Part Three: Effects of Chronically Elevated CO_2 on Mental Performance During 26 Days of Confinement

DIETRICH MANZEY, DIPL.-PSYCH, DR.,
AND BERND LORENZ, DIPL.-PSYCH, DR.

MANZEY D, LORENZ B. *Effects of chronically elevated CO_2 on mental performance during 26 days of confinement.* **Aviat Space Environ Med 1998; 69:506–14.**

Background: Short-term exposures to increased CO_2 concentrations in breathing air up to 5% are assumed to have only negligible behavioral effects. In the present study it was examined to what extent prolonged exposures to moderately elevated levels of CO_2 in the ambient air affect human performance. ***Method:*** During two phases of 26 d of confinement in a diving chamber a group of four subjects was exposed to two different levels of CO_2 (0.7% and 1.2%). Cognitive, visuo-motor, and time-sharing performance were assessed repeatedly before, during, and after the exposure by means of a task battery including grammatical reasoning, memory search, unstable tracking, and dual tasks. In addition, subjective workload and mood ratings were collected. A second group of four subjects served as a control group who performed the different tasks on the same 26-d time schedule without being exposed to confinement and elevated CO_2. ***Results:*** During exposure to 0.7% CO_2 only tracking performance was slightly disturbed compared with baseline levels, whereas performance of the control group remained stable. The time course of this effect suggested that it was related to chamber adaptation rather than to increased levels of CO_2. During exposure to 1.2% CO_2, tracking performance again was significantly impaired. In contrast to the lower exposure condition, the time course of this effect appeared to be related to the CO_2 load and covaried with a loss of subjective alertness. ***Conclusions:*** The study indicates that at least visuomotor performance might be affected by CO_2 concentrations in the ambient atmosphere as small as 1.2% if subjects are chronically exposed to these concentrations in a confined environment. The strength of these effects, however, does not appear to be of operational relevance.

SPACE VEHICLES and habitats are equipped with integrated life-support systems (LSS) which are designed to provide environmental conditions enabling humans to live and work while at the same time preventing adverse effects on their health and safety. Continuous supply of oxygen and removal of carbon dioxide (CO_2) produced by cellular metabolism and exhaled by the station crew is an important task of the LSS. Due to technical limits, however, these systems are generally not able to remove CO_2 down to levels of the "normal" ambient atmosphere, i.e., in the range around 0.03%. Consequently, the proportion of CO_2 in the breathing atmosphere of space habitats must be expected to be much higher and may vary between about 0.3% and 1.5% (19). Within the design of the International Space Station, NASA's system specification requires that during normal on-orbit operations the 24-h average exposure of crewmembers to CO_2 is at or below 0.7% which is equivalent to a partial pressure of 5.3 mmHg (22). This CO_2 concentration is well below the level where, according to the literature, a loss of performance might be expected. A study by Sayers et al. (17) indicates that performance decrements and mood changes may be observable only with CO_2 concentrations above 5.5%. Sheehy et al. (18) did not find any performance changes during a 16-min period of breathing 5% CO_2. Henning et al. (8) examined the influence of short-term exposures (5–7 min) to 6% CO_2 in normoxic and hyperoxic (100% O_2) gas mixtures and found simple and choice-reaction times not to be affected. In a study focussing on interactive effects of CO_2 and nitrogen narcosis, Fothergill et al. (6) examined to what extent cognitive and psychomotor functions are affected by end-tidal partial pressure of CO_2 in a range between 29–57 mmHg induced by a re-breathing circuit. Impairments of performance were found only at high end-tidal CO_2 tensions (57 mmHg), and were primarily reflected by a general slowing of performance. Accuracy of processing was not affected by CO_2. However, since these few foregoing results were derived from rather short-exposure times (7 to 80 min), they might underestimate the impact of chronic exposures to moderatley elevated CO_2 concentrations during prolonged stays in a space habitat or any other environment with a closed atmosphere. Early studies of Weybrew (20,21) and Faucett and Newman (cf., 20) provide at least some hints that during prolonged exposures subtle behavioral effects can already be observed at CO_2 levels as small as 1.5% to 3%, but are difficult to interpret due to methodological constraints.

The present paper presents a study that particularly aimed at assessing potential performance decrements due to *chronically* elevated levels of CO_2 in the range

From the DLR-Institute for Aviation and Space Medicine, Department of Aviation and Space Psychology, Hamburg, Germany.

