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Associations of Human Cognitive Abilities with Elevated Carbon Dioxide Concentrations in an Enclosed Chamber

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Abstract: Fifteen participants were exposed in an enclosed environmental chamber to investigate the effects of elevated carbon dioxide (CO₂) concentration on their cognitive abilities. Three CO₂ conditions (1500, 3500, and 5000 ppm) were achieved by constant air supply and additional ultrapure CO₂. 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. Generalized additive mixed effects model (GAMM) results showed no statistically significant differences in performance on the reaction time (RT) tests, the speed perception test, and the 2-back test. This suggests that elevated CO₂ concentrations below 5000 ppm did not affect participants' perception and short-term working memory. However, a significant increase in response time was observed in the visual search (VS) test, the balloon simulation risk test (BART), and the Stroop test at 5000 ppm compared to lower exposure concentrations. The slower responses reflected the detrimental effects of elevated CO₂ concentrations on visual attention, risky decision-making, and executive ability. The findings suggest that the control level of CO₂ concentrations should be tighter in enclosed workplaces where rapid response and operational safety are required.

Keywords: carbon dioxide; cognitive ability; cognitive test; work performance

1. Introduction

The atmospheric average concentrations of carbon dioxide (CO₂) are approximately 400 ppm, and may increase to the range between 794 and 1142 ppm by 2100 according to the Intergovernmental Panel on Climate Change (IPCC) [1]. The indoor CO₂ mainly comes from outdoor CO₂ brought in by fresh air ventilation and CO₂ generated by human metabolism indoors. Given the likelihood of increasing atmospheric CO₂ concentration, the indoor CO₂ concentration could also increase gradually in future. The typical CO₂ concentration levels are generally lower than 1000 ppm in residential buildings [2]. However, in crowded or confined indoor spaces, CO₂ concentrations may exceed 2000 ppm due to insufficient per capita fresh air ventilation [3–5]. For people working in a typical indoor workplace, high CO₂ exposure can occur for a few hours. However, in special enclosed workspaces (such as submarines and manned spacecraft), exposure to high CO₂ concentrations could last for several days. Considering that higher indoor CO₂ exposure may lead to detrimental effects on human work performance, it is essential to study the direct CO₂ impacts on human cognitive abilities that are closely associated with productivity and work safety.

Table 1 summarizes the studies examining the human cognitive responses to elevated CO_2 concentrations via the addition of pure CO_2 or the manipulation of ventilation rate. For the former, the pure CO_2 was fully mixed with the outdoor air and then sent into the experimental room. For the latter, the outdoor air ventilation rates were reduced to increase the concentrations of CO_2 and other pollutants. The current studies of CO_2 effects on cognitive performance still show a disappointing lack of consistency in results. It



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Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). seems to be that the more complex the task, the greater CO_2 effects would be evidenced. For example, the performance of simple office tasks was not significantly affected by elevated CO_2 concentration below 5000 ppm [6,7], but the performance of complex tasks decreased significantly with elevated CO_2 concentration [8,9]. As shown in Table 1, the strategic management simulation (SMS) test has been used to evaluate the strategic decisionmaking ability. The exposure to elevated pure CO_2 concentration could significantly reduce the SMS test performance starting at 1000 ppm [10,11]. Rodeheffer et al. [12] observed that the SMS performance declined slightly for the subjects exposed to CO_2 concentration of 2500 ppm compared to 600 ppm, but did not further decline when they were exposed to 15,000 ppm. They speculated that the inconsistent finding could be explained by submariners having developed physiological adaptations to high CO_2 level, because they were routinely exposed to high CO_2 concentrations. Although Snow et al. [13] reported that participants did not exhibit significantly worse cognitive test scores at a CO_2 concentration of 2700 ppm, their cognitive flexibility and executive ability still appeared to be negatively affected relative to the CO_2 exposure at 830 ppm, given lack of learning effect.

Table 1. Summary of studies examining CO₂ effects on human cognitive abilities.

Adjust Method	Studies	CO ₂ Levels	Exposure Duration	Number of Subjects	Cognitive Tests	Effects of Elevated CO ₂
	Satish et al. [10]	600 vs. 1500 vs. 2500 ppm	150 min	22	SMS test	Reduced performance
	Allen et al. [11]	550 vs. 945 vs. 1400 ppm	One day (09:00–17:00)	24	SMS test	Reduced performance
	Rodeheffer et al. ^a [12]	600 vs. 2500 vs. 15000 ppm	125 min	36	SMS test	No significant effect
	Snow et al. [13]	800 vs. 2700 ppm	<60 min	31	Stroop test; shifting attention task; continuous performance test; four-part continuous performance test.	Reduced performance of cognitive flexibility and executive function, but no significant effect on other domains.
Addition of pure CO ₂	Zhang et al. [6]	500 vs. 1000 vs. 3000 ppm	255 min	25	Redirection test; digit span memory test; Stroop test; grammatical reasoning test; Stroop test with feedback; Tsai–Partington test; d2 test; arithmetical calculation.	No significant effect
	Zhang et al. [7]	500 vs. 5000 ppm	153 min	10	Addition test; Tsai-Partington test	No significant effect
	Liu et al. [14]	380 vs. 3000 ppm ^b	180 min	12	Mental redirection; grammatical reasoning; digit span memory; visual learning memory; number calculation; Stroop test; visual reaction time; D2 test; Tsai–Partington test.	No significant effect
	Bloch-Salisbury et al. [15]	30 vs. 38 vs. 47 mmHg ^c	120 min	9	Pattern recognition, matching-to- sample, logical reasoning, two-letter search, time estimation.	No significant effect
Maninulation - (Maddalena et al. [16]	900 vs. 1800 ppm	240 min	16	SMS test	Reduced performance
Manipulation of ventilation rate	Haverinen- Shaughnessy et al. [17]	From 0.9 to 7.1 L/s per person ^d	One day	3109	Mathematics test; reading test; science test	Reduced performance

