Effects of carbon dioxide exposure on human cognitive abilities in an enclosed workplace environment

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Abstract. In this study, fifteen participants were exposed in an enclosed environmental chamber to investigate the effects of elevated carbon dioxide (CO_2) concentration on their cognitive abilities. Three CO_2 conditions (1500 ppm, 3500 ppm, and 5000 ppm) were achieved by constant air supply and additional ultra-pure CO_2. All participants received the same exposure under each condition, during which they performed six cognitive tests evaluating human perception, attention, short-term working memory, risky decision making, and executive ability. During each exposure condition, the reaction time (RT) test, speed perception test, visual search (VS), 2-back test, balloon analogue risk test (BART), and Stroop test were successively conducted with rest intervals of approximately 13min. The results showed that there was no statistically-significant difference in the performance of RT tests, speed perception test, and 2-back test. This indicated that the elevated CO_2 concentration below 5000 ppm did not affect the participants' perception and short-term working memory. However, significant increase of response time was observed in the VS test, BART, and Stroop test at 5000 ppm compared with lower exposure concentrations. The slower reaction reflected the negative effects of elevated CO_2 concentration on human visual attention, risky decision making, and executive ability. The findings suggest that work performance could be negatively affected by the exposure to CO_2 at the current occupational concentration limit.

1 Introduction

The atmospheric average concentrations of carbon dioxide (CO_2) are approximately 400 ppm, and may increase to the range between 794 and 1142 ppm by 2100 according to the report of the Intergovernmental Panel on Climate Change (IPCC) [1]. The CO_2 concentrations in different workplaces are generally at a relatively high level according to a large number of studies, and are likely to be higher in several decades. Fisk [2] concluded that the CO_2 concentration in classrooms was generally higher than 1000 ppm. Giaconia et al. [3] reported that the CO_2 concentrations in 14 shout-haul domestic flights were 1192±151 ppm.

Considering that the indoor CO_2 concentration may be at a high level and may cause negative effects on human performance, it is essential to explore the direct CO_2 impacts on human performance associated with labor productivity and production safety. However, previous studies on this issue showed a lack of consistency in results. Reported by Satish et al. [4], Allen et al. [5] and Rodeheffer et al. [6], the Strategic Management Simulation (SMS) test was used to evaluate the decision making ability, and the short-term exposure to elevated CO_2 concentration could negatively affect the decision making performance starting at 1000 ppm. However, contrary conclusions are drawn in other studies. Zhang et al. [7] concluded that the performances in various cognitive tasks were not affected by the elevated CO_2 concentration from 500 ppm to 3000 ppm. Liu et al. [8] recruited 12 subjects to receive a 180-min exposure to 380 and 3000 ppm CO_2, but no significant CO_2 effects were observed on nine cognitive test performances.

The main purpose of this study was to further examine the effect of exposure to CO_2 at the current 8h occupational exposure limit of 5000 ppm on the key human cognitive abilities including perception, attention, short-term working memory, risky decision making, and executive ability, and to provide suggestions on CO_2 concentration control in particular working environment. Subjects were recruited to perform six cognitive tests under three different CO_2 conditions (1500 ppm, 3500 ppm, and 5000 ppm). Their performance metrics were evaluated to examine the effects of CO_2 exposure on human cognition.

2 Methods

Fifteen healthy male college students with engineering background were recruited for this study. The mean age of the participants was 24.2 years (SD: 2.5), and their average body mass index (BMI) was 22.7 Kg/m^2 (SD: 2.7). The experiment was carried out in an environmental chamber with a size of 7.6 m × 3.0 m × 2.1 m. The fresh air supply rate was constantly set as 250 m^3/h by the volume regulator, with which the

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human bioeffluent concentrations were expected to be moderate to low during the tests. The dosing rate of pure CO_2 was controlled by the flowmeter and valve opening to achieve different CO_2 concentrations. In the experimental sessions, the participants were evenly allocated to three groups, and were exposed to the same CO_2 condition by groups in one day. For each group, the tests under different exposure conditions were carried out at the same time period on three consecutive weekdays.

2.1 Cognitive tests

The participants were requested to perform six computer-based cognitive tests under each exposure condition. The cognitive tests were used to evaluate perception, attention, short-term working memory, risky decision making, and executive ability. The tests included reaction time (RT) test [9], speed perception test [10], visual search (VS) test [11], 2-back test [12], Balloon analogue risk test (BART) [13] and Stroop test [14]. The cognitive ability and evaluation metrics corresponding to each test are displayed in Table 1, where *ACC* and *CRT* represent accuracy and correct response time, respectively. For each cognitive test, the higher accuracy and shorter *CRT* indicated better cognitive performance.