This manuscript was received for review in September 1996. It was revised in July 1997. It was accepted for publication in August 1997.

Address reprint requests to: Dr. Dietrich Manzey, who is Scientist at DLR-Institute of Aviation and Space Medicine, Dept. of Aviation and Space Psychology/Project Manager of Space Psychology Branch, Sportallee 54a, 22335 Hamburg, Germany.

expected in space habitats during prolonged confinement. As a contribution to a collaborative international study (19), two experiments were conducted, each involving 26 d of confinement in an unpressurized hyperbaric chamber. During these confinement periods, levels of CO_2 in the ambient air were elevated to 0.7% (first experiment) and 1.2% (second experiment) for 23 d. Performance was assessed by means of a computerized battery of cognitive and visuo-motor tasks which in prior field and laboratory experiments have been proven to be sensitive to behavioral effects of environmental stressors (1), and which have already been used for research in space and space-analog environments (11–15). Processing functions assessed were: a) complex cognitive functions (speed and accuracy of logical reasoning); b) elementary cognitive functions (speed and accuracy of memory retrieval); c) visuo-motor functions (accuracy of fine manual control movements); and d) time-sharing functions (efficiency of dual-task performance). The battery also included mood rating scales (4), and the NASA Task Load Index (NASA-TLX) for the evaluation of subjective workload (7).

EXPERIMENT 1

METHODS

Subjects

The study involved two groups of healthy subjects, the experimental group and a control group. The experimental group consisted of four male university students, aged 22–29 yr. They were selected from a pool of 30 volunteers who had applied for the study. Selection was based on medical examination, personality questionnaires, and a 1 h psychological exploration, in order to ensure good health and a sufficient amount of motivation to participate in the study, as well as high level of psychological compatibility between crewmembers. Subjects were informed of possible discomfort and potential risks and signed a consent form according to the Declaration of Helsinki. The control group consisted of four male university students aged 22–27 yr. They were trained and tested according to the same time schedule as the experimental group but continued to live according to their normal pace of life. Both groups were paid for participation in the study.

Performance Tasks and Subjective Measures

Performance tasks were selected from the AGARD battery of Standardized Tests for Research with Environmental Stressors (STRES) (1). Four tasks were used.

Grammatical reasoning task (GRT): This task required complex logical reasoning operations based on grammatical transformations. Each trial consisted of two statements describing a sequence of three symbols (e.g., & BEFORE *; * AFTER #) presented together with a certain set of three symbols (e.g., & * #). The subject had to evaluate whether the two statements were true for the given set of symbols. If the truth value of both statements were the same, the subject had to press a key for "same." If the truth value differed (one statement true, the other false) they had to press a key for "different." Mean correct response times and percentage of errors were computed for each 3-min run.

Memory search task (MS2; MS4): This task was used to evaluate short-term memory functions by means of reaction time data. Subjects had to memorize a set of letters (the memory-set) and were then presented a series of single letters. By pressing a key for either "yes" or "no," subjects had to indicate whether or not the letter belongs to the memory set. Fixed memory sets of two (MS2) and four (MS4) letters were used in separate 3-min blocks of trials. Mean correct response times and percentage of errors were computed as the performance score for each block.

Unstable tracking task (UTT): In this task a horizontally moving cursor had to be centered by means of a joystick within a marked target located in the middle of the screen. The inherent dynamics of the tracking loop included a positive feedback of the tracking error resulting in system instability which was further increased by a divergent element (lambda = 2) (2,9). Deviating from the AGARD protocol, an external disturbance input consisting of the sum of five sinusoids was introduced into the tracking loop in order to enhance and to homogenize the difficulty of the task. Performance was quantified by calculating the root-mean-square tracking error (RMSE) integrated over blocks of 1 s and averaged across each 3-min run.

Dual-task (DT2; DT4): This task required to perform the UTT simultaneously with MS2 or MS4, respectively, resulting in two versions of dual-task with different memory-load. Subjects were instructed to equally divide their attention between both tasks. Performance scores were the same as for the single tasks.

