

BEHAVIORAL EFFECTS OF ONE-HOUR BREATHING OF HIGH  
CONCENTRATIONS OF CO<sub>2</sub> AND O<sub>2</sub> WHILE DOING PHYSICAL WORK

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ABSTRACT

Attention is drawn to the lack of scientific information pertaining to the effects of breathing elevated (but subclinical) levels of carbon dioxide (CO<sub>2</sub>) on cognitive and psychomotor performance. Furthermore, an appeal is made to reevaluate existing standards for the maximum allowable concentration of CO<sub>2</sub> for self-contained breathing apparatuses (SCBAs), particularly those used for escape during emergencies. An experiment is presented in which psychomotor and mental performance tests were administered to subjects inhaling room air, 50% oxygen (O<sub>2</sub>), and 2% CO<sub>2</sub> (with 50% O<sub>2</sub>) prior to, between, and following two 20-min exercise bouts at 75% of aerobic capacity. Conditions were designed to simulate a one-hour exposure to 2% CO<sub>2</sub> (in a high O<sub>2</sub> concentration similar to that of SCBAs) while running (as in a mine escape). The results showed no effects of these gases on short-term memory, reasoning, choice response time, pursuit tracking, and balance on a stabilometer. Combined with previous studies (Sheehy, Kamon, and Kiser, 1982), the authors have not yet found evidence of impaired performance due to acute (16 min) exposures of up to 5% CO<sub>2</sub> or chronic (60 min) exposures to 2% CO<sub>2</sub>, when inhalation is accompanied by moderate to strenuous exercise.

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This article is divided into two sections: (1) carbon dioxide: an environmental stressor, and (2) CO<sub>2</sub> experiment. The first section consists of discussions pertaining to the need for a reevaluation of current carbon dioxide standards and the physiological and psychomotor effects of breathing

elevated levels of carbon dioxide. The second section is an experiment to ascertain the effects of breathing a high concentration of carbon dioxide and oxygen.

### I. CARBON DIOXIDE: AN ENVIRONMENTAL STRESSOR

Carbon dioxide ( $\text{CO}_2$ ) exposure is a very common environmental stressor. An estimated two million industrial workers are potentially exposed to high levels of carbon dioxide in their work environments (NIOSH, 1976). For example, chronic exposures to  $\text{CO}_2$  are everyday occurrences for people who work in submarines and space vehicles (where the  $\text{CO}_2$  concentration is 1-2%) or in oil tanks, grain silos, and breweries (where  $\text{CO}_2$  concentrations range from 1 to 10%). Even wearing a self-contained breathing apparatus (SCBA), for protection against ambient toxic gases, does not always help. Carbon dioxide, being a normal metabolic by-product, accumulates any time one rebreathes his/her own expired air (e.g., the closed system in SCBAs). To prevent this build-up and the concomitant decrease in oxygen, SCBAs are designed to scrub  $\text{CO}_2$  and supplement  $\text{O}_2$ . The longevity and utility of each system is sometimes determined by its ability to remove  $\text{CO}_2$ . And, since most SCBAs are limited in their  $\text{CO}_2$  scrubbing capacity, prolonged usage results in an increase of the unabsorbed  $\text{CO}_2$  over time. This means that as the  $\text{CO}_2$  scrubber fails, the inspired concentration of  $\text{CO}_2$  rises (usually in an exponential fashion). Aside from such concerns as size, weight, resistance, hot air, and seal (e.g., leakage associated with negative pressure or fitting), one of the major limiting factors in the design of these respirators is the ability of the scrubber to prevent  $\text{CO}_2$  from exceeding the maximum allowable concentration (MAC).

A more definitive basis for establishing the MAC of  $\text{CO}_2$  is needed. A very low limit for the inspired air would at first glance seem desirable since it would prevent possible psychological and physiological reactions. However, meeting such high standards would greatly increase the size and weight of SCBAs, making it more difficult for the wearer to use them. The MACs must, therefore, be established with attention given to minimizing the overall difficulties encountered in using the SCBAs.

### Physiological Effects

Carbon dioxide serves a major role in respiration and cerebral circulation. At high concentrations, it acts as a respiratory and central nervous system (CNS) stimulant, producing increases of up to 75% in cerebral blood flow (Kety and Schmidt, 1984), an increase in pulmonary ventilation (Dripps and Comroe, 1947), decreases in specific airway resistance (Taskin and Simmons, 1972), and local vasodilation. At excessive concentrations, it is a CNS depressant, capable of producing unconsciousness, narcosis, respiratory arrest, and death (Dripps and Comroe, 1947; Friedlander and Hill, 1954). Moreover, because the solubility of  $\text{CO}_2$  is approximately 20 times greater than that for  $\text{O}_2$ , diffusion is rapid and the respiratory and CNS effects are experienced almost instantaneously.

Exercise (physical work) may compound the effects of  $\text{CO}_2$  inhalation due to the increased metabolic  $\text{CO}_2$  production which results in an even higher  $\text{CO}_2$  retention. This increased retention might then reduce the worker's endurance capacities (Craig, Blevins, and Cummings, 1970). Generally speaking, however, at rest or combined with exercise, physiological reactions to breathing up to 10%  $\text{CO}_2$  do not seem to cause a deterioration of essential body functions (Asmussen and Nielsen, 1957; Craig, 1955).

The relative severity of clinical symptoms associated with acute exposures (less than 15 min) of varying concentrations of  $\text{CO}_2$  are summarized in Table 1.

Table 1  
Summary of the Severity of Clinical Symptoms  
From Acute  $\text{CO}_2$  Exposure (< 15 min)

| <u>% <math>\text{CO}_2</math></u> | <u>DEGREE OF SYMPTOMS</u> |
|-----------------------------------|---------------------------|
| 0-7                               | Mild, if present          |
| 7-10.5                            | Pronounced                |
| > 10.5                            | Unconsciousness           |
| > 30                              | Death                     |

Usually, the duration of exposure determines the extent of the clinical symptoms observed. For instance, three combinations of concentration and time are summarized in Table 2 along with the clinical symptoms they produced.

Table 2  
Clinical Effects of CO<sub>2</sub> Inhalation

| <u>% CO<sub>2</sub></u> | <u>TIME</u>        | <u>SYMPTOMS</u>                                                                                           | <u>SOURCE</u> |
|-------------------------|--------------------|-----------------------------------------------------------------------------------------------------------|---------------|
| 30.0                    | 24-28 sec          | Unconsciousness (n=37)<br>(regained after 110 sec)                                                        | 1             |
| 10.4<br>7.6             | 3.8 min<br>7.4 min | Dyspnea, headache,<br>restlessness, dizziness,<br>sweating, visual<br>distortions, irritability<br>(n=42) | 2,3           |
| 3.0                     | 5 days             | Mild frontal headaches in<br>4 of 7 subjects during<br>first 2 days                                       | 4             |

Note: 1 = Friedlander & Hill, 1954; 2 = Schaefer, 1963;  
3 = Dripps & Comroe, 1947; 4 = Glatte, Motsay, & Welch, 1967.

