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

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Psychomotor and mental tests involving reaction time, rotor pursuit, short-term memory for digits and letters, and reasoning ability were administered to subjects inhaling up to 5% CO_2 in air and in gas mixtures containing 50% O_2. The psychomotor and mental tests were given during the 6 min of recovery following 10 min of treadmill running at 80% of aerobic capacity. Although the subjects inhaled the CO_2 during the entire exercise and recovery period there was no difference in performance between the CO_2 inhalation condition and the control condition for any of the performance measures.

INTRODUCTION

Exposure to carbon dioxide is not uncommon in a wide range of occupations. Observations on carbon dioxide (CO_2) exposure range from 1 to 2% in submarines and space vehicles for mostly sedentary activities, to between 3 and 10% in grain silos, oil tanks, and chemical treatment plants where physical activities are performed (NIOSH, 1976). The determination of an acceptable level of CO_2 inhalation that will not adversely affect performance depends on such factors as the level of physical work and the psychological, physiological, or clinical effects involved.

The literature is devoid of attempts to assess the effects of CO_2 as measured by psychological tests. Carbon monoxide (CO), not carbon dioxide (CO_2), adversely affected dual-task performance (Putz, 1979), whereas vigilance was shown not to decrease after exposure to concentrations of CO normally found in urban environments (Roche, Horvath, Gliner, Wagner, and Borgia, 1981). Inhalation of CO_2 during physical exertion could involve hidden psychological effects, such as deterioration of motor control, loss of orientation, and impaired mental performance or reasoning ability, although no physiological effects or clinical symptoms are reported.

Noticeable physiological responses to CO_2 inhalation were an increase in pulmonary ventilation (Dripps and Comroe, 1947), constriction or dilation of blood vessels (Lambertsen, 1971), increases of up to 75% in cerebral blood flow (Kety and Schmidt, 1948), decreases in specific airway resistance (Taskin and Simmons, 1972), changes in the electrocardiogram (McDonald and Simonson, 1953), and apparent premature cardiac contractions (McDonald and Simonson, 1953). Clinical symptoms observed were headaches,

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dizziness, restlessness, and dyspnea (Schaefer, 1963). After 12 to 15 h of exposure to CO_2 concentrations of 2 to 3% during sedentary activities, subjects exhibited lassitude, irritability, and unconsciousness. Within 3 min of exposure to CO_2 levels of 20 to 30%, subjects exhibited increased perspiration, flushing, restlessness, dilation of the pupils, leg flexions, and torsion spasms (Lambertsen, 1971).

Exercise compounds the problems created by CO_2 inhalation. The body's retention of CO_2 normally increases with exposure time; however, exercise increases metabolic CO_2 production, and this results in an even higher CO_2 retention. This excess CO_2 could in turn reduce the worker's endurance for strenuous physical work (Craig, Blevins, and Cummings, 1970). Inhalation of CO_2 during physical work can occur during fire fighting or following an underground mining disaster, when a self-contained respirator (SCR) is used to prevent the inhalation of ambient toxic gases. The SCR is designed to provide oxygen while absorbing the CO_2 produced by the body. Most SCRs, however, are limited in their capacity to absorb CO_2; therefore, during prolonged usage the level of unabsorbed CO_2 will increase with time.

Although physiological responses to inhalation of up to 10% CO_2 during rest and exercise did not indicate deterioration of essential body functions (Craig, 1955; Asmussen and Nielsen, 1957), unknown psychological effects, such as loss of orientation, could be crucial to the user of an SCR during an emergency situation. The duration of SCR use during emergencies is expected to be relatively short, ranging from 30 to 60 min. If there are no hidden effects, however, allowing a higher CO_2 level would permit use of the SCR for a longer period. In some circumstances, this would represent the difference between saving and losing a life.

This study is concerned with psychomotor and mental performance during the inhalation of up to 5% CO_2. Subjects inhaled CO_2 during 10 min of strenuous exercise and the following few minutes of psychomotor or mental testing.

METHOD

Subjects

Three groups of paid volunteers participated in the study. Their age and physical characteristics are summarized in Table 1.

Apparatus

A treadmill was used for the 10-min exercise period. The speed and grade of the treadmill were adjusted to yield O_2 uptake at 80% of the maximal aerobic capacity (80% $\dot{V}_{O_{2}max}$) for each subject.