Subjective measures included ratings of subjective workload perceived during task performance and mood ratings. The NASA Task-Load-Index (TLX) (7) was used for subjective workload assessment. It consists of six different 2-point rating scales which require a subjective evaluation of different workload dimensions (mental demands, physical demands, time pressure, own performance, effort, frustration). In addition, the subject has to evaluate the contribution of each dimension to the overall workload by means of pairwise comparisons. Mood ratings were recorded by 16 ten-point bipolar rating scales which have originally been described by Bond and Lader (4).

Presentation of subjective mood and workload scales, performance tasks, as well as response recording and scoring of performance data (reaction times, tracking error) were controlled by an IBM-compatible laptop (Unisys Powerport 1386 SX). All performance tasks were generated using a commercially available code-generating system (ERTS™, BeriSoft, Frankfurt/Main, Germany) (5), and were presented on the screen of the laptop. Responses for MST and GRT had to be given with the left hand by pressing one of two keys ("D" and "W") on the keyboard. The tracking task had to be controlled by a joystick which was located on the right side of the laptop.

Experimental Design and Procedure

The experiment included 16 experimental sessions. The sessions for the experimental group included 3 pre-confinement sessions of baseline data collection (BDC), 12 sessions during the 26-d confinement period, and 1 post-confinement session. During the confinement period experimental subjects lived together in an unpressurized hyperbaric chamber, which had already been used as a space habitat analog for another ground-based study, and which consisted of a man lock, a living/sleeping chamber, a sanitary section, and a third chamber on a lower level (19). CO_2 level in the chamber was as close to normal as possible (<0.2%) on day 1, 2 and 26, and at 0.7% on the other days. Data were collected on days 1, 3, 5, 8, 9, 12, 15, 17, 19, 22, 24, 26. During these assessments subjects worked on their own at a small table in the man lock where disturbances by other crewmembers or ongoing activities could be avoided. Pre-confinement BDC sessions took place on days −7, −5, and −3 before entering the hyperbaric chamber complex. One post-confinement BDC session took place 3 d after leaving the chamber. BDC sessions were conducted in a room outside the chamber, but under otherwise comparable conditions. Experimental sessions for control subjects were distributed across 6 wk according to the time-line of experimental group, and were conducted in an university laboratory.

Each experimental session lasted about 30 min. At the beginning of each session all subjects completed the mood ratings. Two schemes of task sequence were used in order to control for possible effects of serial order. Scheme A: GRT, MS2, DT2, UTT, MS4, DT4; scheme B: UTT, MS4,DT4, GRT, MS2, DT2. In each group half of the subjects worked on scheme A and on scheme B, respectively. Within subjects the task sequence and time-of-day of testing remained stable. Duration of a single test run was fixed to 3 min for each task. The inter-task interval was controlled by the subject and differed between 20 s and 1 min. No performance feedback was provided during the experimental sessions. On completion of the performance tasks subjects received the NASA-TLX items.

In order to control for possible practice effects which might mask decrements in the performance tasks, the experimental phase was preceded by a practice phase. Practice of the experimental group comprised a total number of 15 sessions that started 6 wk before entering the chamber complex. Training of control subjects was conducted in a laboratory at their university and corresponded in all relevant aspects to the training of the experimental group.

Dependent Variables and Statistical Analyses

Mood scores for each subject and experimental session were calculated for three different dimensions: alertness, contentedness, and relaxation. These dimensions were derived from a factor analysis (principal components) of the 16 subjective mood rating scales across subjects and experimental sessions and correspond to the underlying factor structure of these scales reported by Bond and Lader (4). Mood scores were calculated by summing across rating scales which clearly load on only one of the different mood factors. Overall indices of subjective workload associated with task performance were derived from the NASA-TLX scales by computing subjective weighted workload (WWL) scores as described by Hart and Staveland (7). Performance measures for all tasks and each experimental session were derived from reaction times, error rates and RMSE, respectively. In order to reduce skewness usually found in the distribution of reaction times and to homogenize variances, prior to statistical analysis each single reaction time for correct responses (RTc) of GRT, MS2, and MS4 was transformed by a reciprocal transformation into its corresponding response rate value RR = 60000/RTc (msec). Subjective measures and mean response rates, error rates, and RMSE for each 3-min trial of a task were statistically analyzed by repeated measures ANOVA with groups (experimental vs. control) defined as between-subject factor, and other variables like session (day of testing), memory load (two letters vs. four letters) or task-mode (single-task vs. dual-task) defined as within-subject factors. All tests involving within-subject factors were adjusted for correlations inherent in repeated measures designs by the Huynh and Feldt formulas (cf., 10). Specific hypotheses concerning CO_2-related performance decrements were tested by orthogonal pairwise contrasts.