Headache is one of the most recurrent symptoms of CO<sub>2</sub> inhalation and may be partially attributed to the increase in cerebral blood flow and in cerebrospinal fluid pressure (Small, Weitzner, and Nahas, 1960).

## MACs for CO<sub>2</sub>

In summarizing the standards for CO<sub>2</sub> exposure, Table 3 shows the maximum allowable concentrations (MACs) for different agencies.

At present the MAC for CO<sub>2</sub> is well below the levels known to impair physical or mental performance. Since it requires reasonably large concentrations of CO<sub>2</sub> (5-10%) to substantially impair physical performance or produce clinical symptoms, the question reduces to "what is the highest concentration of CO<sub>2</sub> that can be breathed for a given period of time without mental dysfunction?" The literature is devoid of work in this area and it appears that somewhat arbitrary standards have been implemented. If, for instance, it can be established that breathing up to 3% CO<sub>2</sub> for an hour

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Table 3  
Maximum Allowable Concentrations of CO<sub>2</sub>

| <u>YEAR</u> | <u>AGENCY</u> | <u>% CO<sub>2</sub></u> | <u>CONDITIONS</u>                                               | <u>SOURCE</u> |
|-------------|---------------|-------------------------|-----------------------------------------------------------------|---------------|
| 1943        | USPHS         | 0.5                     |                                                                 | 1             |
| 1947        | US Navy       | 3.0                     | Submarines with<br>17-21% O <sub>2</sub>                        | 2             |
| 1968        | ACGIH         | 0.5                     | Up to 8 hours                                                   | 3             |
| 1972        | NASA          | 4.0<br>3.0<br>1.0       | Up to 10 minutes<br>Up to 1 hour<br>Up to 6 months              | 4             |
| 1973        | NASA          | 1.9<br>1.0              | Up to 3 hours<br>Mission                                        | 5             |
| 1974        | ACGIH         | 1.5                     | Healthy subjects                                                | 6             |
| 1975        | US Navy       | 2.5<br>1.0<br>0.5       | Up to 1 hour<br>Up to 24 hours<br>Up to 90 days                 | 7             |
| Current     | NIOSH         | 0.5                     | In 50% O <sub>2</sub> , after<br>scrubber, during<br>a Man Test |               |

Note: 1. Gafafer, 1943; 2. Consolazio, Fisher, Pace, Pecora, Pitts, & Behnke, 1947; 3. NIOSH, 1976; 4. Calvin & Gazenko, 1975; 5. NASA, 1973; 6. ACGIH, 1974; 7. Calvin & Gazenko, 1975.

does not impair performance, then raising the MAC to as high as 2% could dramatically affect the design of respirators (e.g., decreasing the size, weight, and cost while increasing longevity) without compromising the safety of the worker. On the other hand, even if high levels of CO<sub>2</sub> do not impair physiological functions, great care must be taken to ensure that essential cognitive and motor skills are not affected.

## Psychomotor Effects

Even though there are no disabling physiological effects or clinical symptoms associated with breathing up to 5% CO<sub>2</sub>, there still may be

psychological reactions, such as impaired motor control, slowed reactions, disorientation, or diminished mental capacities, which may jeopardize a worker's health and safety. Regardless of the CO<sub>2</sub> source, impaired cognitive and/or motor performance may make the worker susceptible to accidents and may decrease the probability of survival in emergency situations.

Very little attention has been given to the behavioral effects of CO<sub>2</sub>. In the NIOSH publication, Occupational Exposure to Carbon Dioxide (1976), only seven studies were mentioned. Two of these studies reported detrimental effects on performance and three showed null results. Using a sample size of 42, Schaefer (1963) found that in 15-min exposures of 1.5, 3.3, 5.4, and 7.5% CO<sub>2</sub>, there was a significant decrease in critical flicker fusion for CO<sub>2</sub> concentrations in excess of 3.3%. In the other study showing detrimental effects, Weitzman, Kinner, and Luria (1969) exposed one subject to progressively increasing concentrations of CO<sub>2</sub>, from 0.03% to 3.00%, for 15 hours on each of six days. Visual acuity and accommodation were not affected, but color threshold sensitivity diminished (without mention of significance). Also included in their conclusions was a report on a similar experiment which resulted in no decrements in "sensory function" except for diminished color sensitivity from exposures up to 3% CO<sub>2</sub>. As for the null results, Weybrew (1970) found that over a six-day period, 15-hour exposures to CO<sub>2</sub> at concentrations between 0 and 3% resulted in no impairment of one-digit addition and letter cancellation. However, Weybrew's study, like that of Weitzman et al., used only one subject and was not validated for confinement effects. Storm and Giannetta (1974) exposed six subjects to 4% (30 torr) CO<sub>2</sub> for 14 days and found no effects on complex tracking, eye-hand coordination, and problem solving. Glatte, Motsay, and Welch (1967) found no effects of breathing 3% CO<sub>2</sub> for 5 days on arithmetic, vigilance, hand steadiness, memory, problem solving, and auditory monitoring.

Not only is there a shortage of research on the behavioral effects of CO<sub>2</sub>, but, as can be seen in this brief review, many of the previous studies have had methodological shortcomings (e.g., small sample size, inadequate controls) which severely limit their interpretation. Therefore, further behavioral research is required to make prudent decisions relative to CO<sub>2</sub> standards.

In recent years, two studies have used improved methodologies to investigate the behavioral effects of CO<sub>2</sub>, but each has failed to find performance impairment. Sheehy et al. (1982) exposed their subjects to 4 and 5% CO<sub>2</sub> (with 21 and 50% O<sub>2</sub>) for 16 min and found no deterioration in the performance of psychomotor (simple reaction time, pursuit tracking, and choice response time) or mental (short-term memory and reasoning) tasks. Concerned with the risks due to CO<sub>2</sub> retention in diving, Henning, Sauter, Reddan, and Lanphier (1983) found no effects of breathing 6% CO<sub>2</sub> for 10-14 min on simple and choice reaction time, hand steadiness, and postural sway.

