CARBON DIOXIDE RETENTION INSIDE MOTOR-CYCLE HELMETS

by

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The protective properties of motor-cycle helmets are well documented (1, 2, 3). Helmets offering full-face protection may, however, have some unwanted qualities. Because of interference with the exchange of gas between the lungs and the ambient air, a full-face helmet may act as an external dead space, impairing the carbon dioxide (CO_2) elimination from the body. Insufficient CO_2 elimination causes an increase of the partial pressure of CO_2 (P_{CO_2}) in cerebral structures and other body tissues (hypercapnia). High P_{CO_2} levels may cause severe cerebral dysfunction, e.g., CO_2 narcosis, whereas moderate increases in P_{CO_2} may cause performance impairments and subjective symptoms of "not feeling well". Another inconvenience of hypercapnia is an increase in pulmonary ventilation, that may cause a feeling of breathlessness (4). The use of a full-face helmet may thus, if it acts as an external dead space, have an adverse effect on motor-cycle riding ability.

Dead space properties of a full-face helmet are manifested in a retention of CO_2 inside the helmet. Because of poor gas exchange between the helmet and the ambient air, the metabolically produced CO_2 exhaled in the helmet is accumulated, causing an increase in the CO_2 concentration inside the helmet. The increase in CO_2 is determined not only by factors influencing the gas exchange, such as clothing, speedwind etc, but also by the amount of CO_2 produced. This means that an increased metabolism due to, e.g., physical work accentuates the retention of CO_2 inside the helmet.

The relationship between the P_{CO_2} of inspired air and body tissues during resting conditions is well established (4). However, since driving a motor-cycle requires physical work, the interactive effects of an external dead space and exercise must be studied to determine the CO_2 retention inside motor-cycle helmets.

The present study can be divided into two parts. In the first part motor-cycle helmets are tested in regard to CO_2 retention to determine whether the helmets meet the requirements concerning CO_2 concentration stipulated by the Swedish National Board of Occupational Safety and Health. The hygienic limit value for CO_2 set by the Board is 0.5% for industrial premises, and 1% when exposure is limited to 15 min (5). In the second part the interactive effects of an external dead space and exercise on the P_{CO_2} in the body and on performance are studied.

PART I

Methods

To test motor-cycle helmets in regard to possible CO_2 retention, nine commercially available helmets were selected by the Swedish Standard Association. The sample included five full-face helmets and four open-face helmets, the latter serving as a control group.

The CO_2 concentration inside the helmets was recorded by a Beckman LB2 CO_2 analyzer. To assure that the recorded CO_2 concentration was representative for that of the inhaled air, the subjects were instructed to breath through the nose where the sampling was made via a tube taped to the upper lip.

The helmets were tested in the laboratory as well as under field conditions. The laboratory tests were made (a) in a breathing-simulator supplied by the National Defence Research Institute (Fig. 1), and (b) on 11 healthy subjects (age 18-30 years) at rest and during exercise to study the effects of increased CO_2 production under controlled conditions. During exercise, the subjects were pedalling on a cycle ergometer at a work load of 50 W, corresponding to the physical work executed by a roadcruising motor-cyclist (6, 7).

Testing under field conditions was made on 11 healthy subjects (age 18-27 years) on motor-cycles to study the effects of outdoor clothing and speedwind. Recordings were made with the motor-cycles stationary and at speeds of 30, 50 and 70 km/h. To minimize effects of the ambient wind, which varied between 0-4 m/s, recordings were made under head- and tailwind conditions.

Results

1. The four open-face helmets, with the visor shut, showed no measurable CO_2 retention.

2. All five full-face helmets showed mean CO_2 concentrations well

exceeding the hygienic limit value of 1% under the following conditions (Table 1):

a) in the breathing simulator (Fig. 2),
b) in the laboratory tests at rest and during exercise (Fig. 3),
c) in the field tests with the motor-cycles stationary and, in two of the helmets, at 30 km/h (Fig. 4).

If individual recordings are examined, four of the helmets showed CO_2 concentrations exceeding the hygienic limit value of 1% at 50 km/h, and two of these showed too high concentrations at 70 km/h. In eight instances the CO_2 concentration exceeded 3%, the highest concentration being 3.9%, recorded in the laboratory during exercise.

3. Effects of exercise

Increased CO_2 production due to exercise resulted in higher CO_2 concentrations in four of the helmets (Fig. 3).

