NAVAL MEDICAL RESEARCH UNIT DAYTON

THE EFFECTS OF DIFFERING OXYGEN CONCENTRATIONS ON REACTION TIME PERFORMANCE AT ALTITUDE

William Becker, Ph.D.
william.becker.9@us.af.mil

Jeffrey B. Phillips, Ph.D.
jeffrey.phillips.17@us.af.mil

Matthew E. Funke, Ph.D.
matthew.funke.ctr@us.af.mil

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J. M. Andrews

Jeffrey M. Andrews, CAPT, MSC, USN
Commanding Officer

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6. AUTHORS
Becker, William J., Phillips, Jeffrey B., Funke, Matthew E.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Medical Research Unit Dayton
2624 Q Street, Bldg. 851, Area B
Wright-Patterson AFB, OH 45433-7955

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14. ABSTRACT

Currently, the OBOGS operates in two settings: a low altitude function (less than 11,000 ft) wherein an approximately 60% oxygen concentration is delivered, and a high altitude function, which delivers a 94% oxygen concentration. It is unknown if these limited oxygen concentration profiles are ideal for maintaining adequate levels of performance. The goal of this study was to document the effects of a graduated oxygen delivery schedule on cognitive task performance to determine whether modifications to the in-flight O2 delivery schedule is necessary to maintain peak performance in operational environments.

Analyses of variance revealed no significant differences between baseline performance and performance at altitude, regardless of oxygen concentration or altitude.

With the possible disadvantages of breathing high concentrations of oxygen such as alveolar collapse or hypocapnia, the potential advantages would seem to be offset. As performance was not significantly affected, it is of the opinion of the authors of this research that lower oxygen concentrations can be used in place of the current delivery schedule without an interruption to any flight operation.

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Commanding Officer
Naval Medical Research Unit Dayton

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The On-Board Oxygen Generating System (OBOGS) is the latest oxygen delivery system technology employed in modern air platforms. In OBOGS, engine bleed air is passed through a molecular sieve where harmful gasses such as carbon monoxide are separated from the final product of usable air, while the OBOGS concentrates the remaining oxygen in to a breathable supply for the air crew. This capability is vital for the current generation of air platforms to increase the speed, agility, and extended temporal operation, as removing the cumbersome Liquid Oxygen (LOX) equipment has allowed for a lighter, more space-efficient environment. In addition, the OBOGS also allows for more versatile flight planning, as the air platform is no longer subject to the carrying capacity of liquid oxygen, and deployment is not dependent on the presence of LOX refueling facilities.

Currently, the OBOGS operates in two settings: a low altitude function (less than 11,000 ft) wherein an approximately 60% oxygen concentration is delivered, and a high altitude function, which delivers a 94% oxygen concentration. While higher oxygen concentrations (greater than 103 mmHg PaO_2 within the lung) are thought to be necessary to offset the reduction in ambient air pressure and to ensure adequate blood and tissue oxygenation, it is unknown if these limited oxygen concentration profiles are ideal for maintaining adequate levels of performance. Given the dichotomous nature of the current OBOGS settings, while unexpected, it is possible that a buildup of high concentration oxygen in the tissues, hemoglobin, and organs could lead to physiological issues that would disrupt normal performance.

The use of higher concentrations of oxygen displaces the typical quantity of nitrogen in a given volume and could lead to a form of alveolar collapse known as absorption atelectasis (Dantzker, Wagner, & West, 1975; Lumb, 2007). As nitrogen is a key element of alveolar inflation, if it is replaced with oxygen, the volume of the alveoli would be decreased, which in turn would result in a decline in the ability to exchange oxygen and carbon dioxide through the alveoli-capillary membrane. If this were to occur, a generalized state of hypoxic hypoxia could follow, leading to reduced cerebral oxygen saturation and possibly a disturbance in performance or a loss of consciousness (Edmark, Aunder, Enlund, Ostberg, & Hedenstierna, 2011, O'Neil, & Raub, 1984; Wagner, & West, 1980).