RESULTS

Subjective Data

Mood: The time course of average alertness, contentedness, and relaxation scores for both groups are shown in the top, middle, and bottom graphs of **Fig. 1**a. Visual inspection of the graphs suggests that subjective alertness of the experimental group (open circles) decreased on reaching the mid-confinement period followed by erratical changes during later stages with two distinct drops (day 17 and day 22). This pattern differed from the fairly stable alertness scores obtained by the control group (filled circles). Subjective contentedness remained rather stable in both groups interrupted by a distinct drop in the mid-confinement session (day 12) for the experimental group. The relaxation state smoothly increased in both groups during the first 2 weeks of the experimental phase and subsequently returned gradually to baseline values. However, none of these effects could be confirmed statistically by 2 (Group) × 16 (Session) ANOVAs performed separately on the three mood variables. These analyses only revealed a significant difference between both groups in average relaxation level (main effect group: $F(1,6) = 6{,}61$; $p < 0.05$).

Workload: Subjective workload associated with task performance did not differ between groups and did not change across sessions for both groups (all F-ratios < 1).

Performance Data

Grammatical reasoning: Average response rates and error rates on consecutive sessions are shown for both groups in **Fig. 2a** (top graph). As becomes evident, mean response rates of the experimental group increased steadily across sessions, whereas the performance of the control group remained stable on a lower level. These effects were confirmed by a 2 (Group) × 16 (Session) ANOVA which revealed a significant main effect Session ($F(15,90)=2{,}72$; $p < 0.01$), and a significant Group × Session interaction ($F(15,90)=2{,}29$; $p < 0.01$). No signifi-

