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Effects of Carbon Dioxide Inhalation on Psychomotor and Mental Performance During Exercise and Recovery

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On separate days, 6 highly trained participants performed psychomotor tests while breathing for 60 min 3 carbon dioxide (CO_2) mixtures (room air, 3% CO_2, or 4% CO_2) prior to, between, and following two 15-min treadmill exercise bouts (70% $\dot{V}O_{2max}$). Each individual was extensively practiced (at least 4 days) before testing began, and both gas conditions and order of tasks were counterbalanced. Results showed physiological reactions and work-related psychomotor effects, but no effects of gas concentration on addition, multiplication, grammatical reasoning, or dynamic postural balance. These findings help define behavioral toxicity levels and support a re-evaluation of existing standards for the maximum allowable concentrations (also emergency and continuous exposure guidance levels) of CO_2. This research explored the selection of psychometric instruments of sufficient sensitivity and reliability to detect subtle changes in performance caused by exposure to low levels of environmental stress, in this case differential levels of CO_2 in the inspired air.

carbon dioxide   behavioral toxicology   SCBA   cognition   motor performance   psychomotor performance

1. Introduction

Exposure to carbon dioxide (CO_2) is common in many occupations. Such exposures range from 1 to 2% in submarines to lethal levels in enclosed/confined areas like grain silos, freight containers, and hulls of ships [1] and spacecraft [2]. Inspired air is approximately 0.03% (350 ppm) CO_2 while in the expired air is 4–6%, the most when exercising. While considerable research has been conducted on the effects of hypoxia [3] and carbon monoxide [4, 5] few attempts have been made to determine the maximum tolerable level of CO_2 that does not adversely affect both physical and mental performance.

Carbon dioxide breathing causes numerous cardiorespiratory responses [1, 6, 7, 8] but there appear to be no disabling physiological effects

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or clinical symptoms associated with breathing up to 5% CO_2. Nonetheless, there still may be psychological reactions, such as impaired vision, diminished motor control, slowed reactions and responses, disorientation, or reduced attentional capacities that may jeopardize a worker's health and safety [9, 10]. Impaired perceptual, cognitive, and/or motor performance can make the worker susceptible to accidents and decrease the probability of survival in a variety of emergency situations. Therefore, it is crucial to establish the maximum allowable concentration (MAC) of CO_2 at which performance level remains unimpaired [11]. Some agencies describe these standards in terms of Emergency and Continuous Exposure Guidance Levels for selected contaminants (3–4% expressed in 30 000–40 000 ppm).

Previous research exploring the effects of acute (15 min or less) CO_2 exposures have found little evidence of impaired mental performance due to breathing up to a 6% concentration. Sheehy, Kamon, and Kiser [12] exposed their participants to 4 and 5% CO_2 (with 21 and 50% O_2) 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_2 retention in diving, Henning, Sauter, Reddan, et al. [13] found no effects of breathing 6% CO_2 for 10–14 min on simple and choice reaction time, hand steadiness, and postural sway.

A similar picture emerges in quantifying the effects of chronic (one hour or more) CO_2 exposures. Storm and Giannetta [14] had 6 participants breathe 4% CO_2, for 14 days and found no effects on complex tracking, eye–hand coordination, and problem solving. Glatte, Motsay, and Welch [15] found no effects of breathing 3% CO_2 for 5 days on arithmetic, vigilance, hand steadiness, memory, problem solving, and auditory monitoring. However, exercise compounds any problems created by CO_2 breathing [16, 17, 18]. Even when exposures occur during physical work, there is little evidence to support the existing standards. Vercruyssen and Kamon [8] found no effects of breathing 2% CO_2 for one hour, during and following moderate to strenuous work, on short-term memory, reasoning, balance, choice response time, or pursuit tracking.