The gas mixture for inhalation was stored in a 150-L Douglass bag. Mixing was controlled by using an oxygen analyzer and a medical gas CO_2 analyzer. To add humidity to the gas mixture before inhalation, it was passed from the bag through warm water.

Chest electrodes connected to a digital beat readout were used to monitor heart rate (HR). Auditory reaction time was measured with an automatic performance analyzer and remote response button. The probe stimulus was a 70-dBA tone. The choice reaction time unit consisted of eight telegraph keys mounted equidistantly from a starting button. The stimulus was a number (1-8), which appeared in an illuminated display 30 cm above the board, centered behind the keys. The rotary pursuit apparatus consisted of a light-emitting target, which moved in a circular path, and a tracking stylus that had a photosensitive tip interfaced with a timer. The short-term memory (STM) and reasoning tests were displayed on a graphics terminal. A minicomputer system with a disk drive and CRT executed the STM and reasoning-test programs, and recorded and scored the subjects' responses.

TABLE 1

Means and Standard Deviations for Age, Physical Characteristics, Maximal Heart Rate (HR_{max}), and Maximal Aerobic Capacity ($\dot{V}_{O_2max}$ in ml·kg^{-1}·min) of the Subjects

Experiment	*N*	*Height (cm)*	*Weight (kg)*	*Age (yrs)*	HR_{max}	$\dot{V}_{O_2max}$
Psychomotor	6	182.9 ± 5.8	78.98 ± 9.1	22.4 ± 7.6	186.0 ± 11.0	47.44 ± 4.3
Short-Term Memory	5	179.5 ± 7.2	78.86 ± 8.9	23.8 ± 3.5	185.6 ± 11.2	48.36 ± 4.7
Reasoning	4	182.0 ± 8.7	76.98 ± 13.8	27.5 ± 3.9	184.2 ± 13.3	46.96 ± 4.3

Tests

The experimental testing included psychomotor, short-term memory, and reasoning tests. Figure 1 gives a schematic description of the time sequence for each of the administered tests.

The psychomotor tests consisted of an auditory and choice reaction-time test, and a rotary pursuit task. The auditory reaction-time (ART) test consisted of four blocks of nine trials each. Reaction time was the interval between initiation of the tone and the subject's pressing of the hand-held response button.

The choice response time (CRT) test involved pressing the telegraph key that corresponded to the illuminated number in the display. The measured response time was the interval between the presentation of the stimulus and the depression of the key. Catch trials (i.e., the subject is given the ready signal, but the response number is not presented) and variable foreperiods (0.5, 1.5, and

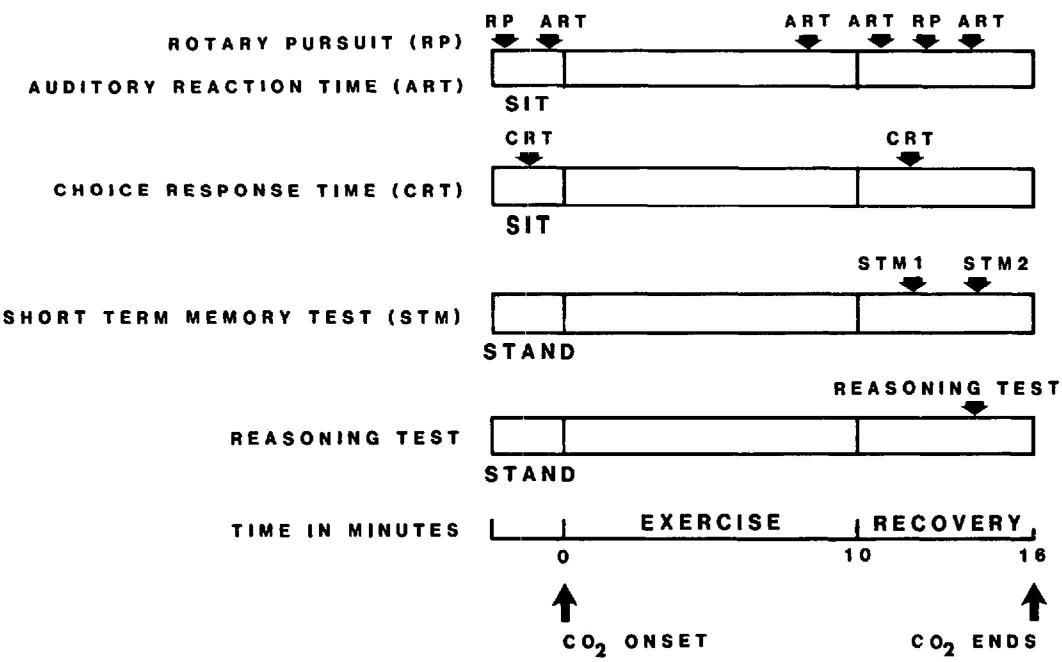

Figure 1. *Graphical description of the time sequence for each of the administered tests.*

