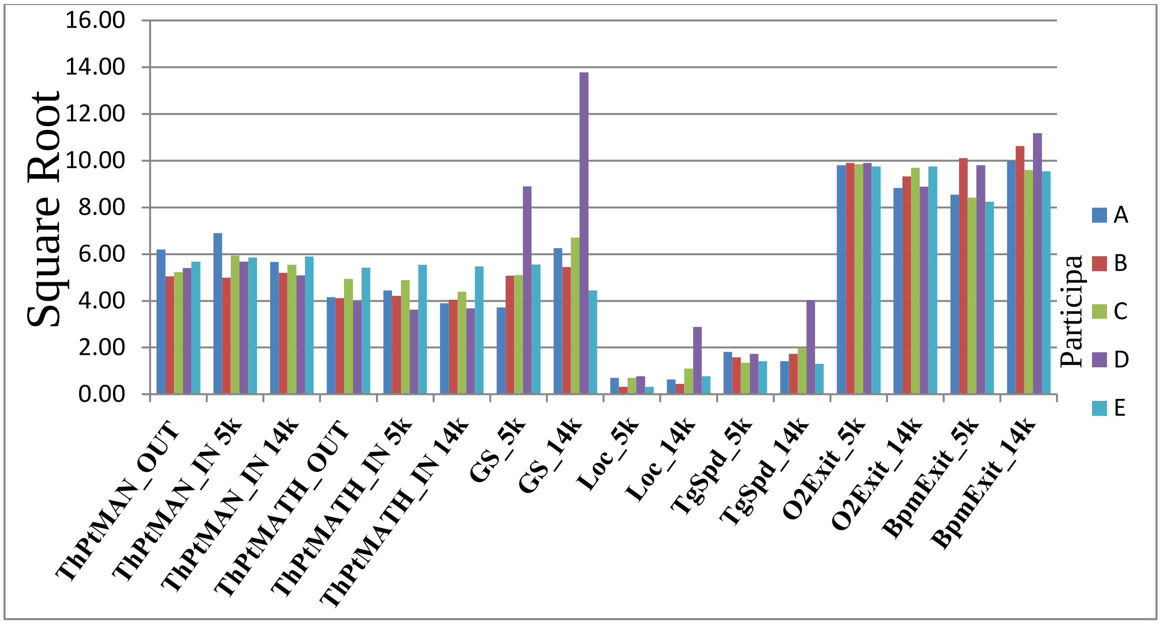

Figure 7. Square root transformation.

Chapter V

Discussion, Conclusions, and Recommendations

After review of the data collected, the researcher was able to make conclusions and discussion points from the results. As expected in a preliminary study with only five subjects, the data did not support the hypotheses stated in Chapter I; however, the results support the need for further research on a larger scale.

Discussion

By the use of descriptive and inferential statistics, the data was able to show the relationship between the cognitive processing ability and the pilot's performance at different altitudes of flight. The discussion will cover the AATD flight excursions and the ANAM™ switching test battery results for the five participants in the study.

Pilot performance-AATD. The researchers examined four skills of a pilot on an instrument approach; they included flying on the localizer, glideslope, target speed, and executing the missed approach. By setting performance limitations on each skill, the researchers measured how each pilot performed in relation to the set standards.

Descriptive statistics. The tolerance that was set for three out of the four excursions were as follows: the localizer was set at one dot left or right of the centerline, the glideslope was set at 50 ft. above or below the centerline, and the target speed was set at 10 kts faster or slower than 100 kts. Between the 2 altitudes of 5,000 ft. and 14,000 ft. the mean absolute value of each participant showed that there was a drop in performance. The 5,000 ft. altitude data remained within the set tolerances of the study, while the 14,000 ft. altitude data varied outside of the set tolerances for some skills and some participants.

The last excursion that was examined was the missed approach at DH. The tolerance was set at DH and above. This is important because it is a violation of the FARs to descend below the DH unless the pilot has the intended runway environment visible and identifiable (FAA, 2010f). The results showed that the participants descended below the set altitude more often during the 5,000 ft. flight than during the 14,000 ft. flight. This conflicts with what was expected. Overall, the descriptive statistics support FAR part 91.211 (FAA, 2010a).