Due to the steep slope of the acquisition trend obtained in previous studies [8] and the fact that most activities encountered in the workplace are well-learned, considerable practice was provided to the participants in the present experiment. Assuming the effect of an environmental stressor is measured by the deviation from an individual's optimal performance, the concern of the present study was to measure the amount of deviation from a stable, best performance state. Initial pilot studies determined the acquisition patterns and the number of trials to a criterion of "near asymptotic performance level." All participants were required to attain this level before being exposed to any stress manipulation. The purpose of the present experiment therefore was to explore the effects of a prolonged, 60-min exposure, to 3 and 4% CO_2 during and following physical work, on well-practiced cognitive and psychomotor performance.

2. Experimental Method

2.1. Experimental Participants

Six right-handed, beardless, male university graduate students volunteered to serve as paid participants. Each participant's first visit to the laboratory involved a medical examination with an extensive ECG workup, including maximum exercise tolerance and pulmonary function tests, practice on all the psychomotor tests, and questionnaires. (The medical support required in this form of experiment and the time for extensive practice required makes this type of research expensive but reduces the number of participants needed for criterion statistical power.) This research was carefully monitored by several human subjects review boards. Each volunteer understood the toxicity risks, agreed to participate, and was paid for being tested. All participants were non-smokers and in good general health. Their demographic characteristics are shown in Table 1.

TABLE 1. Subject Demographic Characteristics

Subjects	Age (years)	Height (cm)	Body Mass (kg)	Body Fat (%)	HR_{max} (bpm)	VO_{2max} ($ml \cdot kg^{-1} \cdot min^{-1}$)
1	27	180.7	77.0	16.3	193	49.5
2	27	182.6	80.0	9.0	178	55.3
3	23	190.3	71.4	12.4	190	58.5
4	33	175.3	62.8	20.1	193	48.5
5	28	177.8	69.6	18.3	190	50.2
6	24	187.5	78.7	10.4	188	51.3
M	27.0	182.4	73.2	14.4	189	51.5
SD	4.0	5.7	6.5	4.5	6.0	4.9

Notes. HR—heart rate

2.2. Experimental Design

A repeated measures 3×3 (CO_2 Gas Concentration by Tests) design was employed to analyze data on each of four dependent measures. Three gas concentration conditions were employed: a room air control, 3% CO_2, and 4% CO_2. Performance tests were administered (a) prior to, (b) between, and (c) following two separate bouts of exercise. For each session, each participant 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 pre-test was always in a fully rested, room air control condition, while the mid- and post-tests followed exercise and occurred during the gas inhalation period. Participants were randomly assigned to counterbalanced random combinations of gas conditions. The order of tests within each performance battery was also counterbalanced.

2.3. Stressor Conditions

The stressor conditions in this study, exercise and CO_2 inhalation mixture, were used to simulate an emergency escape (or rescue maneuver) while either 3 or 4% CO_2 was breathed for one hour, which is the expected life of a self-contained breathing apparatus (SCBA) escape unit, while running slightly over 4.8 km as fast as possible. Most typically, this profile is representative of an emergency mine egress episode that might follow some form of underground disaster. During the exercise periods, each participant ran for 15 min on a treadmill ergometer with the speed and grade adjusted to yield an oxygen uptake of 70% of their maximal aerobic capacity. Each experimental session consisted of two such work bouts spaced with pre-, mid-, and post-tests, each lasting approximately 15 min, during which the dependent measures were collected. Oxygen uptake samples were taken during steady state running, while room air was breathed, in order to record actual exercise intensity (Figure 1). The average intensity for the group was 71.6% ($SD = 3$) of VO_{2max}. On the average, the participants ran slightly more than 4.8 km per day at their estimated maximum speed. While on the treadmill they were cooled with an electric fan placed in front of them, but not blowing directly on their faces. Chest electrodes were connected to a Respironics (USA) Digital Exersentry (SN) for monitoring average heart rate. The experiment was conducted in an air-conditioned laboratory where the room temperature ranged from 23 to 25 °C. Care was also taken to standardize ambient light and sound.