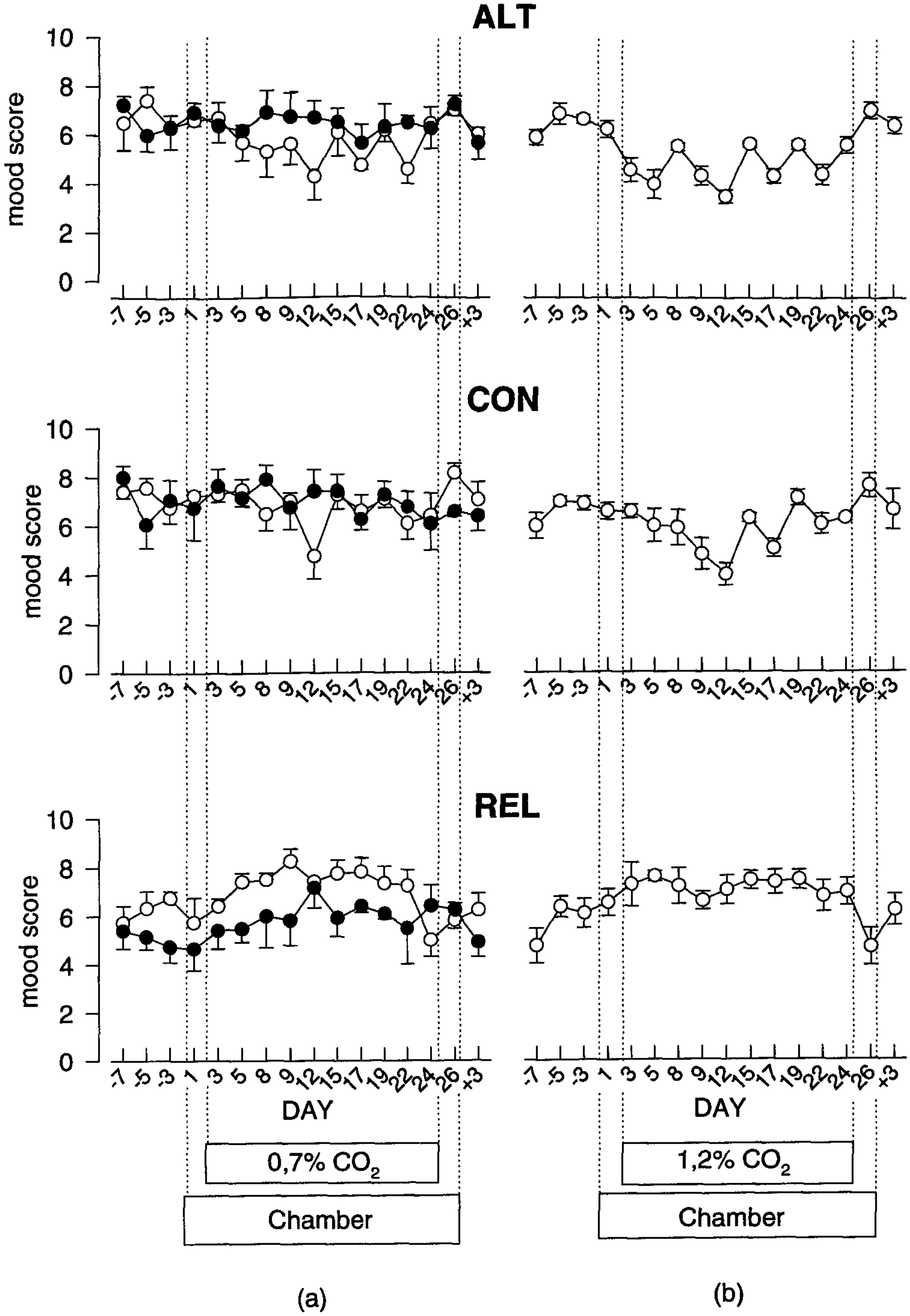

Fig. 1. Mean subjective mood scores and standard errors of means for consecutive sessions during (a) the first experiment (0.7% CO_2) and (b) the second experiment (1.2% CO_2) in the experimental group (n = 4; open circles) and the control group (n = 4; filled circles); ALT: alertness; CON: contentedness; REL: relaxation.

cant main effect was found for the between-subject Group factor. Mean error rates varied between 0.5% and 8.5% across groups and sessions. None of the experimental factors had a systematic effect on this measure (all $p(F) > 0.10$).

Memory search: Mean response rates and error rates for MST pooled across setsizes and task mode (single vs.dual) are shown in Fig. 2a (middle graph). MST data were analyzed by a 2 (Group) × 2 (Setsize) × 2 (Mode) × 16 (Session) ANOVA for both, response and error rates. Mean response rates were significantly higher in the lower memory load condition (Setsize two) and higher under single-task than under dual-task conditions (main effect Setsize: $F\ (1,6)=118,5$; $p < 0.01$; main effect Modus: $F\ (1,6)=45.81$; $p < 0.01$). No other significant main effect was found. Neither the interaction effect Group × Session, nor any other interaction became significant. MST error rates varied between 0.65% and 6.8% across groups and experimental conditions. The ANOVA of error rates revealed only two significant effects, a main effect Setsize ($F\ (1,6)= 15.32$, $p < 0.01$), and a significant Setsize × Session interaction ($F\ (15,90)= 1,92$; $p < 0.05$). Mean error rates were higher for the higher memory load condition (setsize four: 3,9%, setsize two: 3.4%), and this difference varied across sessions without displaying a systematic pattern. No differences between groups were found.

26; t (45)= 7,58; $p < 0.01$). Subjective contentedness was also significantly affected by the session factor (F (15,45)= 4,09; $p < 0.01$), and exibited a time-course with clear drops in the mid-period of confinement. Bonferroni *t*-tests showed that the ratings at days 9, 12, and 17 were significantly lower than values averaged across all pre- and post-BDC sessions (t (45)=3,55, t (45)= 5,18, t (45)=3,06; all $p < 0.05$). Subjective relaxation also changed significantly across sessions (F (15,45) = 2.93; $p < 0.01$). Orthogonal pairwise comparisons corresponding to the comparisons for the alertness ratings revealed that subjective relaxation was higher inside the chamber than outside (t (45)=3.55; $p < 0.01$), and was higher with CO_2 load than without (t (45)= 4.00; $p < 0.01$).

Workload: Subjective workload associated with task performance did not differ between groups and did not change across sessions for both groups (all F-ratios < 1).

Performance

Grammatical reasoning: The time-courses of response and error rates are shown in Fig. 2b (top graph). Mean response rates further increased steadily across sessions resulting in a significant main effect session (F (15,45)=3.83, $p < 0.01$). Error rates varied between 2.5% and 7.5%, and were not affected by session.