## II. CO<sub>2</sub> EXPERIMENT

Previous CO<sub>2</sub> research at The Pennsylvania State University (Sheehy et al., 1982) examined the effects of an acute exposure (16 min) of up to 5% CO<sub>2</sub> (with 21 and 50% O<sub>2</sub>) on reaction time, rotary pursuit tracking, short-term memory (digit and letter recall forward and backward), and grammatical reasoning. While some of these tests were sensitive to the effects of exercise, acute exposure of CO<sub>2</sub> of up to 5% did not impair performance. The next step in the systematic search for the effects of CO<sub>2</sub> might be to increase exposure duration. Furthermore, since the SCBA user typically breathes in excess of 50% O<sub>2</sub> and hyperoxia has been shown to produce deterioration in short-term memory (Poulton, 1974), ascertaining the effects of hyperoxia is also important. Thus, the purpose of the present experiment was to explore the effects of prolonged breathing (60 min) of elevated but subclinical levels of CO<sub>2</sub> and O<sub>2</sub>, during and following exercise, on cognitive and motor performance.

### Method

#### Subjects

Five right-handed, beardless, male university graduate students volunteered to serve as paid subjects in this study. Prior to participating in the experiment, all subjects received a medical examination, including exercise tolerance and pulmonary function tests. All were non-smokers and in good general health. Their demographic characteristics are shown in Table 4.

Table 4

Demographic Characteristics of Participants in CO<sub>2</sub> Inhalation Study

| <u>SUBJECT</u> | <u>AGE(YRS)</u> | <u>HT (cm)</u> | <u>WT (cm)</u> | <u>% FAT</u> | <u>HRmax*</u><br><u>(b·min<sup>-1</sup>)</u> | <u>V̇O<sub>2</sub>max</u><br><u>(ml·kg<sup>-1</sup>·min<sup>-1</sup>)</u> |
|----------------|-----------------|----------------|----------------|--------------|----------------------------------------------|---------------------------------------------------------------------------|
| 1              | 27              | 176.0          | 65.8           | 13.85        | 186                                          | 47.14                                                                     |
| 2              | 26              | 182.6          | 80.0           | 9.01         | 178                                          | 55.33                                                                     |
| 3              | 26              | 180.7          | 77.0           | 16.34        | 193                                          | 49.51                                                                     |
| 4              | 24              | 187.5          | 78.7           | 10.37        | 188                                          | 49.39                                                                     |
| 5              | 29              | 170.2          | 76.0           | 15.00        | 191                                          | 50.00                                                                     |
| MEAN           | 26.4            | 179.5          | 75.5           | 12.91        | 187.2                                        | 50.27                                                                     |
| SD*            | 1.8             | 6.6            | 5.64           | 3.11         | 5.8                                          | 3.03                                                                      |

\*) Maximal heart rate (HRmax); Maximal O<sub>2</sub> uptake (V̇O<sub>2</sub>max); standard deviation (SD).

Design

A two-factor, repeated measures  $3 \times 3$  (Gas and Tests) design was employed to analyze data from each of six performance measures. Performance tests were administered prior to, between, and following two exercise bouts. For each session, each subject breathed one of three different gas mixtures during a one-hour inhalation period from the onset of the first exercise bout to the end of the post-test following the second bout. The three gas concentration conditions can be thought of as: (a) control (room air), (b) high  $O_2$  (50%  $O_2$  with 0.03%  $CO_2$ ), and (c) high  $CO_2$  (2%  $CO_2$  with 50%  $O_2$ ). As illustrated in Figure 1, the three test conditions were described as pre-, mid-, and post-tests referring to their relative position to the exercise bouts.

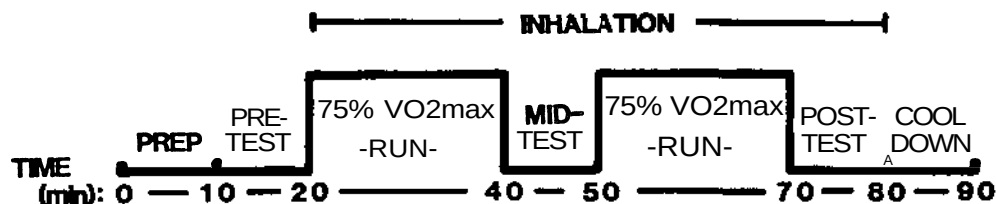


Figure 1. Testing protocol for each testing session. During the 60-min inhalation period subjects breathed either room air (control), high oxygen (50%  $O_2$ ), or high carbon dioxide (2%  $CO_2$ , 50%  $O_2$ ).

The pre-test was always a fully rested, room air control condition, while the mid- and post-tests followed exercise and occurred during the gas inhalation period. Subjects were randomly assigned to gas conditions which were counterbalanced random combinations. The order of tests within each performance battery was also counterbalanced.

Exercise

Each subject underwent a treadmill progressive exercise tolerance test as part of a health assessment procedure to determine his maximal aerobic capacity ( $\dot{V}_{O_2 \max}$ ). During the exercise periods, each subject ran for 20 minutes on a treadmill with the speed and grade adjusted to yield an  $O_2$  uptake of 75% of his  $\dot{V}_{O_2 \max}$ . Each experimental session consisted of two

such work bouts spaced with pre-, mid-, and post-tests, each lasting approximately 10 minutes, during which the dependent measures were collected. Oxygen uptake samples were taken during steady-state running while breathing room air in order to record actual exercise intensity. The average intensity for the group was  $75 \pm 3\%$  (SD) of  $\dot{V}_{O_2}$  max. While on the treadmill, the subjects were cooled with an elastic<sup>2</sup> fan placed directly in front of them. Chest electrodes were connected to a Respirationics Digital Exersentry (SN) for monitoring average heart rate.

### CO<sub>2</sub> Inhalation

A 150-liter Douglas bag served as a mixing reservoir into which room air, CO<sub>2</sub>, and O<sub>2</sub> were mixed before humidification by passage through warm water enroute to the subject in an open-circuit system. The inspired gas mixture was controlled by continuous monitoring of an Applied Electrochemistry S-3A Oxygen Analyzer and an LB-2 Beckman Medical Gas CO<sub>2</sub> Analyzer. Expired air was released into a well ventilated testing room. Three gas mixtures were used in this study: (a) room air (0.03% CO<sub>2</sub> and 21% O<sub>2</sub>) as a control; (b) high oxygen (0.03% CO<sub>2</sub> and 50% O<sub>2</sub>), to test for hyperoxia effects; and (c) high carbon dioxide, (2.00% CO<sub>2</sub> with 50% O<sub>2</sub>), to test for hypercapnia effects (the elevated O<sub>2</sub> was to ensure that there was no hypoxia and to more closely approximate SCBA conditions). The prescribed gas mixture ( $\pm 0.1\%$  SD) was inhaled for a period of 60 minutes ( $\pm 2$  min SD) during each of the experimental sessions.