2.5 s) were employed to eliminate anticipatory responses. Each subject received two blocks of 24 trials.

The rotary pursuit (RP) task assessed the subject's ability to track a moving object. Each subject received six 20-s trials. To eliminate practice effects, subjects were allowed to reach optimum performance levels prior to testing. All testing consisted of the target moving in a clockwise direction at 30 revolutions/min.

The short-term memory (STM) test for digit recall was based on the digit span test used in the Wechsler Adult Intelligence Scale (WAIS) (Wechsler, 1958). The digits were presented singularly for 1 s, followed by a 250-ms pause. The digits were 1.5 cm in height and appeared in the center of the graphics terminal's screen. The main test program consisted of two subroutines, forward digit and backward digit recall.

In the forward recall condition, the test started with a presentation of three digits and proceeded to a maximum difficulty of nine digits. The subroutine for backward serial recall started by presenting two digits and progressed to a maximum difficulty of eight digits. Each test trial consisted of a random grouping selected from the digits 2 through 9. The test trials did not contain repetitions or sequential progressions. The test continued until either two trials at the same difficulty level were answered incorrectly, or the subject had reached the maximum difficulty level.

The short-term memory test for serial letter recall was also based on the WAIS. The testing and sequence were the same as for the digit recall test. Both letter subprograms (forward serial recall, backward serial recall) started, however, by presenting 4 letters, and could progress to a maximum of 12 letters.

All letters were uppercase and 1.5 cm in height. Each trial consisted of a random grouping of letters, consonants only. The trials did not contain repetitions or sequential progressions. The test followed the same format as digit recall, with the criteria for ending the test being either two incorrect answers at the same difficulty level or the attainment of the maximum difficulty level.

The reasoning test was a 4-min test based on grammatical transformations (Baddeley, 1968; Carter, Kennedy, and Bittner, 1981). The subject read a statement followed by a letter pair, and then decided if the statement matched the letter pair. The following are examples of the statements presented:

True or false: D follows C. *CD*
True or false: C is followed by D. *DC*
True or false: D precedes C. *CD*
True or false: C does not precede D. *DC*

The statements comprised all possible combinations of the following six binary conditions: true or false, active or passive, precedes or follows, C or D mentioned first in the statement, letter pair CD or DC, and positive or negative. The computer randomly selected statements, waited for a response (T for true, F for false), and then continued to present statements until 4 min had elapsed.

Procedure

Upon arrival, the subject sat while being fitted with chest electrodes. The test involved 10 min of treadmill running at 80% $\dot{V}_{O_2max}$ (calculated for each subject), followed by the psychomotor or mental tests administered while the subject rested. The gas mixtures were one of the following: control; 4% CO_2, 21% O_2; 5% CO_2, 21% O_2; 4% CO_2, 50% O_2; 5% CO_2, 50% O_2. Gas mixtures were inhaled from the onset of running to the end of the post-exercise tests, which could last up to 6 min.

Subjective reports of feelings and/or discomfort were recorded after each session. All questions regarding the tests were answered at this time.

The procedures specific to the three separate substudies are described as follows.

TABLE 2

Mean Values of Psychomotor Responses during Exercise at 80% $\dot{V}_{o_2max}$ while Inhaling 5% CO_2 in 50% O_2 (CO_2)

	Auditory Reaction (ms)							
	During Running		During Sixth Minute of Recovery		Choice Response (ms) During Recovery		Rotary Pursuit(s) During Recovery	
Subject	Control	CO_2	Control	CO_2	Control	CO_2	Control	CO_2
1	180	190	169	190	593	629	10.12	8.88
2	195	224	200	170	472	522	9.88	9.47
3	179	185	171	171	531	595	11.04	11.54
4	177	187	171	181	483	559	9.22	9.50
5	171	192	151	165	686	685	9.66	7.38
6	205	225	163	179	719	754	11.01	11.27

A block of auditory reaction time (ART) and rotary pursuit (RP) tests served as controls. These were administered prior to exercise. A second block of ART trials began at the eighth minute of exercise. A second block of RP trials, and a third and fourth block of ART trials were administered during the recovery period. The rotary pursuit tests were administered with the subjects seated.