Inferential statistics. Paired sample *t*-tests were used to determine if the null hypotheses were correct. In regards to the localizer excursion, the tolerance was one dot left or right of the centerline and showed a drop in performance between the two altitudes. At 5,000 ft. the mean deviation was .38, and at 14,000 ft. the mean deviation was 2.13 which is double the tolerance. While this supports the hypothesis that there was a drop in performance at higher altitudes, there was no statistical significance. The glideslope excursion displayed the same findings as the localizer excursion. The tolerance was set at 50 ft. above or below the centerline. At 5,000 ft. the mean was 35 ft, and 65 ft at 14,000 ft. The results support the hypothesis that there was a drop in performance at higher altitudes but again the results had no statistical significance.

The target speed excursion tolerance was 10 kts faster or slower than the assigned speed of 100 kts. The data displayed that the mean for both altitudes were within the assigned tolerances, with a slightly greater deviation in speed at 14,000 ft.

The DH excursion results showed no statistical significance. The regulations state that the pilot cannot descend below the DH unless the pilot has the intended runway environment visible and identifiable (FAA, 2010f). The data showed that the participants' means at 5,000 ft. were below the set DH, and at 14,000 ft. the mean was above the DH, which is within FAA regulations.

Cognitive processing skills – ANAM™.

Descriptive statistics. The two variables that were tested were Throughput Manikin and Throughput Math. These variables were extracted from the ANAM™ switching test battery. The switching test battery uses cognitive reasoning to complete a math problem or a picture problem. The higher the score, the more accurate the responses are. The Throughput Manikin descriptive statistics showed a mean score at sea level of 30.5. At the altitudes of 5,000 ft. and 14,000 ft., the mean scores were 34.9 and 30.1 respectively. This shows that there was a drop in performance among the different altitudes, specifically between 5,000 ft. and 14,000 ft.

The Throughput Math descriptive statistics show a mean score at sea level of 20.8. At the altitudes of 5,000 ft. and 14,000 ft., the mean scores were 21.0 and 18.8 respectively. This shows that there was a drop in performance among the different altitudes, specifically between 5,000 ft. and 14,000 ft. The difference between the two variables can be explained by the participants' ability to do math problems better than spatial orientation problems.

Inferential statistics. Two tests were run to test the results from the ANAM™ test battery. The first was a one-way ANOVA which is a large sample test. The results showed no significance between the two variables, Throughput Manikin and Throughput Math, among HAL altitudes of Sea Level, 5,000 ft. and 14,000 ft. The second test was a Freedman's test, designed for smaller sample sizes. Although this test also showed no significance, the *p* values were smaller than the ANOVA *p* values. This result shows a possibility that more participants, generating more data, might yield significant results.

Reliability testing. Correlations were calculated on both altitudes to see if the data that was generated by both devices were significant against each other in attempt to determine validity and reliability. The results from the test showed there was some significance. In order to have significance at the .05 level, a Pearson *r* correlation of .666 had to be obtained in the data set. Although there was significance between the same data collection devices, they were not used in the pilot study to describe the data because pilot performance was tested as a measure of cognitive processing skills for instrument-rated pilots. For the chart that depicts 5,000 ft. (Table 15) the only significant trial was the relationship in pilot performance and cognitive processing skills between ZThroughput Math and ZTarget Speed. In the chart that depicts 14,000 ft. (Table 16) there was a relationship in pilot performance and cognitive processing skills between ZThroughput Man and ZTarget Speed as well as between ZThroughput Man and ZGlideslope. This is important because the ANAM™ is a highly validated instrument, and the Frasca mentor is not. The significance between the two data collection devices indicates the there is a need for further research with a larger population sample size.

The square root transformation was calculated to show the differences among the participants' oxygen levels and heart rate upon exit from the HAL in relation to their scores. The graph showed that the HAL had little effect on participants C and E. Three participants (A, B, and D) showed drops in their oxygen content and an increase in their heart rate upon exit from the HAL. Exit oxygen contents and heart rates for participants A, B, and D trended with their ANAM™ and AATD scores. They showed some outlying scores, indicating possible hypoxia symptoms. There was an interesting trend in the oxygen content upon exit. At 5,000 ft., the exit oxygen levels were higher than the exit oxygen levels at 14,000 ft. This also relates to heart rate which showed the same trends but in an inverse manner. At 5,000 ft., the exit heart rates were lower and at 14,000 ft. the exit heart rates were higher. Overall, Figure 7 showed that relationships existed between both tests given and further suggested that with more data there might be statistical significance.