Additionally, another mechanism through which hyperoxia can lead to declining performance is through hypocapnia, or a displacement of carbon dioxide in the blood by oxygen. The abundance of oxygen and the lack of carbon dioxide have been thought to cause vasoconstriction in the vascular beds, including some within the brain and its structures, leading to a hypoxia-like state (Gibson, 1978; Harding, & Mills, 1983; Van Diest, Stegen, Van de Woestijne, Schippers, & Van den Bergh, 2000).

Given the potentially negative consequences associated with hyperoxia, the goal of this study was to document the effects of a graduated oxygen delivery schedule on cognitive task performance and physical exercise to determine whether modifications to the in-flight O_2 delivery schedule is necessary to maintain peak performance in operational environments. Alternatively, this knowledge will also provide insight into any possible improvement in cognitive function through the use of hyperoxia treatment that will maintain or even improve functional capacity.

Method

A total of 26 participants (24 men, 2 women) served as operators in this study. All participants were required to abstain from alcohol and nicotine for the duration of the study, and were asked not to deviate from their normal amounts of caffeine or medications. Of the total number of participants, 14 served as operators for both an 11,000 ft exposure condition and a 16,000 ft exposure condition, while the remaining 12 participants were included in a 20,000 ft exposure condition.

Human subject testing was approved by the Institutional Review Board of the Naval Aeromedical Research Unit – Dayton.

Apparatus

High Altitude Chamber: The US Air Force School of Aerospace Medicine provided altitude chamber services, including the chamber and personnel to operate and supervise the participants throughout the study.

The altitude training chamber is a man-rated low-pressure hypobaric chamber which uses a vacuum pump to remove gas/pressure from its interior. As the pressure is removed, it simulates the corresponding pressure of a given altitude.

Oxygen Supply System: Oxygen was supplied to all participants from a common premixed bottle in one of six different concentrations, 33%, 40%, 50%, 60%, 70%, and 80% oxygen, with the balance being nitrogen.

Cognitive Performance Test: Each participant was given their own tablet interface to perform a Simple Reaction Time (SRT) test. For this task, participants were required to press their finger on the blue target dot in the bottom half of the touchscreen tablet until an up arrow appeared.

Following the appearance of the up arrow stimulus, the participant was instructed to move their finger from the blue dot to the blue response arrow directly above it, and then return their finger to the dot as quickly as possible. This method of response enabled a separation of the participants' actual response time (the time taken to remove their finger from the dot) and the movement time taken to physically respond (the time taken to press the response arrow), allowing for a much more valid representation of response time. The arrow to which participants responded appeared at random intervals, ranging between two and five seconds following the response to the preceding signal, continuously throughout the assessment periods. Each participant performed the task at their own pace, independent of the others present in the chamber.