4. Effects of outdoor clothing

Compared to the laboratory tests at rest, higher CO_2 concentrations were recorded in the field tests with the motor-cycles stationary (Fig. 2). This indicates a further impairment of the gas exchange, possibly due to the use of obstructive clothing.

5. Effect of speedwind

Although the gas exchange was improved by the speedwind when driving, two of the helmets showed CO_2 concentrations exceeding the hygienic limit value of 1% (Fig. 4).

PART II

Methods

To investigate the interactive effects of an increased dead space and mild exercise on P_{CO_2} in the body and on performance, seven healthy male subjects (mean age 32 years) were studied in the laboratory with respect to:

Physiological variables	Performance variables
End-tidal P_{CO_2}	Psychomotor (Tracking test)
Pulmonary ventilation	Cognitive (Arithmetic test)

In addition, breathing resistance, partial pressure of oxygen, and heart rate were monitored.

The effect of an increased dead space was simulated by changing the CO_2 concentration of the inspired air. The subjects were exposed to three CO_2 levels: 0% (normal air), 3%, and 5%, both at rest and during exercise. The 0% level served as control, the 3% level corresponded to the worst cases of CO_2 retention observed inside the tested helmets, and the 5% level was included to obtain further data for trend analysis.

The subjects were seated in a chair inhaling humidified gas from a large bag via a large-bore tubing and a low-resistance respiratory valve. During exercise the subjects were pedalling a cycle ergometer at a work load of 50 W (6, 7). End-tidal P_{CO_2} was recorded by a Beckman LB2 CO_2 analyzer. Sampling was made via a tube connected to the expiratory side of the respiratory valve. Pulmonary ventilation was determined by the Douglas bag method.

Two types of performance tests were used, namely (a) a tracking test for evaluation of psychomotor performance, and (b) an arithmetic test to evaluate effects on higher mental ability. Intercorrelation of the two tests for the 7 subjects was 0.142.

The tracking test was based on a microcomputer, generating a target moving according to a pattern with random parameters on a cathode ray tube. The task was to track the target as closely as possible for 2.5 min by means of a joy-stick controlled dot. The distance to the target was recorded and the average distance for the last two minutes was computed to obtain the test score.

The arithmetic test was a paper and pencil test with equivalent forms, each made up of 52 problems requiring a multiplication and an addition or a subtraction. The test score was the number of correctly solved problems in 2 min.

Each subject was signed to one of six different sequences of CO_2 exposure (0-3-5%, 0-5-3%, etc) and was tested on a single day. Each session started with practice trials in order to stabilize performance on the psychomotor and arithmetic tasks, test-retest correlations for the 7 subjects after practice was 0.781 and 0.845, respectively. The practice trials were followed by six experimental trials performed at 10 min intervals, two trials (rest/exercise or exercise/rest) for each CO_2 level. Each trial lasted for 12 min, 7 min to establish steady state with respect to end-tidal P_{CO_2}, and 5 min for the performance tests which always started with the tracking test.

Data from the various CO_2 and work-load conditions were analyzed by the method of paired comparisons (Student's t-test).

Results

1. Physiological effects

Values referred to are means of the measurements obtained during the 6th and 7th min of the experimental trials.

End-tidal P_{CO_2} and pulmonary ventilation showed significant increases ($P<0.02$) during exposure to 3% CO_2 as well as to 5% CO_2, both at rest and during exercise (Figs. 5-6).

The effects relevant to motor-cycle driving with a full-face helmet, i.e., the interactive effects of exposure to 3% CO_2 and 50 W exercise, were:

End-tidal P_{CO_2} increased by an average of 1.1 kPa (8.4 mm Hg) (Fig. 5). Thus a moderate hypercapnia.

Pulmonary ventilation increased from an average of 10.3 l per min to an average of 34.6 l per min (Fig. 6).

2. Effects on performance

The psychomotor and arithmetic tests failed to show significant performance impairments during exposure to 3% CO_2, both at rest and during exercise. Both tests, however, showed significant ($P<0.02$) performance impairments during exposure to 5% CO_2 but only during exercise (Figs. 7-8).

Discussion

The hygienic limit value for CO_2 is 0.5% in daily work, and 1% when working is limited to 15 min. The CO_2 retention in all full-face helmets tested exceeded 0.5% under laboratory conditions and also when driving at a speed of 30 km/h.