### Performance Measures

Two types (batteries) of performance measures, each containing three individual tests, were used in this experiment: (a) Cognitive Performance Tests, and (b) Psychomotor Performance Tests. Thus, six performance tasks were administered, each in a pre-, mid-, and post-test format. Five counter-balanced orders of tests within each battery were developed with each subject being randomly assigned to one of the orders.

### Cognitive Performance Tests

Three different cognitive tests were used: a grammatical reasoning test and two short-term memory (STM) tests (forward and backward serial letter recall).

Grammatical Reasoning. Reasoning, based on grammatical transformations (Baddeley, 1968), has been shown to be a stable (Carter, Kennedy, and Bittner, 1981) metric of "higher mental processes" that is sensitive to nitrogen narcosis (Baddeley, de Figuerido, Hawkswell Curtis, and Williams, 1968) and hypocapnia (Gibson, 1978). This test consisted of a four-minute task adapted from Baddeley's (1968) grammatical transformation task. Seated in front of a cathode ray terminal (Digital VT52-AE), the subjects read a statement followed by a pair of letters, decided whether or not the statement matched the letter pair, and then entered the appropriate "True" or "False" response on a standard alpha-numeric keyboard. The statements were randomly drawn from 64 possible combinations of six binary conditions (see Baddeley, 1968; Baddeley et al., 1968) and were presented one-at-a-time until the four-minute time interval elapsed. The following are examples of the statements presented:

True or False. A follows B--AB

True or False. B precedes A--BA

True or False. B does not follow A--AB

True or False. A is not preceded by B--BA

The stimulus presentation and data collection were completely on-line using a Digital Equipment Corporation (DEC) PDP-11 computer. The criterion measures were the response rate (i.e., the total number performed in each four-minute interval), accuracy (i.e., number of correct responses/total number of responses), and response times for each statement.

Short-Term Memory (Letter Recall). Based on the Wechsler (1958) Adult Intelligence Scale (WAIS), letter recall was used to assess functional memory span, a fundamental component of all human performance. A DEC PDP-11 system consisting of a disk drive and monitor was used to present the letters in a forward or backward serial fashion, as well as record and evaluate each response. The order of directional recall was counterbalanced between subjects (i.e., forward-backward, backward-forward). The letters were presented singularly for one second followed by a 250-msec pause. All letters were consonants in upper case, 1.5 cm in height, and presented in the center of a Tektronics 4006-1 graphics terminal screen. Each trial consisted of a random grouping of letters such that there occurred no repetitions of the same letter (e.g., B, F, D, D, K) or sequential progressions (e.g., P, Q, R, S, T). Beginning with a sequence of four letters, each correct recall of

a series of letters would increment the number of letters presented on subsequent trials, until either two incorrect responses were recorded at the same difficulty level, or a maximum of 12 letters were reached. If the subject failed to correctly recall the sequence of letters on a particular trial, he was given a second trial at the same difficulty level (with different letters). If the subject answered the second trial correctly, he progressed to the next higher difficulty level (i.e., the number of letters presented was incremented by one); if the subject failed to answer the second trial correctly, the test was terminated.

### Psychomotor Performance Tests

Three different psychomotor tasks were used: (a) Choice Response Time (CRT), (b) Rotary Pursuit (RP), and (c) Stabilometer.

Choice Response Time. A Marietta Choice Response Time (Model 14-210-M) apparatus, with eight telegraph keys mounted on a baseboard equidistance from a starting button, was used to measure choice response time (i.e., the time interval from the presentation of a visual stimulus to the completion of a correct key depression response). The stimulus appeared in a lighted display mounted approximately 30.5 cm above the baseboard and centered behind the keys (60 cm from the subject's eyes). The keys were not numbered, but were arranged in sequential order (1-8) from left to right. Each trial began with a "ready" command by the investigator after which the subject assumed the ready position by depressing the start button. At the end of a fixed 0.5 sec foreperiod (during which a red warning light positioned atop the stimulus box was illuminated), the stimulus number appeared and the response time clock began. A correct response (pressing the appropriate key) resulting in the disappearance of the stimulus display and stopping of the clock. Twenty-four trials comprised a data block, of which the first eight trials (random presentation of each key once) were used as practice and the next sixteen (random presentation of each key twice) were used for data analysis.

Rotary Pursuit Tracking. Considered a valid test of psychomotor performance (Fleishman, 1960), this measure was selected because of its use in previous stressor studies; particularly, those involving hypocapnia (Gibson, 1978), hypercapnia (Storm and Giannetta, 1974), and hyperventilation

(Labuc and Withey, 1978; Withey, Spreight, Labuc, and Legg, 1979). A Lafayette Photoelectric Rotary Pursuit apparatus was used to assess the subject's ability to track a moving object with a hand-held stylus. The apparatus consisted of a light emitting target moving clockwise in a circular manner at 30 RPM. The tracking stylus contained a photosensitive tip which was connected to a Hunter Decade Interval Timer, to limit the recording period to a 20-sec interval, and a Hunter Model 220 Klockounter to record the time on target (in msec). The subject was permitted to track for approximately 30 seconds prior to each test to reduce warm-up, practice, equipment start-up, and limb inertia effects. Three 20-sec trials, with approximately 30-sec inter-trial rest intervals, were given to each subject during each test. Ambient light was controlled and the sensitivity of the apparatus was calibrated for each experimental session to a vertical tolerance of 2.6 cm (i.e., if the stylus was raised more than this distance above the target, the clock counter would stop recording on-target performance).

Stabilometer. Since dizziness and loss of balance are characteristic clinical symptoms associated with CO<sub>2</sub> inhalation, the ability of the subject to maintain his balance, as measured by a horizontal pivoting platform Stabilometer, was included as a psychomotor test. This measure was also selected because of the information available on its susceptibility to practice (Ryan, 1965) and fatigue (Nunney, 1963) effects as well as its retention (Ryan, 1962b) and stress reaction (Ryan, 1962a) characteristics. The apparatus consisted of a 37.5 cm x 95 cm x 2.1 cm wooden platform with an axle and bearings positioned directly beneath such that the subject could stand on it, straddling the axle, and attempt to balance (i.e., keep the platform horizontal). Microswitches were positioned on the stabilometer frame to record the amount of time the platform was tilted (off-balance). A Hunter Decade Interval Timer was used to limit the recording period to 20-seconds. A Hunter Model 220C Klockounter was used to record the total time the subject was off balance per 20-sec trial. Three trials, with approximately 30-sec inter-trial rest intervals, were given to each subject during each test.

### Procedure

Each subject participated in eight sessions as presented in Figure 2.