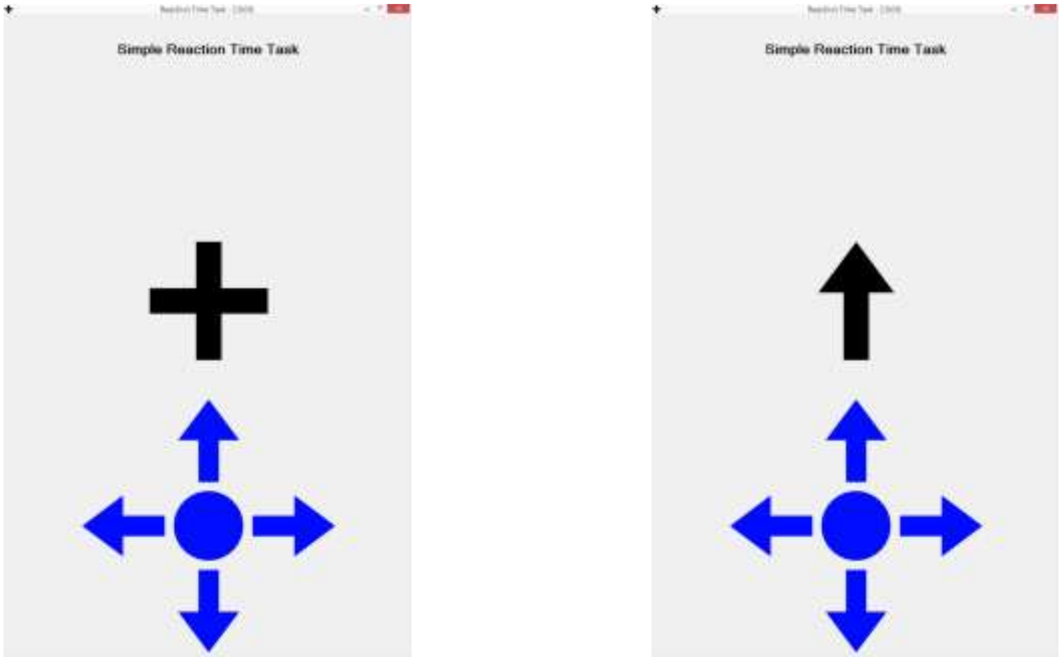

Figure 1. Examples of the neutral waiting screen and the response screen in the left and right panels, respectively.

Blood Oxygen Saturation and Heart Rate Monitoring: Blood SpO_2 and the heart rate of each subject were monitored real-time via a reflectance oximeter placed on the forehead. The monitor is a commercially purchased clinical oximetry system manufactured by NONIN Inc, which was engineered to be battery operated and capable of withstanding a low oxygen environment by a NAMRU – Dayton electrical engineer.

Leg Press Anaerobic Exercise: Participants were asked to place their feet against force plates positioned in front of their seats in the altitude chamber, and were instructed to apply a pressure of 200 lbs to the plate, indicated by the illumination of an LED upon the achievement of the desired force, for 30 seconds. This exercise closely matches the physiologic response of the anaerobic straining exercise that pilots perform during high-G flight maneuvers, and was used to determine if the lower oxygen concentrations could support normal task performance following such a strain.

Examples of participants completing the SRT task and the leg press exercise can be seen below in Figure 2.

Figure 2. Participants completing the simple reaction time task and the leg press anaerobic exercise.

Procedure

Upon reporting to NAMRU, participants were instructed on the details of the study and their participation therein, and then were asked to sign an informed consent document. After agreeing to participate, those without prior altitude chamber experience attended a lecture informing them of possible complications associated with the simulated high altitudes to which they were to be exposed. Following this, participants were exposed to a simulated altitude of 17,500 ft for approximately 30 min without supplemental oxygen to familiarize themselves with their subjective symptoms of hypoxia as preparation in the event of an oxygen delivery malfunction during the subsequent research exposures.

After the hypoxia familiarization training, participants were assigned to either the 11,000 and 16,000 ft exposure profiles or the 20,000 ft profile to be performed during the course of a week. Three of the aforementioned oxygen concentrations were assigned to each altitude profile; 33%, 40%, and 60% to the 11,000 ft condition, 40%, 50%, and 70% to the 16,000 ft condition, and 50%, 60%, and 80% to the 20,000 ft condition. Those who participated in the 11,000 ft and 16,000 ft conditions were eligible to complete up to two exposure profiles in a 24 hour period, while those assigned to the 20,000 ft were limited to a single exposure during that timeframe. The order of gas concentration exposures were randomized within each altitude.

In all altitude profiles, the schedule of events was the same – a normobaric baseline period followed by 30 min total of hypobaric exposure. The exposure time was separated in to two 15 min blocks, which were further divided into five continuous three min periods. Immediately prior to the hypobaric exposure, participants performed the Simple Reaction Time task at sea-level, during which a standard baseline response time was established. Next, the participants entered the hypobaric chamber and began the task once the proper altitude was reached. Throughout the first, third, and fifth period of the initial 15 min block, all participants were tasked with the completion of the Simple Reaction Time task. During the second and fourth periods, half of the participants were instructed to perform the leg press task for the duration of the period, while the other half were instructed to rest until the beginning of the next period. The subsequent 15 min block was conducted in the same manner, though in the second and fourth periods, those who performed the leg press task during the first block were given a rest break, and those who rested were asked to perform the leg press task. Thus, for each participant, the outlined procedure yielded one baseline reaction time assessment and a total of six exposure reaction time assessments.