Memory search: The time course of the memory-search performance (averages pooled across setsizes and task-mode) is shown in Fig. 2b (middle graph). As becomes evident from this figure, speed and accuracy of short-term memory search remained stable on baseline level across all experimental sessions. A 2 (Setsize) × 2 (Mode) × 16 (Session) repeated measures ANOVA revealed only a significant main effect of Setsize (F (1,3)=47.97; $p < 0.01$ for response rates), indicating a higher performance with the lower memory load. In addition, single-task memory search tended to be faster than dual-task memory search (main effect Mode: F (1,3)=5,96; $p < 0.10$). No interaction was found between experimental factors.

Tracking: The statistical analysis of the time course of tracking error by a 3 (Mode) × 16 (Session) ANOVA only revealed a significant main effect of session (F (15,45)= 2.61; $p < 0.05$). As can be inferred from Fig. 2b (bottom graph) mean tracking performance (pooled across single- and dual-task conditions) started to decrease 2 d after elevation of CO_2 concentration in the chamber (day 5) and remained below baseline level until reaching day 17. Another decrease in tracking performance was observed at day 22. Pairwise comparisons confirmed a relationship of these tracking effects to the CO_2-load in the chamber. Tracking performance averaged across in-chamber sessions did not differ significantly from average tracking performance during outside-sessions (t (45)= 1.45; one-tailed $p > 0.10$). However, within in-chamber sessions the average tracking error was higher for sessions with CO_2 load (days 3 through 24) than for sessions without CO_2 load (days 1 and 26, t (45)= 1.68; one-tailed $p < 0.05$). Inspection of individual tracking data revealed that three of the four experimental subjects showed considerable first drops in tracking performance at days 5 or 8, respectively.

DISCUSSION

In contrast to Experiment 1, the second experiment provides several hints to detrimental behavioral effects of a prolonged exposure to a CO_2 concentration of 1.2% in the ambient atmosphere. Whereas performance in the GRT and MST, dual-task efficiency, and perceived workload remained unchanged on baseline level during exposure to 1.2% CO_2, the time-course of both subjective alertness ratings as well as tracking performance displayed a clear relationship to the introduction of CO_2-load that was not observed with the lower CO_2 concentration in Experiment 1. Compared with baseline values, subjective alertness was significantly reduced at days 3 and 5 in the chamber. Tracking performance did not vary from pre-BDC level at the first and third day in the chamber, but showed a considerable decrement at day 5, 2 d after CO_2 elevation, and remained worse than baseline performance for most of the in-chamber assessments under CO_2 load.

These behavioral effects challenge the current assumption derived from earlier studies that only CO_2 concentrations beyond 5.5% in the ambient atmosphere will entail disturbing effects on behavioral functions (17). Most of the earlier studies were conducted with much smaller exposure times (e.g., 8, 17, 18) or intermittent exposure schedules (e.g., 21). That the tracking decrements in Experiment 2 were not seen during the morning assessments of in-chamber day 3, which were conducted 3 to 4 h after elevation of CO_2, suggests that they reflect no acute, but rather accumulative or delayed effects of long-term exposure to CO_2. This would be in accordance with results from early submarine research, which has shown that, "with regard to the behavioral changes expected in humans exposed to abnormal high levels of CO_2 (1–1.5%) it appears that there may be some subtle, but no acute effects, as indicated by performance decrements during simulated dives . . . and during protracted submerged missions" (21, p. 1).

Given the small elevation of CO_2 concentration in the present experiment, it appears unlikely that the tracking effects observed indicate any direct effects of CO_2 on visuo-motor functions. More likely, the tracking effects are associated with the decrease in alertness under CO_2 load which became evident from the subjective mood ratings. This is suggested by the high covariation in the time-courses of alertness and tracking performance in Experiment 2. It may be suggested that the raised CO_2-level in the chamber caused a reduction of alertness by affecting central activation mechanisms. These reductions in alertness might have lead to a slowing of performance, which particularly became evident in the tracking task because this task is specifically sensitive to variations in the effective response time-delay of subjects (2). Such an interpretation would be in accordance with several other studies where a close association between alertness, fatigue effects and tracking decrements were found using an unstable tracking task (e.g., 3, 12, 14, 15). Furthermore it would converge with results from Fothergill et al. (6) who found raised end-tidal CO_2 tensions particularly affecting response speed in different cognitive and psychomotor tasks.