Four of the helmets were tested at 50 km/h and two of these at 70 km/h. In all these cases the CO_2 concentration in the inhaled air exceeded 0.5%. Motor-cycle driving under normal conditions is, however, not a full day's occupation, but is usually undertaken for more than 15 min.

The results showed both interindividual and intraindividual variations. It is likely that this was due to differences in, e.g., the posture of the body, the clothing, the ways to put on the helmet, the helmet fitting etc. Iho et al. (8) reported figures that differ somewhat from the values observed in this study. They used another measuring technique, which also can influence the results. However, both the values of Iho et al. and those of the present study are too high according to current hygienic limit values, especially in case a CO_2 level of 0.5% is considered the limiting value for traffic situations.

Several adverse effects of high CO_2 concentration in inhaled air are well-known, e.g., hypercapnia and breathlessness. When driving an unstable vehicle like a motor-cycle, it seems unsatisfactory to be under the influence of such physiological stresses. For a person unconscious due to a motor-cycle accident head trauma, the situation may be even worse, especially if the respiratory response to increased CO_2 is impaired. Even a small increase in arterial P_{CO_2} may lead to severe brain oedema and unrepairable brain damage.

Conclusions

The study shows that the CO_2 concentration inside full-face motor-cycle helmets is too high in many true traffic situations. The following suggestions seem justified.

1. The visor should be so designed that it can be opened easily as soon as the driver stops, e.g., at a red light.
2. A ventilation opening should be tested on different parts of the helmet to find the best possible ventilation with the least possible draught and with maintenance of an acceptable sound level.
3. The results of the investigation show that the standards of approval for helmets should be completed with a standard for maximum CO_2 concentration inside the helmets.
4. Moped riders should be recommended to use either open-face helmets or full-face helmets with the visor open, because the ventilation of most full-face helmets with the visor closed is dissatisfactory at low speeds.
5. In the event a person is injured and loses consciousness, the visor should be easy to open, as a high concentration of CO_2 in an unconscious person is extremely dangerous to the brain functions.

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HELMET	LABORATORY TESTS									FIELD TESTS											
	BREATHING SIMULATOR			SUBJECTS						SUBJECTS											
				REST			EXERC. (50W)			STATIONARY			30 km/h			50 km/h			70 km/h		
	Mean	SD	n	Mean	SD	n	Mean	SD	n	Mean	SD	n	Mean	SD	n	Mean	SD	n	Mean	SD	n
I	1.8	.29	5	1.3	.37	9	1.6	.57	9	1.8	.47	7	.9	.39	7	.7	.21	7	*		
II	1.3	.14	5	1.4	.42	5	1.9	.55	5	1.6	.37	4	.9	.22	4	*			*		
III	2.5	.19	4	2.2	.46	3	2.6	.55	3	2.6	.57	7	1.4	.52	7	1.0	.49	6	1.1	.14	2
IV	2.0	.07	5	2.2	.28	11	2.1	.50	11	2.6	.32	4	1.6	.54	6	1.8	.14	2	1.8	.07	2
V	1.3	.04	4	1.1	.36	10	1.4	.28	10	1.7	.25	7	.7	.32	6	.9	.39	8	*		

TABLE 1. Mean CO_2 concentration inside five full face helmets, tested in the laboratory and in the field (* = no tests performed).