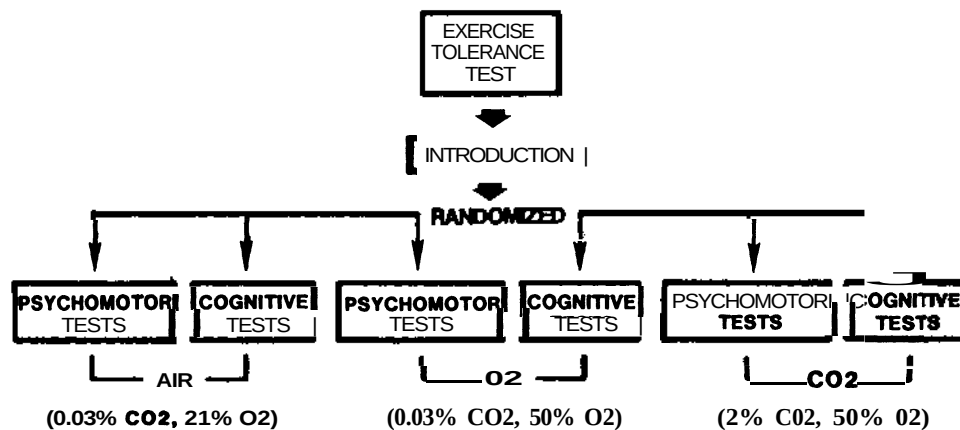


Figure 2. Schematic for the Experimental Sessions (1 box = 1 day). Subjects began with the graded exercise tolerance test from which their aerobic capacity ( $\dot{V}O_{2max}$ ) was determined. Next the subjects were familiarized with the exercise and the wearing of the breathing apparatus, and practiced all of the performance tests during the introduction session. The psychomotor tests (choice response time, stabilometer, and rotary pursuit) and the cognitive tests (STM forward letter recall, STM backward letter recall, and grammatical reasoning tests) were given randomly, one set per session.

Following an exercise tolerance test, the subjects participated in seven 90-minute sessions, one per day with at least 48 hours rest between the sessions involving exercise. The introductory session was used to explain the experiment, complete the informed consent documents, introduce the dependent measures and experimental protocol, and provide considerable practice on each of the performance measures. Following this introductory session, the same protocol was used each day (see Figure 1).

Upon arrival to the laboratory, the subject was fitted with chest electrodes, given a brief warm-up on each task, and then given the pre-test performance measures which were completed in approximately 10 minutes. The gas inhalation period began with the subject running on a treadmill for two 20-min work bouts at an intensity equivalent to 75% of his aerobic capacity. Between and following these work bouts were the mid- and post-tests, respectively (each also lasting approximately 10 minutes). The face mask was removed after the post-test (making the total inhalation period approximately one hour) and the subject was required to walk on the treadmill at 3 mph for at least 6 min as a "cool-down" before departing the lab. During and following the cool-down, the subject was asked to provide subjective

information on his perceived exertion, clinical symptoms (discomforts), performance quality, etc. All eight testing sessions per subject were completed within three weeks.

#### Laboratory Environment

The experiment was conducted in an air-conditioned laboratory where the room temperature ranged from 23 to 25° C. Also, measures were taken to control ambient light and sound.

#### Treatment of the Data

The dependent measures were analyzed using a multivariate analysis of variance on repeated measures. All post-hoc follow-up analyses were done using the Tukey Wholly Significant Difference (WSD) technique. In all cases, the level of significance was  $p = 0.05$ . An additional univariate analysis of the repeated measures was performed on each subject to test for learning (sequence) effects. (See Jackson and Raven, 1983, for a discussion of statistical and research designs for industrial respiratory research.)

Equipment failure caused seven out of 450 data values (1.6%) to be grossly inappropriate. Omitting all of the results for those subjects involved would remove 20% of the data on each measure. Therefore, five values (one for the stabilometer, two for reasoning, and two for rotary pursuit) were estimated according to Winer (1962) in a technique designed to have no effect on the individual cell means (interaction) in the data matrix. The two pre-test values for reasoning were estimated by using the average of the remaining pre-test values per subject.

### Results and Discussion

#### Cognitive Performance Measures

The group mean and standard deviations for each of the cognitive tests for each experimental condition are shown in Table 5. None of the cognitive performance tests revealed a significant effect of hyperoxia or hypercapnia, but one non-gas test contrast was significant. As seen in Figure 3, the rate at which subjects performed the post-exercise test portion of the grammatical reasoning task ( $M = 14.33$  lines/minute) was significantly [ $F(2,8) = 5.72$ ,  $p = .029$ ] faster than that for the pre-exercise test ( $M = 13.23$  lines/minute) or mid-exercise test ( $M = 13.31$  lines/minute).

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Table 5

Means and Standard Deviations for the Cognitive Tests

|                   |                                   | AIR              |                  |                   | 50% O <sub>2</sub> |               |               | 2% CO <sub>2</sub> & 50% O <sub>2</sub> |               |               |
|-------------------|-----------------------------------|------------------|------------------|-------------------|--------------------|---------------|---------------|-----------------------------------------|---------------|---------------|
| TEST              |                                   | PRE <sup>1</sup> | MID <sup>1</sup> | POST <sup>1</sup> | PRE                | MID           | POST          | PRE                                     | MID           | POST          |
| Short Term Memory | Forward <sup>2</sup> : Mean (SD)  | 6.6 (0.6)        | 6.2 (1.3)        | 7.2 (2.3)         | 6.8 (1.9)          | 7.2 (0.8)     | 6.8 (1.3)     | 6.4 (2.2)                               | 6.4 (0.6)     | 5.6 (0.9)     |
|                   | Backward <sup>2</sup> : Mean (SD) | 6.8 (1.5)        | 6.8 (1.3)        | 6.4 (0.9)         | 7.4 (1.1)          | 6.8 (1.3)     | 6.2 (1.9)     | 7.0 (2.2)                               | 5.6 (1.3)     | 6.2 (0.8)     |
| Reasoning         | Accuracy <sup>4</sup> : Mean (SD) | 0.956 (0.021)    | 0.956 (0.022)    | 0.960 (0.035)     | 0.947 (0.049)      | 0.956 (0.035) | 0.955 (0.047) | 0.963 (0.011)                           | 0.975 (0.021) | 0.969 (0.025) |
|                   | Rate <sup>5</sup> : Mean (SD)     | 13.45 (2.64)     | 13.60 (2.95)     | 14.50 (3.06)      | 13.95 (2.48)       | 13.35 (2.21)  | 14.70 (1.40)  | 13.75 (3.05)                            | 14.13 (1.76)  | 14.94 (1.82)  |