Before accepting the conclusion that the results of alertness and tracking data in Experiment 2 indeed reflect CO_2-related behavioral effects, at least two other possible interpretations of the data should be considered. Firstly, the fact that the subjects were informed not only about the elevation of CO_2 but also about when this environmental stressor was introduced, might have biased their responses toward the observed direction. Whereas this hypothesis might explain the decrement in alertness ratings at day 3, it is neither in accordance with the stability of tracking performance at this critical day, nor with the general stability of all other performance indicators (speed and accuracy of different cognitive functions, time-sharing efficiency) after the CO_2-load had been introduced. Therefore, it appears unlikely that the observed effects were due to the demand characteristics of the experiment. Secondly, it could be argued that even though the experimental subjects had prior experience with the hyperbaric chamber and the study protocol, there was still an inevitable confounding between effects of CO_2 and the specific living conditions in the chamber. Consequently, the observed behavioral effects in Experiment 2 again might not be related to CO_2 load but to difficulties with adapting to the confined chamber environment. This hypothesis is suggested by both the drop of contentedness in the midterm of the chamber stay, which probably reflects a confinement effect like the one observed in Experiment 1, as well as the time-courses of subjective alertness ratings and tracking performance after day 12, which also closely resemble the ones observed in the first experiment. However, the hypothesis conflicts with the obvious stability of tracking performance at the first and third day in the chamber, which marks a clear contrast to Experiment 1. This stability clearly points to the pre-experience of the subjects and the absence of problems to adapt to the chamber environment in the second run. Therefore, although the behavioral effects observed after day 12 in the chamber might be related to other effects than CO_2, there are good reasons to interpret at least the effects observed between days 3 and 12 as direct (alertness) or indirect effects (tracking performance) of the elevated CO_2 concentration.

However, the strength of these effects is weak and their practical significance, particularly for prolonged manned spaceflights, might be questioned. This becomes evident from comparing the results of Experiment 2 with those obtained in other field settings with the same task battery. For example the performance tasks used in the present study have also been used before for performance monitoring during a 60-d confinement study (12), two experiments during a short-term (8 d) and long-term (14 mo) space mission (13,14,15), and a 30-d simulated deep-sea saturation dive (11). In these experiments, decrements of tracking performance and/or subjective alertness were found during adaptation to the extreme environmental conditions. However, apart from the confinement study (12), the observed performance effects were much stronger than in the present experiment. This applied specifically for the space experiments. In these experiments large impariments of tracking performance were found during the first 8 to 10 d in space which appeared to be related to combined effects of microgravity and fatigue. During the short-term space mission, these decrements were even accompanied by clear impairments of dual-task efficiency which point to possible attentional selectivity effects during the adaptation to the space environment (14). Compared with these performance disturbances, the CO_2-related behavioral effects observed in Experiment 2 are very mild. Therefore, it can be assumed that mood effects and performance decrements caused by a CO_2 load around 1.2% in a space station will most probably not be of operational significance in the overall assembly of stressor effects in this extreme environment.

SUMMARY AND CONCLUSIONS

In order to evaluate potential performance deficits that can be attributed to increased CO_2 exposure during long-duration spaceflights, two simulation experiments were performed. Both experiments required the same crew of four male volunteers to live confined in an unpressurized hyperbaric chamber complex for 26 d. The experiments differed in the level of chronic CO_2 load imposed on the crew, 0.7% and 1.2%, respectively. Comparing mood and performance under CO_2 load with mood and performance observed under baseline conditions, indications of CO_2-related behavioral effects were only found with the higher CO_2 concentration. What are the implications of these results with regard to acceptance levels of chronically increased CO_2 inhalation in confined environments like space-habitats? Firstly, it can be stated that chronic exposure to CO_2 concentrations up to 0.7% in the ambient atmosphere do not cause any detrimental effects on human subjective mood or performance. Secondly, the behavioral effects observed in the present study during chronic exposure to 1.2% CO_2 were limited to subjectively perceived reductions in alertness and slight performance decrements in a tracking task. According to their pattern and strength, these behavioral effects are similar to those that have been found before during confinement, but are much weaker than those provoked by other stressors of the space environment. Therefore, even prolonged exposures to CO_2 concentrations as high as 1.2% appear to be tolerable with regard to their behavioral effects.