During a separate test session, the choice response time (CRT) tests were administered with the subjects seated. The CRT test was given only during the 4% CO_2 and 5% CO_2 in 50% O_2 conditions. The sequence is shown in Figure 1. Subjects received one block of 24 trials prior to exercise, and the second block in the postexercise period.

For the short-term memory tests the subjects were divided into two groups differentiated by order of recall (e.g., forward-backward, or backward-forward serial recall). The sequence of testing is depicted in Figure 1. Upon reporting for the first session, the subject took a shortened practice test. The STM test program was initiated by the experimenter after 10 min of exercise. All trials, feedback (e.g., correct, incorrect answer), and prompts (e.g., "please enter your response, then press return") were programmed and delivered via the graphics terminal. The av-

TABLE 3

Means and Standard Deviations for the Number of Digits Recalled (S) and the Number of Errors (E) per Test for CO_2-O_2 Inhalation

		Control		4% CO_2 21% O_2		5% CO_2 21% O_2		4% CO_2 50% O_2		5% CO_2 50% O_2	
		S	E	S	E	S	E	S	E	S	E
Test 1	$\bar{X}$	7.6	1.0	7.7	1.2	7.6	1.8	7.0	1.4	7.4	1.6
	SD	0.89	1.00	0.84	1.10	1.14	0.45	0.71	0.55	1.14	0.89
Test 2	$\bar{X}$	7.2	0.6	7.4	1.0	7.8	0.8	7.6	0.8	7.2	1.4
	SD	1.30	0.56	1.14	1.00	0.84	0.84	1.14	0.84	1.30	1.14
Combined 1 and 2	$\bar{X}$	7.4	0.8	7.6	1.1	7.7	1.3	7.3	1.1	7.3	1.5
	SD	1.07	0.79	0.97	0.99	0.95	0.82	0.95	0.74	1.16	0.97

erage test time per subject was 6 min. The number of errors and maximum difficulty level obtained (number of digits or letters correctly recalled) were recorded for each subject.

The STM test for serial letter recall was administered to the same subjects during different sessions. The subjects reported for 10 sessions.

Upon reporting for the first session of the reasoning substudy, the subjects received a 2-min practice test. The reasoning test was administered after exercise, and lasted 4 min (see Figure 1). The subjects were tested at the same time of day for all five sessions.

RESULTS

A representative sample of the CO_2 inhalation test data for the psychomotor tests is shown in Table 2. There were no significant differences between controls and CO_2 conditions for the auditory reaction time and rotary pursuit tests. A significant difference was observed for the choice response time test, ($F = 4.21$, $p < 0.05$), but only during inhalation of 5% CO_2 in 50% O_2. Aside from this difference, no trends or consistencies were observed. The difference indicated a somewhat slower response during CO_2 inhalation, but only for the 5% CO_2 condition.

The data for the STM tests are shown in Tables 3 and 4. The first and second STM test, for digit or letter recall, did not differ significantly in terms of the number of items recalled per condition. A significant difference was found between the number of errors ($F = 3.35$, $p < 0.10$) for the first and second STM tests for digit recall (Table 3), with higher error rates associated with the first test. However, no differences were observed in the number of errors between CO_2-O_2 experimental conditions. The other difference ($F = 4.35$, $p < 0.05$) was between subjects for average response time (in STM letter recall tests).