<sup>1</sup>Pre-exercise (PRE), Midway through exercise (MID), and Post-exercise (POST) performance

<sup>2</sup>Number of correct letters recalled

<sup>3</sup>Standard Deviation (SD)

<sup>4</sup>Ratio of number of correct answers to number of answers attempted

<sup>5</sup>Attempts per minute

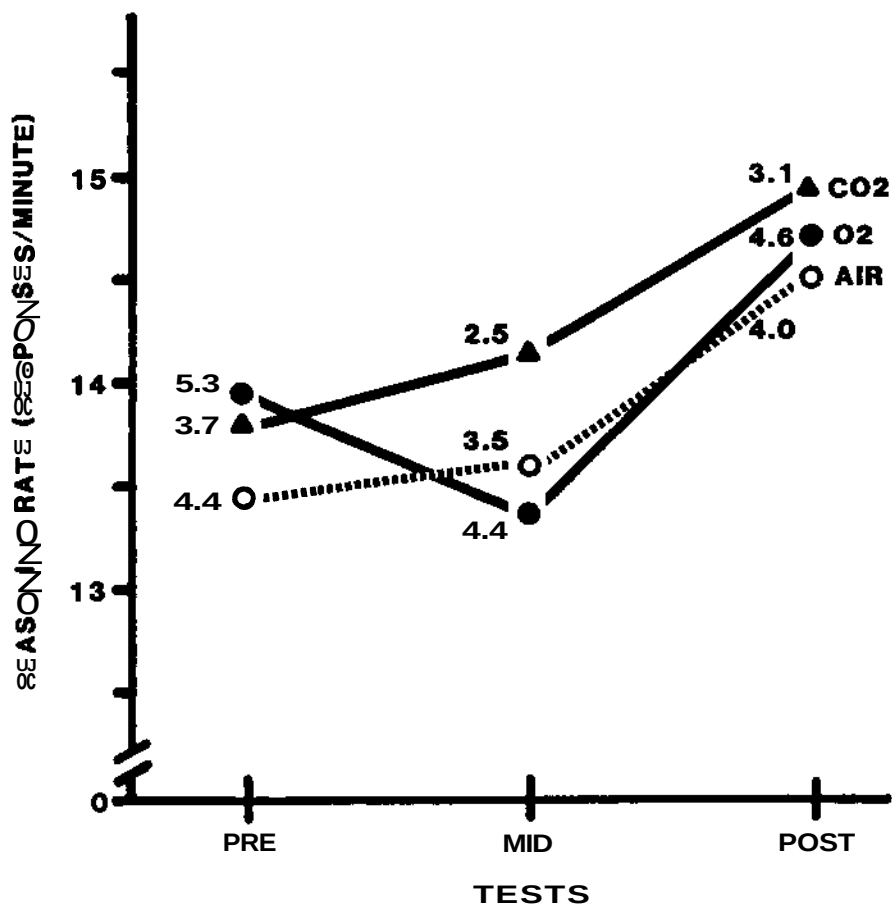


Figure 3. The mean (n = 5) reasoning rate, before, midway through and after exercise, while inhaling room air (AIR), 50% O<sub>2</sub> (O<sub>2</sub>), and 2% CO<sub>2</sub> with 50% O<sub>2</sub> (CO<sub>2</sub>). The mean percent errors are included as an index of performance accuracy.

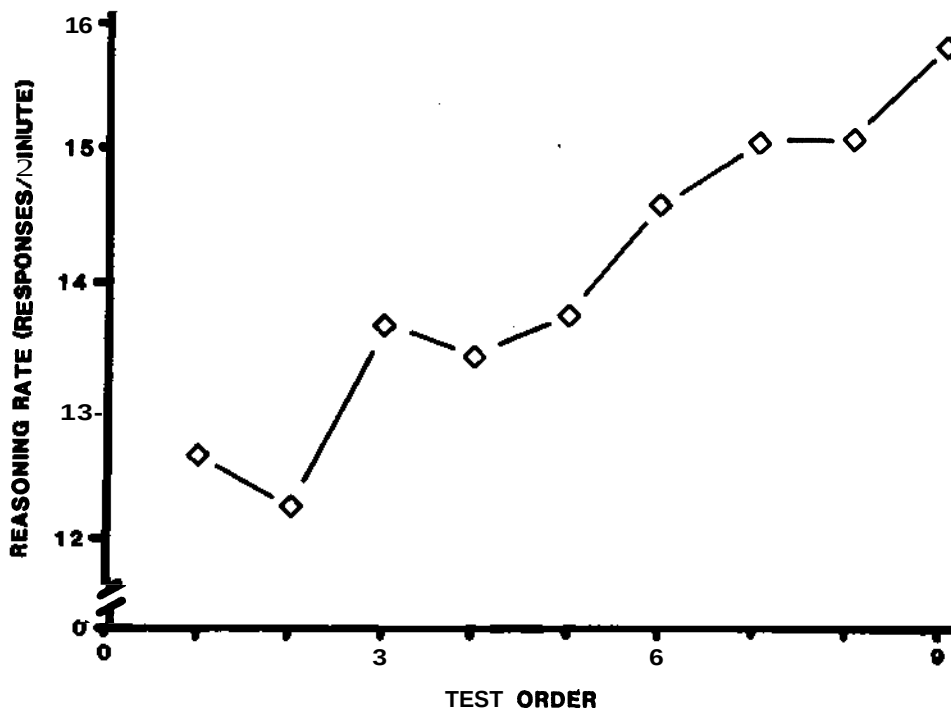


Figure 4. The mean ( $n = 5$ ) reasoning rates in chronological order.

In a closer look, however, a univariate analysis of these data revealed a significant [ $F(1,8) = 5.96$ ,  $p = .011$ ] practice (learning or sequence) effect which may explain a large portion of the high post-test rates. As shown in Figure 4, the speed of reasoning improved from session to session regardless of the manipulations of the independent variables. Since the accuracy of responding did not differ significantly across conditions, there was no reason to suspect a possible speed-accuracy trade-off. In fact, the obtained trend suggests that, regardless of the gas breathed, accuracy improved concurrently with rate and was consistently better following exercise, than at rest. Exercise in the mid- and post-tests may also account for some of the elevated reasoning rate, but this cannot be determined by the present design.

The most meaningful finding here is that the gas concentrations inspired did not impair cognitive performance. If anything, as unusual as it seems, the trends shown in Figure 3 hint that  $\text{CO}_2$  and exercise may even improve reasoning rate. None of the other main or interaction effects tests for reasoning or short-term memory were significant ( $p > .05$ ).