ACKNOWLEDGMENT

The work reported in this paper was supported by a grant from the Deutsche Agentur für Raumfahrtangelegenheiten (DARA GmbH).

REFERENCES

1. Advisory Group for Aerospace Research, and Development (AGARD). Human performance assessment methods. Neullysur-Seine: AGARD, 1989; AGARDograph No. 308
2. Allen RW, Jex HR. Visual-motor response of crewmen during a simulated 90-day space mission as measured by the critical task battery. Proceedings of the 7th Annual Conference on Manual Control. Washington: NASA, 1972; NASA SP-281: 239–46.
3. Batejat D, Lagarde D. Circadian rhythm and sleep deprivation: effects on psychomotor performance. Med Sci Res 1992; 20:167–8.
4. Bond A, Lader M. The use of analogue scales in rating subjective feelings. Br J Med Psychol 1974; 47:211–8.
5. Beringer J. Development of a code generating software for conducting psychological reaction time experiments (in German) (Europäische Hochschulschriften, Reihe XLI, Informatik). Frankfurt/Main: Lang, 1993.

6. Fothergill DM, Hedges D, Morrison JB. Effects of CO_2 and N_2 partial pressures on cognitive and psychomotor performance. Undersea Biomed Res 1991; 18:1–19.
7. Hart FG, Staveland LE. Development of NASA-TLX (Task Load Index): results of empirical and theoretical research. In: Hancock PA, Meshkati N, eds. Human mental workload. Amsterdam: North-Holland, 1988; 139–83 .
8. Henning RA, Sauter SL, Lanphier EH, Reddan WG. Behavioral effects of increased CO_2 load in divers. Undersea Biomed Res 1990; 17:109–20.
9. Jex HR, McDonnell JD, Phatak AV. A "critical" tracking task for manual control research. IEEE Trans HFE-7 1966; 7:138–44.
10. Kirk RE. Experimental design, 2nd ed. Belmont: Brooks/Cole, 1982.
11. Lorenz B, Brooke ST, Holmes C, et al. Cognitive and psychomotor performance monitoring during the AURORA '93 450-meter simulated saturation dive. In: National Hyperbaric Centre, ed. AURORA '93 Dive Report, Vol. 2. Aberdeen: National Hyperbaric Centre, 1993; 21–37.
12. Lorenz B, Lorenz J, Manzey D. Performance and brain electrical activity during prolonged confinement. In: Bonting SL, ed. Advances in space biology and medicine, Vol. 5. Greenwich: JAI, 1996; 157–83.
13. Manzey D, Lorenz B, Schiewe A, et al. Behavioral aspects of human adaptation to space: analyses of cognitive and psychomotor performance in space during an 8-day space mission. Clin Invest 1993; 71:725–31.
14. Manzey D, Lorenz B, Schiewe A, et al. Dual-task performance in space: results from a single-case study during a short-term space mission. Hum Factors 1995; 37:667–81.
15. Manzey D, Lorenz B, Polyakov V. Mental performance in extreme environments: results from a performance monitoring study during a 438-day spaceflight. Ergonomics (In press).
16. Sandal GM, Vaernes R, Ursin H. Interpersonal relations during simulated space missions. Aviat Space Environ Med 1995; 66:617–24.
17. Sayers JA, Smith REA, Holland RL, Keatinge WR. Effects of carbon dioxide on mental performance. J Appl Physiol 1987; 63:25–30.
18. Sheehy JB, Kamon E, Kiser D. Effects of carbon dioxide inhalation on psychomotor and mental performance during exercise and recovery. Hum Factors 1982; 24:581–8.
19. Wenzel J, Luks N, Plath G, et al. The influence of CO_2 in a space-like environment: Study design. Aviat Space Environ Med 1998; 69:285–90.
20. Weybrew BB. Psychological problems of prolonged marine submergence. In: Burns N, Chambers R, Hendler E, eds. Unusual environments and human behavior. Glencoe: Free Press, 1963; 87–125.
21. Weybrew BB. An exploratory study of the psychological effects of intermittent exposure to elevated carbon dioxide levels. Groton: Naval Submarine Medical Center, 1970; Naval Submarine Medical Center Report No. 647.
22. Wright BD. Simulation analysis of nominal CO_2 partial pressures on the International Space Station. Am Soc Gravitation Space Biol Bull 1995; 9:25.