Results

Oximetry. A preliminary examination of the oximetry values revealed that deviations from maximum oxygenation ($O_{2\text{maximum}}$ 100%; $O_{2\text{minimum}}$ 91%) were somewhat uncommon in this study, occurring only 36% of the time. Of those deviations, the mean minimum oxygenation value across participants, altitudes, and oxygen concentrations was 97.26%. Consequently, oximetry values were not analyzed further.

Performance Effects. As described by Ratcliff (1993), the harmonic mean should be used when an average of rates is to be combined in to a single unit of measure, such as an average of response speeds throughout a time interval, as is the case in the current study. The harmonic means of participants' reaction times were used to index the central tendency of the speed of their responses within each altitude and oxygen concentration during the course of the research effort. To calculate the harmonic mean of a set of reaction times, simply divide the total number of measured reaction times by the sum of the reciprocals of each of the reaction times, and then take the reciprocal of that quotient. The computational formula for the harmonic mean is as follows, where *n* is the number of responses of quantities A, B, C…

$$Harmonic\ Mean = \frac{n}{\frac{1}{A}+\frac{1}{B}+\frac{1}{C}+\cdots}$$

The harmonic mean of participants' reaction time values from both the baseline and experimental trials can be seen in Figures 3, 4, and 5, for the 11,000 ft, 16,000 ft, and 20,000 ft conditions, respectively.

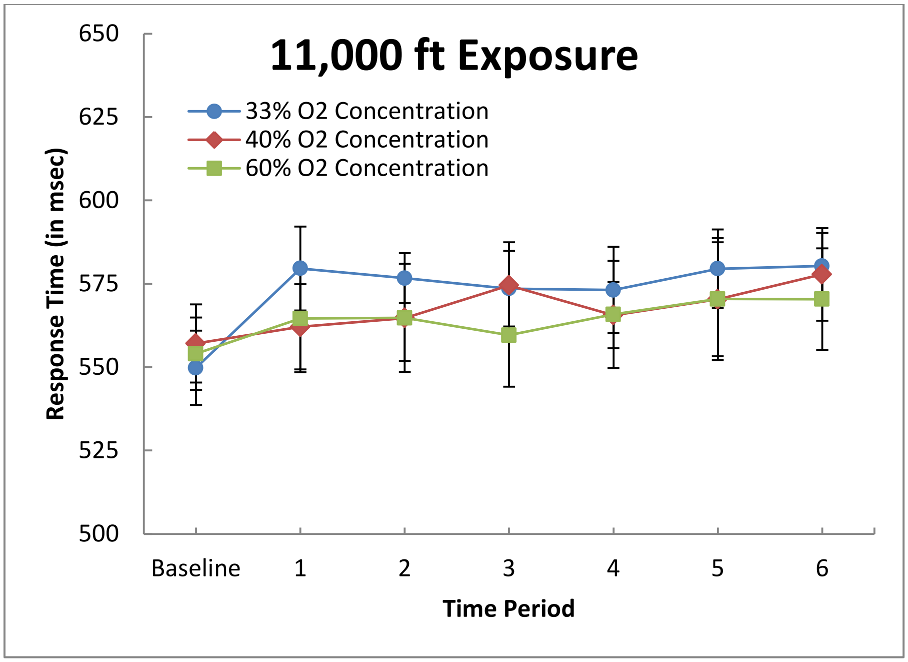

Figure 3. Response time values in the 11,000 ft exposure condition during each time period. Error bars are standard errors.