2.2 Statistical analysis

Generalized additive mixed effect model (GAMM) analyses [15] were performed to study the associations of cognitive test performance metrics with CO_2 exposure concentrations, treating the participant as a random effect, as shown in Eq. (1) and Eq. (2). The differences were considered as statistically significant when $p< 0.05$.

$$y = \beta_1 + \beta_2(MediumCO_2) + \beta_3(HighCO_2) + b + e \quad (1)$$

$$y = \beta_1^* + (-\beta_2(LowCO_2)) + \beta_3^*(HighCO_2) + b^* + e^* \quad (2)$$

Where, y is the cognitive test performance metrics; β_1 and β_1^* are the fixed intercepts; β_2 and β_3 are the fixed effects of medium CO_2 and high CO_2 compared to low CO_2, respectively; β_3^* is the fixed effect of high CO_2 compared to medium CO_2; b and b^* are the random effects of individual differences between participants; e and e^* are the residuals.

Table 1. The cognitive ability and evaluation metrics corresponding to each cognitive test.

Tests	Cognitive abilities	Performance metrics	Meaning of the metrics
RT test	Perception	ACC_{sim} (%)	Simple reaction time
		CRT_{sim} (ms)	
		ACC_{dis} (%)	Discriminative reaction time
		CRT_{dis} (ms)	
		ACC_{cho} (%)	Choice reaction time
		CRT_{cho} (ms)	
Speed perception test	Perception	Deviation rate (%)	
VS test	Attention	ACC_{total} (%)	For all trials
		CRT_{total} (ms)	
		ACC_{report} (%)	For trials with the report of target character
		CRT_{report} (ms)	
		False alert rate (%)	
		Missing report rate (%)	
2-back test	Short term working memory	ACC (%)	For all trials
		CRT (ms)	
BART test	Risky decision making	Average number of pumps	
		Critical response time (ms)	
		Final response time (ms)	
Stroop test	Executive ability	ACC_{total} (%)	For all trials
		CRT_{total} (ms)	
		ACC_{con} (%)	For consistent word color and meaning
		CRT_{con} (ms)	
		ACC_{incon} (%)	For inconsistent word color and meaning
		CRT_{incon} (ms)	

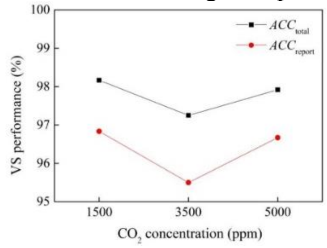
3 Results

3.1 Perception

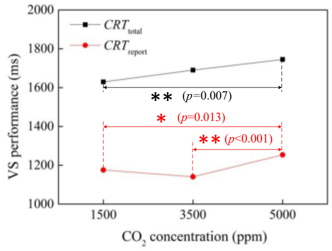
The performance metrics of the reaction time tests changed slightly with the elevated CO_2 concentrations, but the differences were not statistically significant. The average deviation rates of the speed perception test slightly decreased, without statistically-significant differences. In sum, the elevated CO_2 concentrations did not affect the perception ability significantly.

3.2 Attention

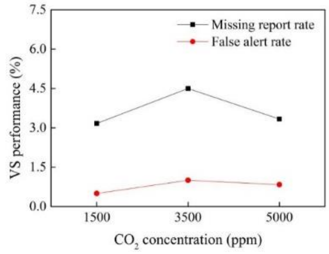
The CO_2 effects on the VS performance metrics were depicted in Fig. 1. As shown in Fig. 1, the CRT_{total} and CRT_{report} increased significantly with the elevated CO_2 concentration from 1500 ppm to 5000 ppm (p=0.007 for CRT_{total}, and p=0.013 for CRT_{report}), and the CRT_{report} also increased significantly when the concentration increased from 3500 ppm to 5000 ppm (p<0.001). Extremely significant (p<0.01) increase could be observed for the CRT_{total} from 1500 ppm to 5000 ppm and the CRT_{report} from 3500 ppm to 5000 ppm. Therefore, the attention ability could be obviously impaired at the elevated CO_2 concentration of 5000 ppm, manifested as longer response time.



(a) Accuracy



(b) Response time



(c) Missing report rate and false alert rate

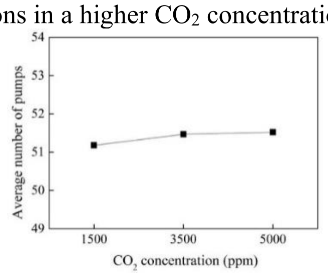
Fig. 1. GAMM results of CO_2 concentration effect on the performance metrics of the VS test. * ($p< 0.05$), ** ($p< 0.01$).