Table 6  
Means and Standard Deviations for the Psychomotor Tests

| TEST                                        | A I R            |                  |                   | 50% O <sub>2</sub> |                 |                 | 2% CO <sub>2</sub> & 50% O <sub>2</sub> |                 |                 |
|---------------------------------------------|------------------|------------------|-------------------|--------------------|-----------------|-----------------|-----------------------------------------|-----------------|-----------------|
|                                             | PRE <sup>1</sup> | MID <sup>1</sup> | POST <sup>1</sup> | PRE                | MID             | POST            | PRE                                     | MID             | POST            |
| STABILOMETER <sup>2</sup><br>Mean<br>(SD)   | 6.55<br>(0.78)   | 7.03<br>(0.89)   | 7.24<br>(0.62)    | 6.99<br>(0.82)     | 7.56<br>(0.81)  | 7.64<br>(0.90)  | 6.07<br>(2.45)                          | 7.45<br>(2.17)  | 7.02<br>(2.63)  |
| ROTARY PURSUIT <sup>4</sup><br>Mean<br>(SD) | 16.53<br>(2.34)  | 16.39<br>(2.53)  | 16.47<br>(2.58)   | 17.27<br>(1.85)    | 16.50<br>(2.92) | 16.12<br>(2.91) | 16.26<br>(3.00)                         | 15.63<br>(2.83) | 15.19<br>(2.53) |
| TIME <sup>5</sup><br>Mean<br>(SD)           | 539<br>(33)      | 535<br>(38)      | 525<br>(41)       | 518<br>(59)        | 513<br>(40)     | 525<br>(52)     | 520<br>(30)                             | 507<br>(32)     | 518<br>(29)     |
| ERRORS <sup>6</sup><br>Mean<br>(SD)         | 3.00<br>(1.87)   | 3.60<br>(2.30)   | 2.80<br>(0.84)    | 3.80<br>(1.79)     | 3.00<br>(2.00)  | 3.40<br>(1.52)  | 2.80<br>(1.30)                          | 2.80<br>(1.30)  | 2.20<br>(1.30)  |

<sup>1</sup>Pre-exercise (PRE), Midway through exercise (MID), and Post-exercise (POST) performance

<sup>2</sup>Seconds OFF balance

<sup>3</sup>Standard Deviation (SD)

<sup>4</sup>Seconds ON target

<sup>5</sup>Time in msec

<sup>6</sup>Absolute number of errors

## Psychomotor Performance Measures

The means and standard deviations for the psychomotor tests are tabulated in Table 6. Neither choice response time nor its error rate showed performance changes due to hyperoxia or hypercapnia. Although these elevated gas concentrations did not significantly affect tracking or balancing performance, each test did possess significant results.

As shown in Figure 5, rotary pursuit tracking was impaired with time. Breathing room air while exercising had no effect on tracking performance, but breathing elevated concentrations of either O<sub>2</sub> or CO<sub>2</sub> while exercising resulted in a significant [ $F(2,8) = 5.23$ ,  $p = .035$ ] decrease in time on target of the post-test conditions ( $\bar{M} = 16.69$  sec) and mid-tests ( $\bar{M} = 16.18$  sec). Although not significant, the impairment trend in tracking due to CO<sub>2</sub> inhalation does look suggestive. It is possible that with a slightly larger

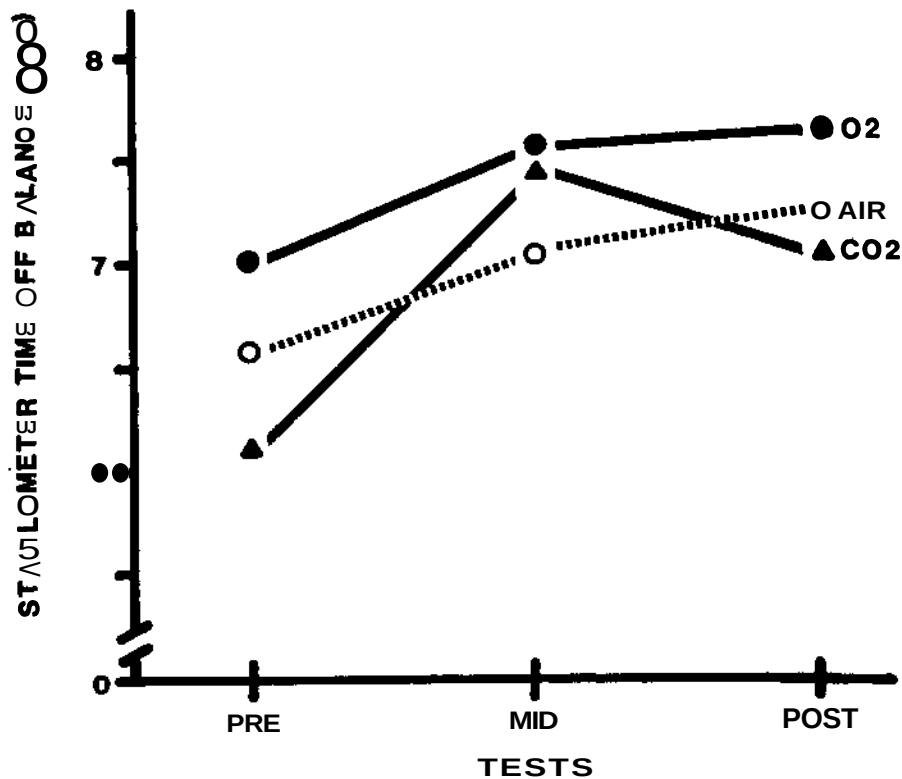


Figure 6. The mean ( $n = 5$ ) for time off balance during a 20-second stabilometer task performed before, midway through and after exercise while inhaling room air (AIR), 50% O<sub>2</sub> (O<sub>2</sub>), and 2% CO<sub>2</sub> with 50% O<sub>2</sub> (CO<sub>2</sub>).

sample size, this test may have shown deleterious effects of CO<sub>2</sub> breathing on pursuit tracking.

Labuc and Withey (1978) and Gibson (1978) found that hyperventilation impaired tracking performance, which suggests that tracking may be sensitive to acute CO<sub>2</sub> changes. However, as these data show, for simple tracking while breathing 2% CO<sub>2</sub> and as Storm and Giannette found for complex tracking during exposure to 4% CO<sub>2</sub>, tracking may not be affected by (or sensitive to) chronic hypercapnia.

Hyperoxia and hypercapnia did not affect balancing on a platform stabilometer; however, it appears exercise may cause a decline in performance. As shown in Figure 6, time off balance was significantly greater for the mid-tests ( $\bar{M} = 7.42$  sec) and post-tests ( $\bar{M} = 7.30$  sec) [ $E(2,8) = 7.22$ ,  $p = .016$ ] than for the resting, room air pre-tests ( $\bar{M} = 6.54$  sec).