The data for the reasoning tests are shown in Table 5. No significant differences were

TABLE 4

Means and Standard Deviations for the Number of Letters (S) Recalled, the Number of Errors (E) per Test, and the Elapsed Test Time (ELT)

		Control			*4% CO_2 21% O_2*			*5% CO_2 21% O_2*			*4% CO_2 50% O_2*			*5% CO_2 50% O_2*		
		S	E	ELT	S	E	ELT	S	E	ELT	S	E	ELT	S	E	ELT
Test 1	$\bar{X}$	7.4	1.4	86	5.8	1.4	55	6.2	1.2	58.8	5.2	1.4	79.6	5.8	1.2	49.6
	SD	2.79	0.55	43.29	2.05	0.55	27.49	1.3	0.45	31.66	1.92	0.89	31.96	0.84	0.45	10.41
Test 2	$\bar{X}$	6.4	1.6	78.6	6.2	1.4	60.6	3.6	1.2	39	5	1.8	77.4	4.6	1.4	44.8
	SD	2.07	0.89	56.9	1.1	0.55	11.9	2.07	0.45	14.37	3.6	0.84	63.72	2.88	0.55	23.03
Combined 1 & 2	$\bar{X}$	6.9	1.7	82.3	6.0	1.4	57.8	4.5	1.2	36.9	5.1	1.6	78.5	5.2	1.3	47.2
	SD	2.38	0.82	47.83	1.56	0.52	20.16	2.27	0.42	21.13	2.72	0.84	47.54	2.88	0.48	17.03

TABLE 5

Means and Standard Deviations for the Number of Statements Completed, Errors per Session, and the Average Response Time per Question (in Seconds)

	Control	*4% CO_2 21% O_2*	*5% CO_2 21% O_2*	*4% CO_2 50% O_2*	*5% CO_2 50% O_2*
Statements Completed	51.50 ± 9.50	42.00 ± 14.7	41.00 ± 11.60	51.50 ± 14.0	43.75 ± 13.30
Number of Errors per Session	1.25 ± 0.96	1.50 ± 0.58	2.00 ± 1.40	2.00 ± 0.82	2.75 ± 2.20
Average Response Time per Question	4.78 ± 0.90	6.36 ± 2.60	6.29 ± 2.10	4.94 ± 1.40	5.80 ± 1.50

found for the number of errors or statements completed in the five conditions. However, the control and 4% CO_2−50% O_2 conditions had the same average number of statements completed, whereas in the other three conditions (4% and 5% CO_2, 21% O_2; 5% CO_2, 50% O_2), fewer statements were completed but the difference failed to reach statistical significance ($p > 0.10$).

DISCUSSION

The finding that there was no deterioration in psychomotor and mental performance as a result of inhalation of up to 5% CO_2 has important positive implications.

Unlike CO, which is an external toxic gas, CO_2 is produced internally, yet it could affect performance if it were to be retained in the body. However, although some physiological responses such as increase in pulmonary ventilation and changes in blood flow to the brain were observed, it was interesting to find that subclinical concentration of CO_2 did not affect such complicated tasks as short-term memory, reasoning ability, and psychomotor reactions. It should be noticed that the subjects of this study were young, healthy, physically fit adult males. Age and gender might constitute important factors in the deterioration of performance during CO_2 inhalation.

The observed significant difference in errors between the first and second short-term memory tests for digit recall cannot be attributed to CO_2 inhalation. If CO_2 had caused the difference then the effect would appear in error rates between the conditions of gas mixtures. The other observed significant difference in response time for short-term memory letter recall can be explained by the large individual variability in the responses.

The use of 4-5% CO_2 levels in this study was based on some pilot observations in our laboratory, in which higher CO_2 concentrations resulted in persistent headaches after the test session. This has also been observed by others (Dripps and Comroe, 1947; Schaefer, 1963; Sechzer, Egbert, Linde, Cooper, Dripps, and Price, 1960). Therefore, we set the upper limit of this study at 5% CO_2. Even under these conditions, some subjects complained of headaches and lightheadedness. In most cases, 2 or 3 min of walking in room air would alleviate these symptoms. However, for most subjects, these symptoms gradually subsided from one session to the next, until, in later sessions, the symptoms were no longer reported. This implies that "habituation" to CO_2 is possible. The lack of deterioration in psychomotor and short-term memory performance for inhalation of up to 5% CO_2 could mean an improvement in the life-support capacity of the self-contained respirator, if higher inhaled CO_2 concentrations are allowed. Increasing the permissible CO_2 levels would enable longer usage of the CO_2 scrubbing system, and, since oxygen supply is not restricted for many respirators, the usefulness of the SCR would be prolonged.

In summary, our results are encouraging with respect to acceptance of CO_2 in inhaled air. Inhalation of subclinical concentrations of CO_2 did not affect mental and psychomotor performance. It should also be noted that the short-term memory test was sensitive enough to show the effects of strenuous exercise, whereas CO_2 did not cause a decrement in performance.

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