A 150-L Douglas bag served as the mixing reservoir into which room air, CO_2 and O_2, were mixed before heating and humidification by passage through warm water en-route to the participant in an open-circuit system. The inspired gas mixture was controlled by continuous monitoring and adjustment using an Applied Electrochemistry S-3A Oxygen Analyzer (AEI Technologies, USA) and an LB-2 Beckman Medical Gas CO_2 Analyzer (Beckman Insturments Ltd., Canada), each of which was calibrated before each session with a known concentration of gas. Three gas mixtures were used in this study; (a) room air (0.03% CO_2 and 21% O_2), (b) 3% CO_2 (with 50% O_2), and (c)

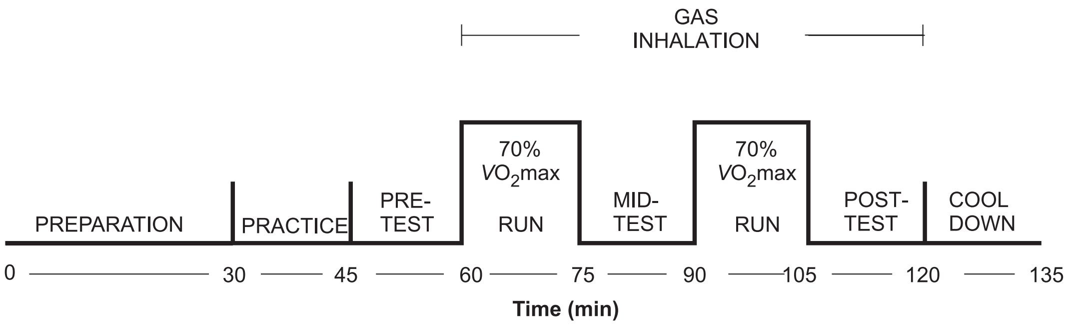

Figure 1. Testing protocol for each experimental session. Following extensive practice, each participant performed this protocol three times—while breathing room air, 3% CO_2, and 4% CO_2.

4% CO_2 (with 50% O_2). (Hyperoxic conditions minimized the peripheral chemoreflexive drive and ensured brain tissue oxygen was high in all experimental conditions despite fluctuations in brain blood flow caused by changes in PCO_2.) Heating and humidification of the inspired air increased the likelihood that participants were unable to distinguish between the respective gas conditions. The prescribed inspired gas mixture (SD = 0.1%) was inhaled for 60 min (SD = 0.2) during each experimental session. Expired air was released into the well-ventilated testing room. Heart rate, blood pressure, ratings of perceived exertion, and a battery of physiological parameters were monitored and recorded throughout the experiment.

Four performance tasks were administered, each in a pre-, mid-, and post-test format (Figure 1). Grammatical reasoning and arithmetic tasks (addition and multiplication) were considered cognitive tasks that quantified decision-making speed and accuracy. Postural balance was considered a psychomotor task reflecting vestibular integrity and neuromuscular control. Selection of these behavioral measures was based on preliminary pilot studies and results from other investigations that used different stressors. These measures were considered representative of several skills necessary to successfully escape from an underground mine during an emergency. Therefore, any performance degradation due to CO_2 inhalation and/or exercise would provide valuable information for refining an effective methodology for behavioral toxicology while also defining the design parameters for escape instruction, emergency apparatus, and mining safeguards.

Six counterbalanced orders of tests were developed with each participant being randomly assigned to one of the possible orders. Before beginning the experiment, they received at least 4 days of practice with immediate knowledge of results to establish near asymptotic performance levels on each of the performance measures. These near asymptotic levels were re-established in a practice period prior to each testing session. In three cases the participants were not able to perform at their previous best levels so they were sent home and asked to return the next day when they were able to perform at their personal best levels. One person required an additional day of practice (9 total days of laboratory testing, 2–3 hrs per day) to insure there was no additional learning during the gas and exercise experimental conditions. The amount of practice given was based on learning pilot studies and the results obtained previously in the laboratory [8, 12]. No individual experienced significantly better performances during experimental treatments demonstrating that 8 hrs of practice was sufficient.