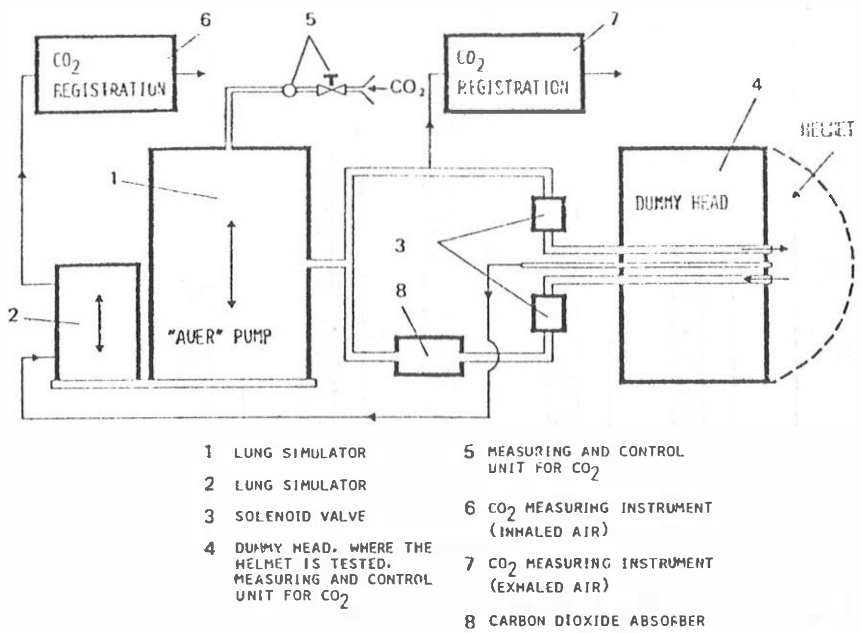

Fig. 1. Breathing simulator

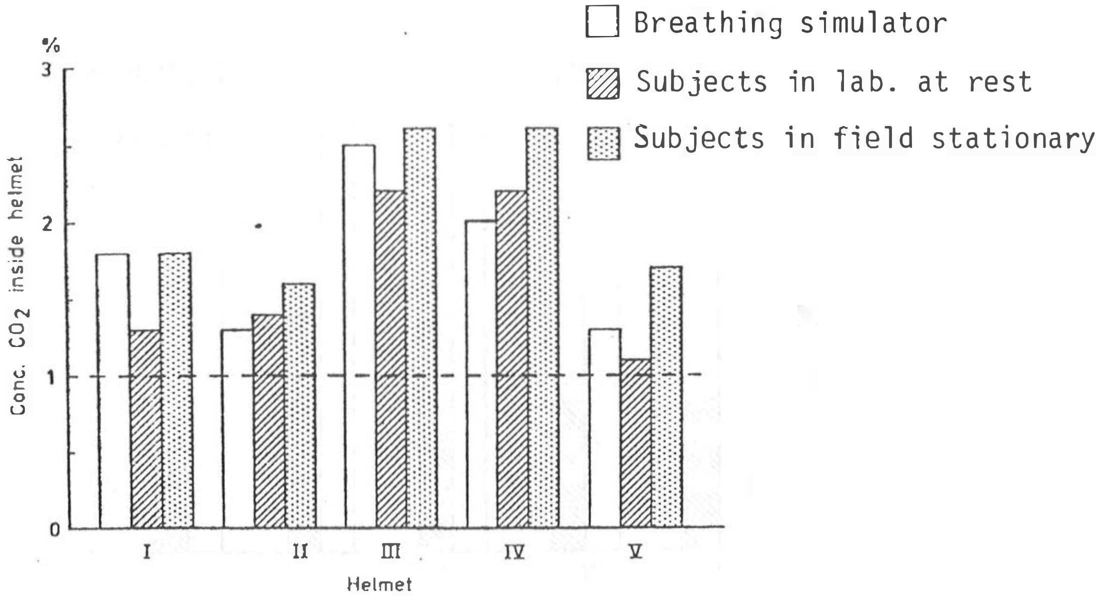

Fig. 2. Mean CO_2 concentration inside five full-face helmets tested in a breathing simulator and on subjects at rest, under laboratory and field conditions. The dotted line marks the hygienic limit value for CO_2 for 15 min work determined by the Swedish National Board of Occupational Safety and Health. For a full day's work the limit is 0.5%.