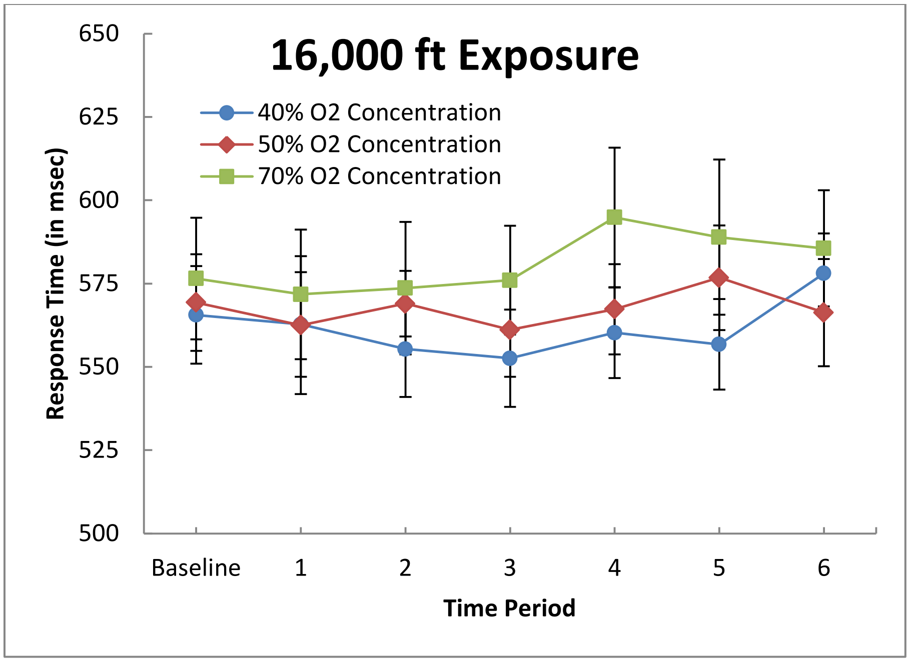

Figure 4. Response time values in the 16,000 ft exposure condition during each time period. Error bars are standard errors.

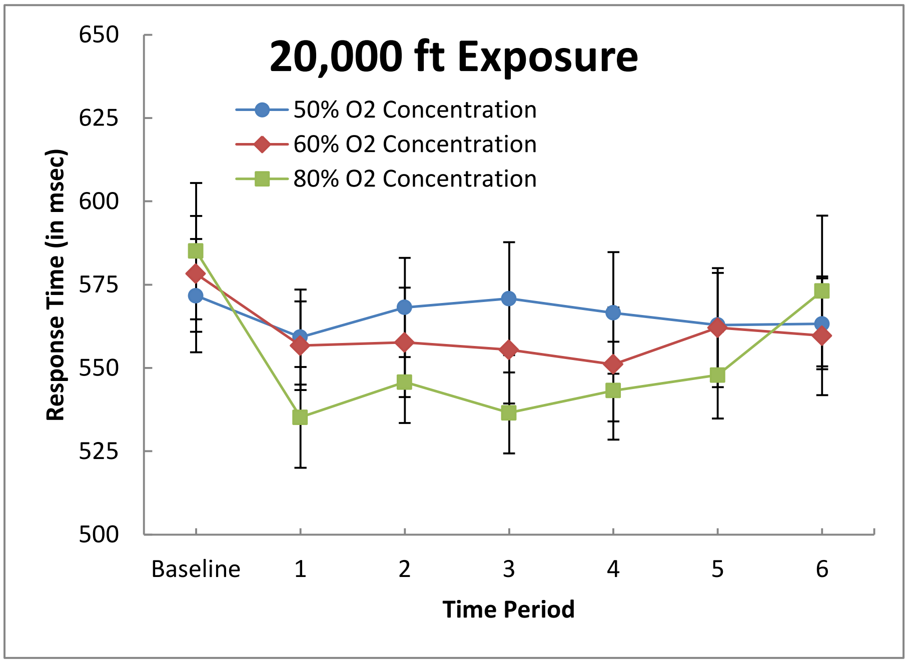

Figure 5. Response time values in the 20,000 ft exposure condition during each time period. Error bars are standard errors.