Reasoning, or grammatical transformation, has been shown to be a stable [19, 20, 21] metric of higher mental processes, i.e., sensitive to nitrogen narcosis [22], age [23], hypocapnia [24], oxy-helium diving [25], and trimix breathing during dives of 660 m [26]. This test consisted of a 3-min task adapted from Baddeley's [27] grammatical transformation task. Seated in front of a computer screen, the participants read a statement followed by a pair of letters and decided whether or not the statement matched the letters. They responded with an appropriate *True* or *False* judgment by pressing one of two keys adjacent to the return key on the keyboard. Responses were made with the index finger (*False* key) or middle finger (*True* key) and ring finger (return key). The statements were randomly drawn from 64 possible combinations of six binary conditions [22, 27] and were presented one at a time until the 3-min 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, and the measures taken were the response rate (i.e., the total number performed in each 3-min interval), accuracy (i.e., number of correct responses/total number of responses), and response times for each statement.

Tasks similar to the addition and multiplication tests already described have been shown to be sensitive to sleep deprivation [23, 28, 29], abrupt awakening at different times of night [30], hyperbaric and cold conditions [31, 32, 33], elevated body temperature [34], heat stress [35], exercise [36, 37], oxyhelium diving [25, 38], trimix dives to 660 m [26], repeated diving [39], and compressed [40]. Moreover, a similar arithmetic task has been used by Morgan and Alluisi [41] in general assessments of human performance under stress [42]. Such tasks have been instrumental in development of performance evaluation tests for environmental research [20, 42]. Consequently, addition and multiplication tasks were used in this experiment.

The addition task involved simple vertical addition. Participants were presented problems, each comprised of five rows of two-digit numbers, to be summed as quickly and as accurately as possible. Using the digits 1–9, numbers were randomly generated for each problem. Fifteen problems appeared in three rows of five on each form, 13 equivalent forms were randomly assigned across participants and conditions. Each individual practiced for 30 s (a warm-up) before completing as many problems as possible in 2 min. The criterion measures were the number of problems completed (speed) and the percentage of errors (accuracy). To ensure the maximum speed was obtained, participants were told that error rate in the 5–15% window was tolerable.

In the multiplication task participants were presented with numerals that were to be multiplied as quickly and accurately as possible. Each problem consisted of three-digit multiplicand, a two-digit multiplier, and a five-digit product. Using the digits 1–9, numbers were randomly generated for the multiplicand; the digits 2–9 were used for the multiplier, with the restriction that the product must be a five-digit number. Fifteen problems appeared in three rows of five on each form; 13 equivalent forms were randomly assigned across participants and conditions. The participants were given a 30-s practice period before beginning the 2-min test. The criterion measures were the number of problems completed (speed) and the percentage of errors (accuracy). Again, to ensure maximum speed, participants were informed that an error rate of 5–15% was tolerable.

Because dizziness and loss of balance are characteristic clinical symptoms associated with CO_2 inhalation, the ability to maintain balance on a horizontal pivoting platform stabilometer was assessed with the stabilometer balancing task. This measure was also selected because of the information available on its susceptibility to practice [43] and fatigue [44] as well as its retention [45] and stress reaction [46] characteristics. The apparatus consisted of a $37.5 \times 95 \times 2.1$ cm wooden platform with an axle and bearings positioned directly beneath so that the participant could stand upon it, straddling the axle, and attempt to balance. Microswitches were positioned on the stabilometer frame to record the amount of time the platform was tilted (off-balance). A record of the total time the participant was off balance per 20-s trial was taken. Rigorous training (more than 150 practice trials) on this task preceded the start of the experiment. All participants experienced keeping the platform fully horizontal (i.e., 0.0 s off-balance) for the entire 20-s test; and some individuals were able to do this consistently. Participants performed five trials, separated by approximately 30-s inter-trial rest intervals, during each test.