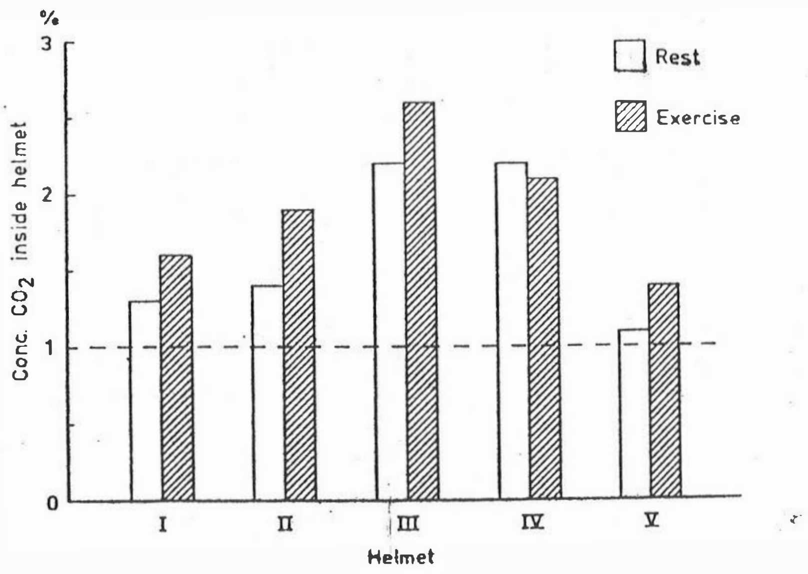

Fig. 3. Mean CO_2 concentration inside five full face helmets tested in the laboratory. on subjects at rest and during exercise (50 W).

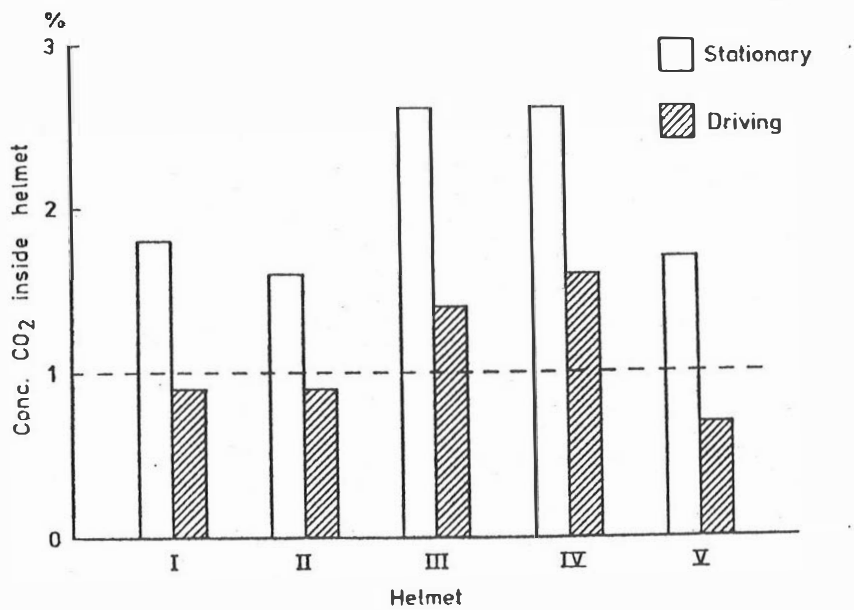

Fig. 4. Mean CO_2 concentration inside five full face helmets tested in the field on subjects while stationary and at 30 km/h.

The dotted line marks the hygienic limit value for CO_2 for 15 min work determined by the Swedish National Board of Occupational Safety and Helath. For a full day's work the limit is 0.5%.