To determine if differences existed between the sea-level baselines and those recorded at altitude, participants' reaction times were tested for significance by means of a single factor, repeated measures analysis of variance (ANOVA). The analyses did not reveal any significant differences for all combinations of altitude and oxygen concentration, $p > .05$, as reaction times were largely stable throughout the duration of the study. Specific values for the nine ANOVAs can be seen below in Table 1.

Table 1. *Analysis of Variance Outcomes for All Combinations of Altitude and Oxygen Concentrations.*

Altitude	O_2 Concentration	DF Numerator	DF Denominator	F Value	Probability	Effect Size (Partial Eta Squared)	Observed Power
11000 ft	33%	6.00	78.00	2.04	0.07	0.14	0.71
11000 ft	40%	6.00	78.00	1.07	0.39	0.08	0.40
11000 ft	60%	6.00	78.00	0.67	0.67	0.05	0.25
16000 ft	40%	6.00	78.00	1.68	0.14	0.12	0.61
16000 ft	50%	6.00	78.00	0.91	0.50	0.07	0.34
16000 ft	70%	6.00	78.00	0.84	0.54	0.06	0.31
20000 ft	50%	6.00	66.00	0.42	0.87	0.04	0.16
20000 ft	60%	6.00	66.00	1.10	0.37	0.09	0.40
20000 ft	80%	6.00	66.00	2.00	0.08	0.15	0.69

Oxygen Concentration and Exercise.

Participants were further divided into exercise conditions, wherein the leg press exercise was completed twice during the first half of exposure (between SRT assessments 1 and 2, and assessments 2 and 3), or during the second half of exposure (between SRT assessments 4 and 5, and assessments 5 and 6). The harmonic mean of participants' reaction time values from the exercise first condition can be seen in blue, while those in the exercise second condition can be seen in red, during each experimental trial in Figures 6, 7, and 8, for the 11,000 ft, 16,000 ft, and 20,000 ft conditions, respectively, for each oxygen concentration.

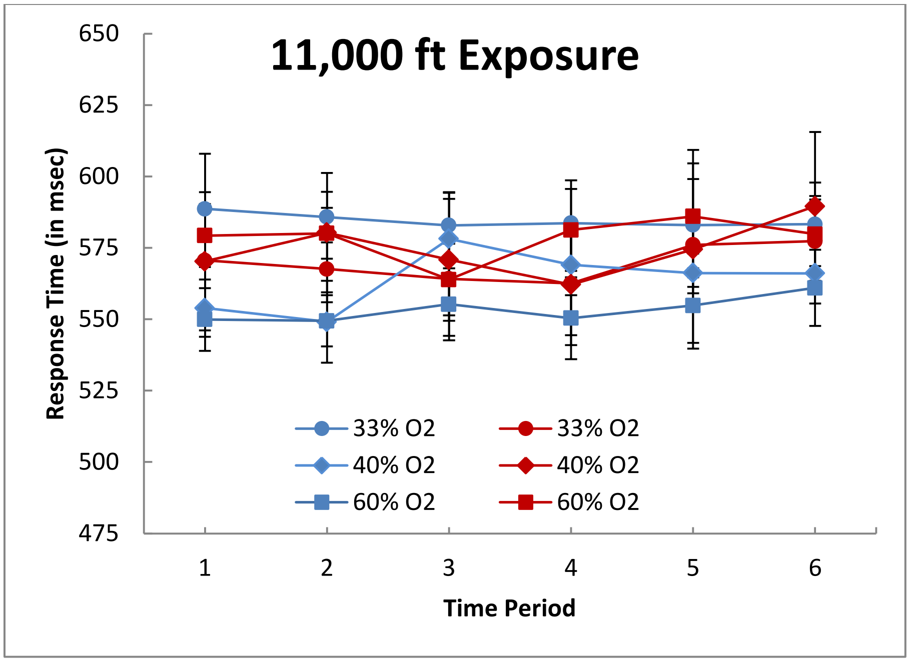

Figure 6. Mean response times in the exercise first (blue) and exercise second conditions (red) for each oxygen concentration as a function of time period. Error bars are standard errors.