Because the purpose of this study was to explore the effects of these gas concentrations on performance while simulating the conditions of a mine escape, exercise was not an independent variable and was, therefore, intentionally confounded in the design. Thus, it cannot be concluded that exercise produced these effects because there was not a control condition of breathing the gases without running. Nonetheless, the obtained trend suggests that the stabilometer may be sensitive to the effects of exercise. No other psychomotor contrasts were significant.

Caution. A word of warning is called for when interpreting these results. Just because  $\text{CO}_2$  was not found to impair performance does not mean that the  $\text{CO}_2$  MACs should be raised. It means that under the conditions specified, these measures failed to show a sensitivity to  $\text{CO}_2$ . In fact, there remains the possibility that under slightly different circumstances, or with different measures,  $\text{CO}_2$  at these levels might produce pronounced effects.

Many stressor experiments are contaminated by uncontrolled (confounding) variables and this study was no exception. Some obvious considerations include age, health, body size and fitness level; however, such factors as volunteer and smoking status,  $\text{CO}_2$  sensitivity, gender, and personality characteristics may also contribute unwanted variance and cloud the interpretation of results.

Although a very homogeneous sample population, the subjects in this study may not have been representative of the population of individuals using SCBAs. These subjects were healthy, young, active non-smoking adult male volunteers with fitness levels higher than those of many workers who might don SCBAs. For instance, Kamon, Doyle, and Kovac (1983) collected physiological data on six miners simulating an escape from an underground coal mine following an explosion. Compared with the demographic characteristics of the subjects in this study (see Table 4), the coal miners were older (45.2 vs 26.4 yrs), shorter (172 vs 179.4 cm), heavier (78.6 vs 75.5 kg), and with lower maximum heart rate (176.8 vs 187.2 bpm) and aerobic capacities (34.1 vs 50.3 ml/kg/min). Ayou and Selan (1981) also discuss the unique characteristics of miners.

Furthermore, since the physical performance of smokers is considerably impaired relative to non-smokers (Morgan, 1983) and volunteers may not

possess the same mental or physical characteristics as non-volunteers, the external validity of many laboratory studies, including this one, becomes questionable. Because there are considerable individual differences in tolerances and reactions to  $\text{CO}_2$  (e.g., Morgan, 1983), the subjects used in this study may have been insensitive to the  $\text{CO}_2$  levels employed. Gender and personality have also been linked to ventilatory responses to  $\text{CO}_2$  inhalation (Dempsey, 1979; Lum, 1975; Mora, Grant, Kenyon, and Patel, 1976; Saunders, Heilpern, and Rebuck, 1972; Shershow, King, and Robinson, 1973). Thus, age, body size, gender, degree of lung impairment, personality, volunteer status, experience, aerobic capacity,  $\text{CO}_2$  sensitivity, smoking habits and anxiety (trait and state) may certainly be factors which contribute to different results and alternative interpretations. Like many other laboratory studies, carefully controlling various sources of variance in this study may have diminished its ecological validity. Further research of this sort using subjects directly from the populations of interest is necessary to ensure the generalizability of experimental results.

### Clinical Symptoms Reported

Each subject experienced two sessions of  $\text{CO}_2$  inhalation. The most frequently reported symptom during these exposures was a dry throat (4 of 5 subjects, but two of these also reported dry throats in the air conditions). While one subject appeared very sensitive to  $\text{CO}_2$ , having a moderate headache with dizziness and weakness throughout the inhalation period, most subjects were not aware of the gas conditions and could not detect changes in their ventilation. During the first work bout, three subjects noticed slight headaches which became most intense when exercise ceased (during the first 3-min of mid-test). For all of these subjects, the headaches disappeared during the cool-down period (while breathing room air and walking on the treadmill). All  $\text{CO}_2$  reactions were most intense on the first day of exposure. No headaches were reported during the second exposure to  $\text{CO}_2$ , only dry throats. These findings hint at the possibility of individual differences in  $\text{CO}_2$  intolerance and adaptation (habituation, desensitization, or acclimatization) to  $\text{CCl}_4$ . Further studies should explore these areas.

## Conclusions

Working at 75% of  $\dot{V}_{O_2}$  max while breathing elevated concentrations of  $O_2$  (50%) or  $CO_2$  (2% with 80%  $O_2$ ) was not found to affect cognitive and psychomotor performance as measured by the six tests used in this study. A trend in the data implied that hypercapnia may impair tracking performance, but this pattern failed to reach significance. The data also suggested that exercise may have disrupted balance, or viewed another way, that the stabilometer test may have been sensitive to exercise. Consequently, with no performance impairment attributed to breathing elevated levels of  $O_2$  or  $CO_2$ , either these gas levels do not influence cognitive and psychomotor performance, or the measures used in this study were not sensitive to such effects.

The design of SCBAs is severely limited by the present MAC of  $CO_2$ . Since there is no evidence to suggest these subclinical levels cause physiological dysfunctions, and because there is almost no data available on the effects of  $CO_2$  breathing on cognitive and psychomotor performance, the current standards appear to be based on speculations. Therefore, if studies similar to this one repeatedly show no deterioration in performance, then the existing MACs should be reevaluated.

If higher concentrations of inhaled  $CO_2$  were allowed, considerable improvements could be made in the life-support capacities of SCBAs. For instance, higher permissible  $CO_2$  levels would enable longer usage of the unit. For instance, shallower beds for the scrubbing agents could decrease the size and weight of the SCBA unit. If the weight of the SCBA alone can produce a 20% decrement in both submaximal (Myhre, Holden, Baugardner, and Tucker, 1979) and maximal (Raven, Davis, Shafer, and Linnebur, 1977; Raven, 1983) work capacity, then using a smaller and lighter unit might greatly aid physical performance during escape and rescue activities (also see Morgan, 1983). The size and weight consideration becomes especially important when considering SCBA users who have limited capacities to begin with (due to age, lung disease, low fitness level, etc).

While there is not sufficient data available at this time to make recommendations for raising the MAC of  $CO_2$ , evidence is accumulating to suggest the issue be considered in future meetings concerning SCBA standards.

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Previous work in our laboratory (Sheehy et al., 1982) found no effects of acute exposure (16 min) of up to 5% CO<sub>2</sub> on behavioral performance measures; this study found no effects of chronic exposure (60 min) of up to 2% CO<sub>2</sub>. Continued behavioral studies may someday establish a standard of high utility which does not compromise the safety of the worker.

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