2.4. Experimental Procedure

Each participant served in eight sessions, one per day. Following an exercise tolerance test (Day 1), each individual participated in four 150-min practice sessions, one each day (Days 2–5), before receiving a counterbalanced random order of experimental sessions (Days 6–8). The first practice session was used to explain the experiment, complete the informed consent, introduce the dependent measures and experimental protocol, and provide considerable practice on each performance measure. In the course of these practice sessions, participants experienced at least thirty-six 3-min grammatical reasoning tests, one hundred and fifty 20-s stabilometer tests, and twelve 2-min addition and multiplication tests. Also, the participants ran on the treadmill while breathing the highest concentration of CO_2 (4%) to become familiar with the experimental protocols, the respiratory hoses, treadmill running, and the stressor (CO_2 inhalation). In the experiment itself, participants were performing well-learned tasks and had previous experience with all aspects of the experimental procedures, including familiarity with the stressor itself. Each experimental session took approximately 125 min to complete and was separated with at least a 48-hr rest interval.

Upon arrival to the laboratory, each subject was fitted with the chest electrodes, given a brief warm-up on each task, and then given the pre-test performance measures that were completed in approximately 15 min. Asymptotic performance levels were usually re-established in one trial for grammatical reasoning, addition, and multiplication. The stabilometer usually required 10 trials. In all, practice and preparation totaled 24.7 min (*SD* = 4.2). On three occasions a participant was asked to reschedule because they were unable to re-establish optimal performance during the preparation period.

The pre-test measures (control—no face mask, no exercise, no gas mixtures) were gathered in 25.2 min (*SD* = 2.8). The gas inhalation period began with the participant running on a treadmill for two 15-min work bouts at an intensity equivalent to 70% of their aerobic capacity. Between and following these work bouts were the mid- and post-tests, respectively, each also lasting approximately 15 min (mid-test was 15.6 min, *SD* = 1.5; post-test was 15.8 min, *SD* = 3.5) (Figure 1).

The face mask was removed after the post-test, making the total inhalation period 64.4 min (*SD* = 3.5), and the participant was required to walk on the treadmill at 4.8 km/hr for at least 6 min as a cool-down before departing. During and following the cool-down, they were asked to provide subjective information on their perceived exertion, clinical symptoms (discomforts), performance quality, etc. All eight testing sessions for each individual participant were completed within a 3-week total period without exception.

The dependent measures were analyzed using a repeated measures analysis of variance (ANOVA) [47, 48]. All post-hoc analyses were done using the Tukey wholly significant difference (WSD) technique [49]. In all cases, the .05 level of significance was employed. An additional univariate analysis of the repeated measures was performed on each participant across all criterion measures to test for learning (sequence) effects (see Jackson and Raven [50] for a discussion of statistical and research designs for industrial respiratory research).

3. Results and Discussion

Performance means and standard deviations for each dependent measure are shown in Table 2. Only two measures produced significant results ($p < .05$): multiplication rate and time off-balance on the stabilometer. The mean multiplication rate as a function of inspired gas and test phase is illustrated in Figure 2. Next to each mean rate value is the mean percentage error for that condition. Multiplication rate was significantly faster, $F(2, 10) = 7.57$; $p = .001$. The lowest percentage of errors was at the mid-test while participants breathed 4% CO_2, not other gas mixtures. This finding is difficult to interpret, however, because breathing 4% CO_2 also produced the slowest multiplication rate on the post-test. This pattern implies a degradation on behalf of participants that may reflect a form of threshold transition change as fatigue and demand increase [51].

Mean off-balance time during the platform stabilometer testing is also shown in Figure 3 as a function of inspired gas and test phase. Balance (as measured by the average time off balance in a 20-s interval on trials 2–5) was significantly impaired, $F(2, 10) = 14.59$; $p = .001$, on the mid-test ($M = 3.72$ s) and post-test ($M = 3.54$ s) compared to the pre-test ($M = 1.54$ s) presumably due to the exercise level. However, because the purpose of this study was to explore the effects of these gas concentrations on performance during physical work and not to examine exercise effects per se, physical activity was 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 various gas concentrations without running. Despite the fact that the values obtained on the pre-tests were very similar—suggesting high inter-test reliability—the gas trend shown on the post-test was not significant ($p > .05$).