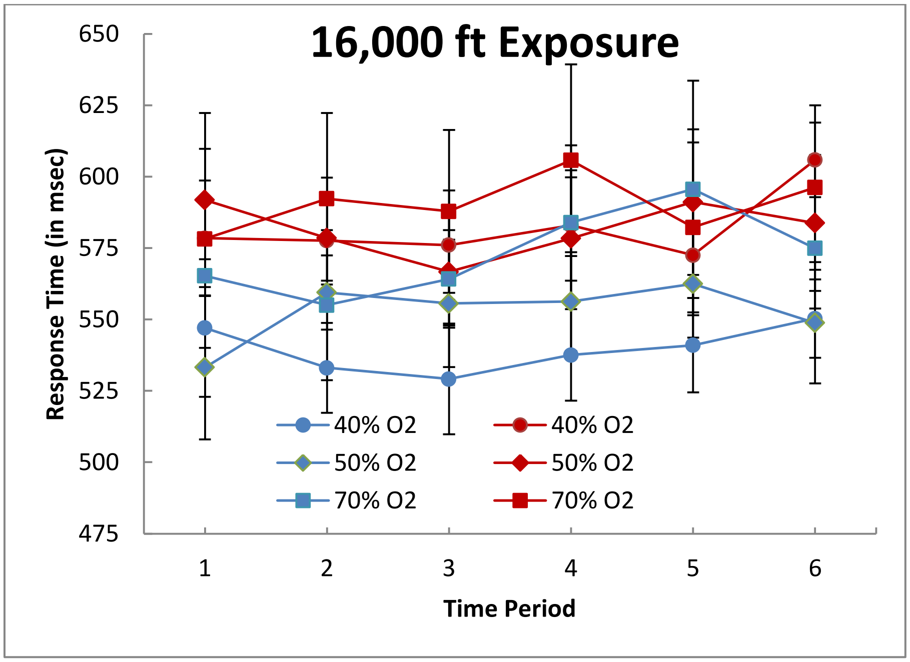

Figure 7. Mean response times in the exercise first (blue) and exercise second (red) conditions for each oxygen concentration as a function of time periods. Error bars are standard errors.

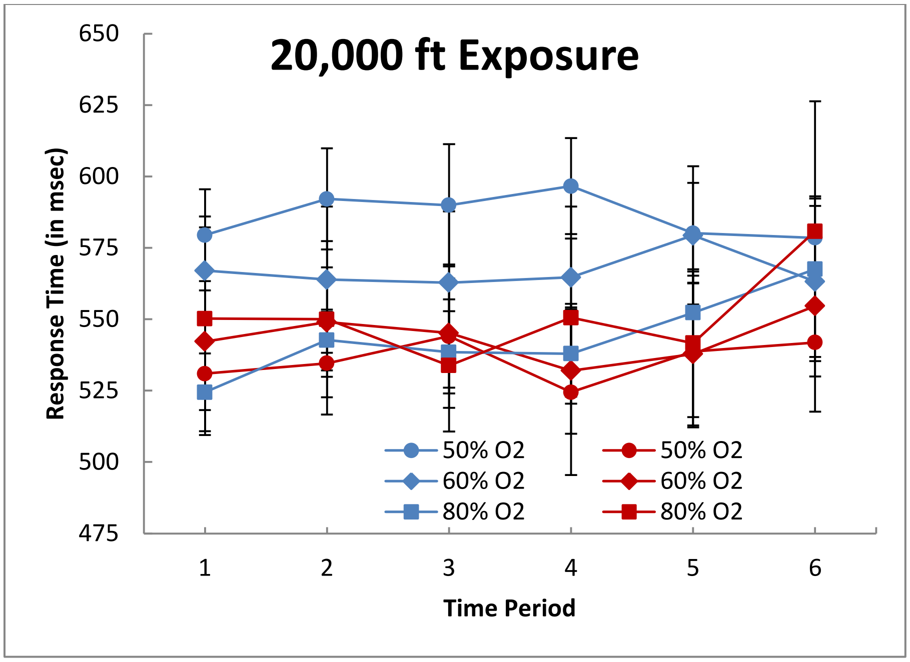

Figure 8. Mean response times in the exercise first (blue) and exercise second (red) conditions for each oxygen concentration as a function of time periods. Error bars are standard errors.