Conclusions

Conclusions from this pilot study's findings are as follows. First, the sample size was too small for the study to be significant which indicates a classic Type II error. Next, as expected, some of the participants were not familiar enough with the Mentor AATD, which might have caused some skewing of the data. Because of the size and time constraints of the study, only two altitudes were tested in the HAL. In addition, the ANAM™ tests and the AATD pilot performance had to be completed in one constant lab session in order to finish data collection in the 30-minute time allotted. At this time, no changes to the FAA's regulations on oxygen requirements, as discussed in Chapter II of this study, will be recommended.

Recommendations

The results of this study demonstrated some anecdotal differences in the test results. The differences were not of a significant nature as expected, so that statistically valid conclusions could not be drawn. To validate whether low-level altitudes can produce hypoxia symptoms affecting cognitive processing skills, further research is required on the topic of low-level oxygen deprivation involving more participants. This would involve expanding the sample size to a minimum of 30-40 participants. To obtain a proper data set, it is recommended to test 212 participants, based on 435 eligible participants enrolled in the flight program at ERAU. This ideal but somewhat impractical design would yield a 5% margin of error and 50% variability, so no type II errors would be present (Watson, 2001). Next, at least five altitudes should be studied, ranging from Sea Level to 14,000 ft. MSL. More accuracy could be obtained if HAL sessions were split so that only one test would be run at a time. For example, the ANAM™ switching battery test could be run three times in the HAL at altitude and twice outside the HAL at Sea Level to get more accurate data. The AATD should also be run in the HAL at altitude and outside the HAL at Sea Level. Splitting the sessions would provide more time to complete the pilot performance test in the Mentor AATD.

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Appendix A

Permission to Conduct Research

EMBRY-RIDDLE
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April 13, 2011

Dr. Guy Smith
Mr. David Shideler
College of Aviation
Embry-Riddle Aeronautical University
600 S. Clyde Morris Blvd.
Daytona Beach, Fl 32114

Reference: Institutional Review Board Approval – 11-123 IRB
Effects of Oxygen Deprivation on Pilot Performance And Cognitive Processing Skills

Dear Dr. Smith and Mr. Shideler:

In compliance with Embry-Riddle Aeronautical University's policy on Human Subjects and PHS 45 CFR 46.110, in my capacity as the Chair of the Institutional Review Board, the Institutional Review Board has reviewed the **Plan for the Protection of the Rights and Welfare of Human Subjects** for the proposed research project entitled ***Effects of Oxygen Deprivation on Pilot Performance And Cognitive Processing Skills*** and has determined that this study can be conducted as presented.

Best of luck in your endeavors.

Sincerely,

Dr. Albert Boquet
Chair of the Institutional Review Board

Appendix B

Data Collection Devices

Automated Neuropsychological Assessment Metrics (ANAM™)

Mean Throughput Manikin

Participant	OUT Sea Level	IN 5,000	IN 14,000
A	38.38	47.64	32.16
B	25.54	24.98	27.08
C	27.29	35.31	30.76
D	29.17	32.31	2589
E	32.21	34.38	34.71

Mean Throughput Math

Participant	OUT Sea Level	IN 5,000	IN 14,000
A	17.34	19.72	15.16
B	16.95	17.8	16.39
C	24.39	23.92	19.26
D	15.99	13.17	13.49
E	29.42	30.7	29.92

Advanced Aviation Training Device (AATD)

Mean Localizer Excursion

Participant	5,000	14,000
a	0.5	0.4
b	0.1	0.2
c	0.5	1.2
d	0.6	8.3
e	0.1	0.6

Mean Glide Slope Excursion

Participant	5,000	14,000
a	13.8	39.1
b	25.8	25.6
c	26	45
d	79.1	189.8
e	30.9	19.8

Mean Target Speed Excursion

Participant	5,000	14,000
a	3.3	2.0
b	2.5	3.0
c	1.8	3.9
d	3.0	16.3
e	2.0	1.7

Mean Decision Height Excursion

Participant	5,000	14,000
A	-67.4	3
B	2.9	-24.8
C	109.5	45.8
D	-42.1	27
E	-61.5	11.3
Target	322	227