The most meaningful finding is that the gas concentrations tested in the present work did not substantively impair cognitive or psychomotor performance. Indeed, the trends shown in Figure 2 hint that CO_2 and exercise may actually have even improved multiplication rate. Other than the two significant effects discussed, none of the other main effects or interactions

TABLE 2. Performance Means and Standard Deviations

		Air			3% CO_2			4% CO_2		
		Pre-	Mid-	Post-	Pre-	Mid-	Post-	Pre-	Mid-	Post-
Addition	Problems completed in 2 min	13.8 ±3.1	13.7 ±2.9	14.0 ±2.9	13.3 ±3.6	14.5 ±3.0	13.8 ±4.1	13.8 ±4.0	13.3 ±2.4	13.0 ±4.1
	% errors	12.5 ±10.5	14.7 ±9.4	1.2 ±2.9	6.0 ±4.9	9.0 ±8.2	8.8 ±10.7	12.7 ±15.4	7.8 ±7.5	8.3 ±5.0
Multiplication	Problems completed in 2 min	30.0 ±7.7	30.2 ±6.4	30.3 ±7.9	28.3 ±7.9	30.7 ±7.3	31.0 ±7.6	29.7 ±6.3	33.0 ±6.2	28.5 ±7.0
	% errors	9.5 ±8.1	7.8 ±12.5	13.3 ±15.5	16.0 ±16.2	11.8 ±9.6	9.0 ±10.0	6.7 ±6.6	6.0 ±4.8	13.2 ±8.0
Reasoning	Problems completed in 3 min	98.2 ±17.0	101.8 ±14.0	102.3 ±15.2	98.3 ±15.6	102.3 ±16.3	101.0 ±17.0	107.3 ±29.2	104.8 ±30.6	107.2 ±29.1
	% errors	6.7 ±5.4	5.5 ±3.5	5.5 ±4.0	5.2 ±3.0	5.7 ±3.4	7.8 ±7.7	6.2 ±3.7	7.5 ±3.9	7.3 ±6.5
Stabilometer	Trial 1	2.34 ±2.12	5.00 ±3.23	4.69 ±3.49	1.57 ±1.48	3.25 ±1.96	4.36 ±1.77	1.85 ±1.50	4.07 ±2.85	4.67 ±2.90
	Trial 1–3	1.84 ±1.58	4.21 ±2.52	3.62 ±2.38	1.44 ±0.83	3.89 ±2.06	4.00 ±2.10	1.99 ±0.92	4.46 ±2.58	4.26 ±2.82
	Trial 1–5	1.96 ±1.61	3.96 ±2.33	3.41 ±2.21	1.30 ±1.01	3.76 ±2.07	3.74 ±2.10	1.62 ±0.99	3.89 ±2.57	3.94 ±2.76
	Trial 2–5	1.86 ±1.04	3.70 ±1.87	3.07 ±1.54	1.18 ±0.55	3.61 ±1.49	3.40 ±1.71	1.57 ±0.45	3.84 ±2.20	4.15 ±2.62

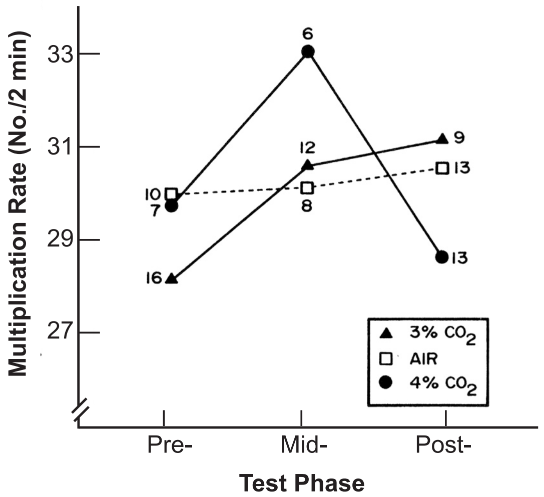

Figure 2. Mean multiplication rate as a function of gas inhaled and test phase. Percentage errors per condition are indicated next to each multiplication rate. Pre-test was performed while breathing room air, at rest, without respiratory hoses. Mid- and post-tests were performed following 15 min of exercise at 70% $\dot{V}O_{2max}$.