3.3 Short-term working memory

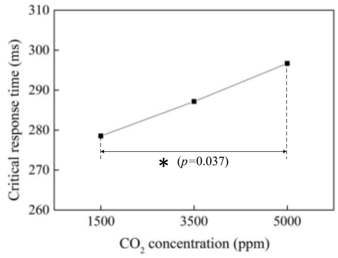
The *ACC* and *CRT* of the 2-back test are performance metrics of short-term working memory. There were no statistically significant differences in *ACC* and *CRT* between any two CO_2 exposures, indicating that the high CO_2 concentration did not affect the short-term working memory significantly.

3.4 Risky decision making ability

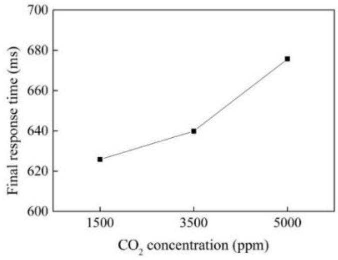
The GAMM results of the BART test can be seen in Fig. 2. As shown in Fig. 2, the average number of three performance metrics all increased with the CO_2 concentration rose, but only the difference of critical response time between 1500 ppm and 5000 ppm was statistically significant (p=0.037). The results indicated a slightly increasing will of the participants to make a risky decision at higher CO_2 exposure. Furthermore, the participants took a longer response time to make risky decisions in a higher CO_2 concentration.



(a) Average number of pumps on unexploded balloons



(b) Critical response time of pumps on unexploded balloons

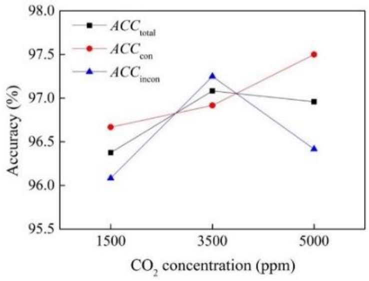


(c) Final response time of pumps on unexploded balloons

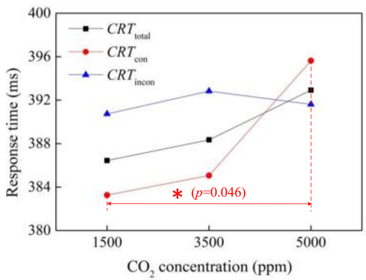
Fig. 2. GAMM results of CO_2 concentration effect on the performance metrics of the BART test. * ($p< 0.05$).

3.5 Executive ability

Executive ability was evaluated through the Stroop test. As shown in Fig. 3, the CRT_{con} increased significantly (p=0.046) and the CRT_{total} was also slightly longer, with the CO_2 concentration elevated from 1500 ppm to 5000 ppm. This indicated that the participants took longer time to execute the trials with consistent word color and meaning when they were exposed to higher CO_2 concentration. Nevertheless, the other performance metrics were only slightly varied with the increased CO_2 concentration.



(a) Accuracy



(b) Response time

Fig. 3. GAMM results of CO_2 concentration effect on the performance metrics of the Stroop tests.* ($p< 0.05$).

In sum, the elevated CO_2 concentration did not affect the perception and the short-term working memory significantly, but had certain effects on the visual attention, risky decision making, and executive ability, in which obvious effects were observed on the visual attention. The significant negative effects were mainly observed in the increased response time, indicating detrimental effects of high CO_2 exposure on human vigilance. It is worth noting that the tests adopted in this study were relatively easy. Greater CO_2 effects are likely to be seen in tasks with a greater cognitive load than tested in this study.

4 Conclusions

In this study, fifteen participants were recruited to perform six classic cognitive tests at the CO_2 exposure concentrations of 1500 ppm, 3500 ppm, and 5000 ppm to investigate the effects of artificially raised pure CO_2 on their cognitive abilities. The results showed that the elevated CO_2 exposure concentration below 5000 ppm did not affect the human perception and short-term working memory, whether for accuracy or reaction time. However, the human attention, risky decision making, and executive abilities were impaired at 5000 ppm, as indicated by the significant increase of response time. The attention impaired obviously at 5000 ppm as the response time increased extremely significantly. Therefore, the potential impairment of human work performance could occur at the current 8-h occupational exposure limit. The findings suggest a stricter control level of CO_2 exposure concentration in the enclosed workplaces with high cognitive performance requirements for rapid response and operational safety.

Acknowledgements

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