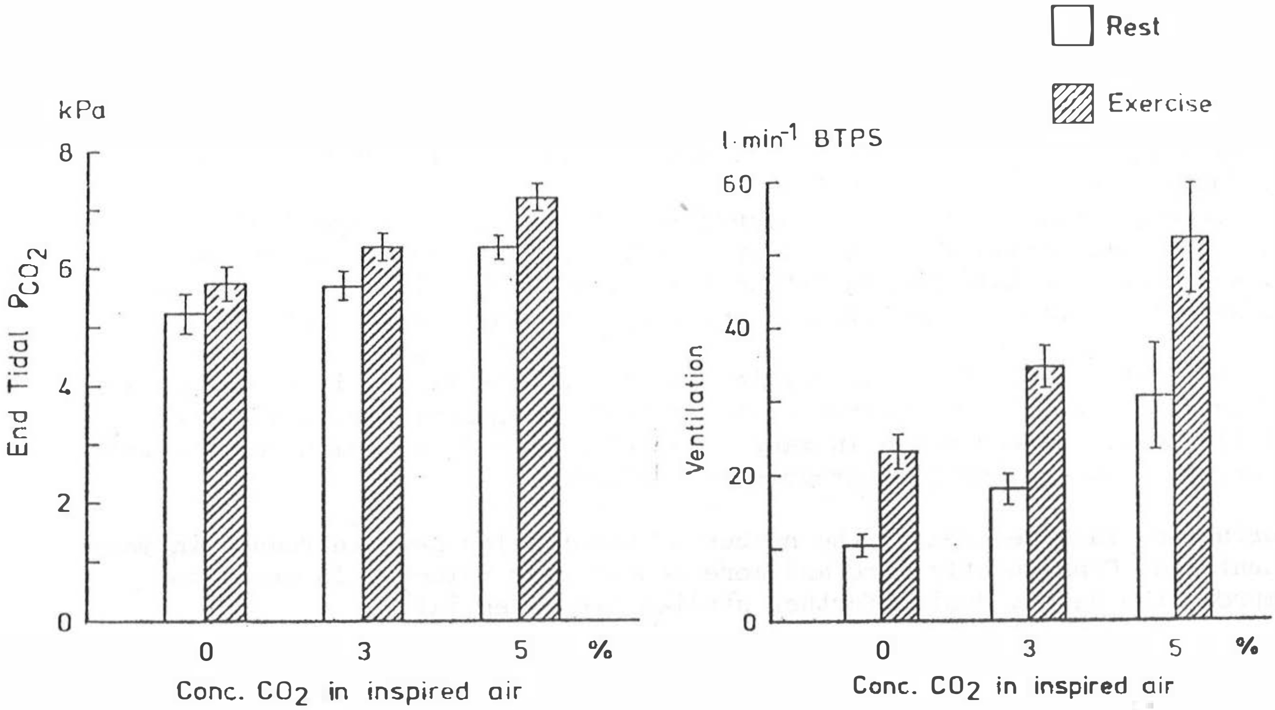

Fig. 5-6. Mean end-tidal P_{CO_2} and pulmonary ventilation recorded during the sixth and seventh min of exposure to 0, 3 and 5% CO_2. Vertical bars = SD.

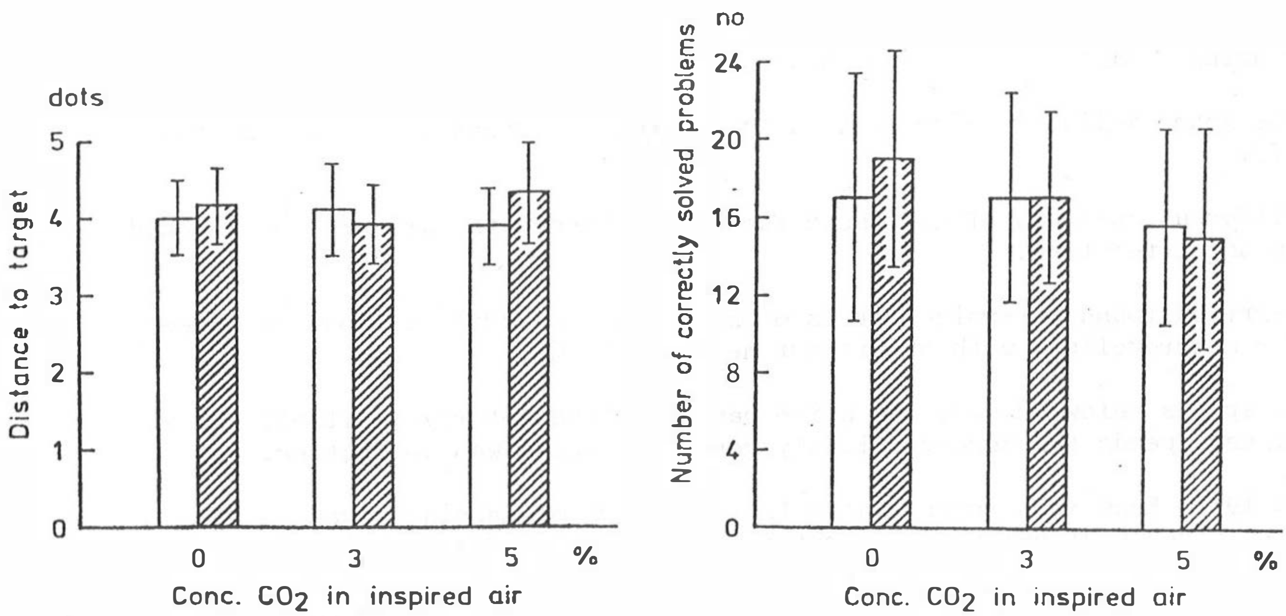

Fig. 7-8. Mean test scores for the tracking test and the arithmetic test recorded under exposure to 0, 3, and 5% CO_2. Vertical bars = SD. (Note that in Fig. 7 - tracking test, a higher value indicates an impairment of performance.)