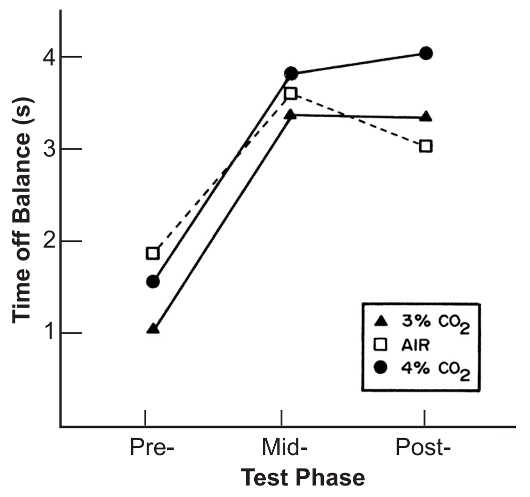

Figure 3. Mean time off balance as a function of gas inhaled and test phase. Pre-test was performed while breathing room air, at rest, without respiratory hoses. Mid- and post-tests were performed following 15 min of exercise at 70% $\dot{V}O_{2max}$. Five 20-s trials were performed with the average of trials 2–5 illustrate.

reached significance ($p > .05$). Vercruyssen and Kamon [8] warn against the misinterpretation of null results in stress studies. Affirming the null hypothesis, and suggesting there is no effect due to the stressor conditions, is not grounds for raising MACs of CO_2. It simply means that under the conditions specified, these dependent measures predominantly failed to show a sensitivity to CO_2. There still remains the possibility that different dependent measures or CO_2 at higher concentration levels, or longer exposure durations might produce significant effects. If a further spectrum of dependent measures were employed and all failed to reveal CO_2 effects, then this would constitute further evidence supporting the notion that humans can tolerate these subclinical levels of CO_2 without impairments in cognitive and motor performance.

Vercruyssen and Kamon [8] also identify potential confounding variables to be considered in evaluating the external validity of such claims. The most important organismic variables are age, health, body size, fitness level, differing smoking status, CO_2 sensitivity, degree of lung impairment, experience, gender, and personality characteristics. The participants in this study were obviously not representative of the population in general or of that segment of professional individuals using SCBAs. To maximize statistical power, the participants in this experiment comprised a homogeneous population of healthy, young, active, non-smoking, adult male volunteers with relatively high fitness levels. Each demographic characteristic provides a possible source of systematic variance and, therefore, must be given careful consideration when interpreting the results of this investigation [8, 52, 53, 54, 55].

Aside from increased ventilation, the most common clinical symptom caused by CO_2 breathing is a headache [56, 57]. The most frequently reported symptom during CO_2 exposures in this experiment was a 66% incidence of dry throat (although 2 participants also reported dry throats in the control condition). While one subject appeared very sensitive to CO_2, having a moderate headache with dizziness and weakness throughout the inhalation period, the others were not aware of the gas conditions and could not detect changes in ventilation. During the first work bout, 3 participants noticed slight headaches that became more intense when exercise ceased (during the first 3 min of mid-test). For all of these individuals, the headaches disappeared during the cool-down period (while breathing room air and walking on the treadmill). All CO_2 reactions were most intense on the first day of exposure. No headaches were reported during the second day exposure to CO_2, only dry throats (despite heated and humidified inspired air). These findings hint at the possibility of individual differences in CO_2 tolerance and adaptation (habituation, desensitization, or acclimatization) to CO_2 [55, 58]. Previous studies have also reported similar findings [8, 12, 59, 60]. Employing a battery of subjective state change rating scales might therefore prove beneficial in subsequent studies, particularly in explaining changes in perceived exertion [61].