Within each altitude, the effects of exercise on reaction time performance were examined with time on task and oxygen concentration via a 2 (exercise condition) × 3 (oxygen concentration) × 6 (time period) mixed-model ANOVA, which revealed no statistically significant main effects or interactions, $p > .05$. Specific values for the three ANOVAs can be seen in Table 2, below.

Table 2. *Analysis of Variance Outcomes for All Combinations of Exercise, Oxygen Concentration, and Time Period for All Altitudes.*

	11,000 ft Exposure					
	DF Numerator	DF Denominator	F Value	Significance	Effect Size	Observed Power
Exercise	1	12	0.10	0.76	0.01	0.06
O_2 Concentration	2	24	0.63	0.54	0.05	0.14
Time Period	5	60	0.67	0.65	0.05	0.23
Exercise × O_2 Concentration	2	24	1.92	0.17	0.14	0.36
Exercise × Time Period	5	60	0.95	0.45	0.07	0.32
O_2 Concentration × Time Period	10	120	0.34	0.97	0.03	0.17
Exercise × O^2 Concentration × Time Period	10	120	0.52	0.87	0.04	0.26
	16,000 ft Exposure					
Exercise	1	12	1.23	0.29	0.09	0.18
O_2 Concentration	2	24	1.96	0.16	0.14	0.37
Time Period	5	60	1.34	0.26	0.10	0.44
Exercise × O_2 Concentration	2	24	0.68	0.51	0.05	0.15
Exercise × Time Period	5	60	0.63	0.68	0.05	0.21
O_2 Concentration × Time Period	10	120	0.87	0.57	0.07	0.44
Exercise × O_2 Concentration × Time Period	10	120	0.97	0.48	0.08	0.49
	20,000 ft Exposure					
Exercise	1	10	0.87	0.37	0.08	0.14
O_2 Concentration	2	20	0.44	0.65	0.04	0.11
Time Period	5	50	1.62	0.17	0.14	0.52
Exercise × O_2 Concentration	2	20	2.00	0.16	0.17	0.36
Exercise × Time Period	5	50	0.91	0.48	0.08	0.30
O_2 Concentration × Time Period	10	100	1.21	0.29	0.11	0.60
Exercise × O_2 Concentration × Time Period	10	100	0.65	0.77	0.06	0.32

Discussion

The goal of the present study was to index the effects of a graduated oxygen delivery schedule on operator performance while under hypobaric conditions. Toward that end, three oxygen concentrations, all of which were suitable to maintain an adequate partial pressure of oxygen at the lung to ensure perfusion, were evaluated for their effects on performance at 11,000, 16,000, and 20,000 ft in an altitude chamber.

Regarding performance efficiency, the overall speed of responses among participants did not change significantly from sea-level to any of the oxygen concentrations at any of the altitudes. As was expected, the partial pressure of oxygen contained in the inhaled gaseous mixture was physiologically sufficient to preserve similar levels of response speed at altitude when compared to the baseline measures taken. Still, it should be noted that the absence of significant findings in this research effort does not preclude the possibility of the occurrence of a more subtle effect.

One disadvantage to decreasing the oxygen content of the breathing mixture is the potential reduction of the effectiveness that oxygen pre-breathing provides as a prophylaxis against the development of decompression sickness (DCS). Pre-breathing 100% oxygen prior to high altitude exposure reduces risk of DCS at a range of altitudes, but only if the high concentration of oxygen is breathed continuously throughout the entire flight. With a proposed reduction in the concentration of oxygen to be breathed, such protection would be no longer be efficacious.

With the possible disadvantages of breathing high concentrations of oxygen such as alveolar collapse or hypocapnia, the potential advantages of it would seem to be offset. As performance was not significantly affected, it is the opinion of the authors of this paper that lower oxygen concentrations can be used in place of the current delivery schedule without adverse effects to flight operations.

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