Another interesting experimental confound is the mental distraction caused by the physiological effect of hypo- or hypercapnia (e.g., tingling, hyperventilation, anxiety). For example, the ability to rehearse and recall in a free recall list learning task was impaired by hypocapnia leading Marangoni and Hurford [62] to conclude that conditions reducing alveolar CO_2 ($PaCO_2$; e.g., hyperventilation caused by perceived stress, nervousness, or inappropriate breathing habits) could lead to degraded learning and diminished academic performance. Thus, care must be taken to experimentally distinguish the influence of respiratory compensations, and the interference they may cause, from the toxicity reactions of the imposed stressor.

Recent research concerned with elevated $PaCO_2$ on cortical electrical activity and psychomotor functioning has been limited by methodological inconsistencies including (a) uncontrolled changes in breathing frequency and/or volume (e.g., [63, 64, 65]); (b) the use of different concentrations of CO_2 often without reporting $PaCO_2$ (e.g., nearly all of the ergonomics and industrial hygiene CO_2 literature); (c) a range of inhalation periods with dependent measures gathered during exposure and recovery, sometimes inconsistently (e.g., [64, 66]); and (d) individual variations in sensitivity to CO_2 and $PaCO_2$ changes as indicated by irritability, discomfort, or other physiological reactions (e.g., nearly all of the behavioral research on CO_2 to date). However, Bloch-Salisbury, Lansing, and Shea [67] did an admirable job in controlling extraneous factors to arrive at their conclusion—modest, acute increases or decreases in end tidal $PaCO_2$ do not affect cognitive functioning or alertness, despite significant changes in the EEG power spectra. Furthermore, they attribute much of the CO_2 decrement effects found in other studies to alterations in ventilation, discomfort, or other physiological reactions.

A dearth of empirical evidence concerning the effects of breathing elevated, but subclinical, levels of CO_2 on cognitive and psychomotor performance has inhibited any recommended revision of standards for MACs, emergency exposure guidance level (EEGL), or continuous exposure guidance level (CEGL) of CO_2. A conservative limit for the inspired air would initially seem desirable because it would prevent possible adverse behavioral and physiological reactions. However, meeting such high standards greatly increases the size and weight of respiratory devices, creating user difficulties and introducing potential hazards associated with weight and portability during emergency egress. MACs should be established to minimize the overall difficulties encountered in using such respiratory devices, particularly during emergency escape from mines while maintaining acceptable CO_2 inspiration levels that do not adversely affect the capability of the user.

Emergency breathing systems, e.g., SCBAs, must be able to sustain life and maximize the probability of successful escape from a hazardous environment without constraining the escape activities of the user. Because 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 re-evaluated [68, 69]. If higher concentrations of inhaled CO_2 were allowed, considerable improvements could be made in the life-support capacities of SCBAs [8, 60, 70].

4. Summary and Conclusions

Unlike what may be expected based on current standards, i.e., where the MAC is 0.5% CO_2 [1], breathing as high as 4% CO_2 for one hour, during and following physical work, produced the expected physiological responses (e.g., increased ventilation), but did not substantially impair either cognitive and motor performance (i.e., speed or accuracy of addition, multiplication accuracy, speed or accuracy of reasoning, and stabilometer balance). Breathing 4% CO_2 caused an unexplained improvement in multiplication, but this finding is difficult to interpret and the authors are reluctant to suggest that breathing CO_2 improves mental performance. The data also suggest that exercise impaired balance but CO_2 did not, or, viewed another way, that the stabilometer test may have been sensitive to exercise effects.

Finding little performance change attributed to breathing elevated levels of CO_2, may be explained in one of at least three ways: (a) the cognitive processes required to perform the experimental tasks are flexible enough to mitigate the effects of the stressor, (b) the dependent measures employed were not sensitive to the type of degradation effects encountered, or (c) breathing up to 4% CO_2 during physical work does not significantly impair cognitive and psychomotor performance. In terms of the present results, it appears that the third of these explanations is the most likely one to be correct. If most data suggest a no-observed-adverse-effect level (NOAEL) for CO_2 of about 2.8% (28 000 ppm) on the basis of dyspnea and intercoastal pain findings, the present investigation suggests the NOAEL might actually lie somewhere at or above 4%.

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