Adjust Method	Studies	CO ₂ Levels	Exposure Duration	Number of Subjects	Cognitive Tests	Effects of Elevated CO ₂
	Bakó-Biró et al. [18]	From 1 to 8 L/s per person ^d	One day	332	Simple reaction time; choice reaction time; color word vigilance; addition reaction time; digit span memory; digit classification; digit-symbol matching; picture memory; word recognition	Reduced performance
	Twardella et al. [19]	1145 vs. 2115 ppm	One day	417	Concentration performance; total number of characters processed; total number of error rates	Reduced performance
_	Scully et al. [20]	600 vs. 1200 vs. 2500 vs. 5000 ppm	240 min	22	SMS tests; cognition tests	No significant effect
	Coley et al. [21]	690 vs. 2909 ppm	150 min	18	Picture presentation; simple reaction time; digit vigilance; choice reaction time; picture recognition; Bond–Lader visual analogue scales of mood and alertness	Reduced performance

Table 1. Cont.

a. The study used the between-subject design, and the others used the within-subject design. b. The participants were exposed at 35 °C, not a thermal comfort environment. c. The PaCO₂ increased (mean = 47 mmHg) or decreased (mean = 38 mmHg) from the resting level (mean = 30 mmHg). d. Compared the ventilation rate instead of CO₂ concentration.

However, several other studies indicated that pure CO₂ effects on cognitive abilities were not potent. Zhang et al. [6,7] reported that no significant effect of CO₂ concentration on office task performance were observed in the 500–5000 ppm exposure range, regardless if the task difficulty was simple or moderate. Similarly, Liu et al. [14] found that no significant differences were observed in the performance of nine cognitive tests when participants were exposed to CO_2 concentrations up to 3000 ppm, compared with 380 ppm. Bloch-Salisbury et al. [15] reported that neither the partial pressure of carbon dioxide in the arterial blood ($PaCO_2$) increases (mean = 47 mmHg) nor decreases (mean = 38 mmHg) from the resting level (mean = 30 mmHg) would affect the cognitive performance, which was probably attributed to the low statistical power of small sample size. In contrast to the addition of pure CO₂, an impaired cognitive performance was more commonly observed under restricted ventilation conditions [16–19,21]. Only one study of astronaut-like subjects indicated no significant changes in SMS and cognition test batteries as concentration rose from 600 ppm to 5000 ppm via decreased ventilation rates [20]. The outcomes conflicted with those of similar studies [10,11], which was likely caused by differing characteristics of the various subject populations.

As summarized above, the previous findings remain controversial regarding the effects of additional pure CO_2 on human cognition. More research evidence is needed to investigate the sole effects of CO_2 exposure on different kinds of cognitive abilities. Particularly, the potential adverse impacts of high CO_2 exposure may affect work performance and safety in confined workplaces, which merit further exploration. Therefore, the main purpose of this study was to examine experimentally the sole effects of CO_2 exposure on several work-related cognitive abilities including perception, attention, short-term working memory, risky decision-making, and executive ability, and to further provide a reference for the exposure limit of CO_2 concentration in the working environments. In this study, fifteen subjects were recruited to take six cognitive tests under three different CO_2 conditions (1500, 3500, and 5000 ppm) in an enclosed environmental chamber. The performance metrics of

the cognitive tests were evaluated by statistical models to analyze the effects of elevated CO_2 concentrations from a moderate level to the occupational limit. Based on the observed effects, the effects of test difficulty and physiological regulation on cognitive performance are further discussed.

2. Methods

2.1. Participants

The participants were limited to healthy adult males considering that the operators in high-duty workplace environments are mostly male. Therefore, fifteen healthy male college students with an engineering background were recruited for this study. The mean age of the participants was 24.20 ± 2.48 years, and their average body mass index (BMI) was 22.67 ± 2.70 kg/m². They were all right-handed, and had no history of disorders such as color blindness, neurological errors, allergy, and alcohol addiction. The participants were informed that they would be tested under three CO₂ concentration conditions, but were not notified which conditions they were exposed to. Additionally, they were asked to maintain adequate sleep (not less than eight hours per day) before coming to the experimental site. Stimulants such as drugs, perfumes, alcohol, and caffeinated drinks were prohibited before and during the tests. All participants signed consent forms, completed the tests without dropping out, and received compensation after the experiment. The experimental protocol was approved by the Institute Review Board (IRB) of Beihang University.

2.2. Environmental Conditions

The experiment was carried out in an environmental chamber with a size of 7.6 m \times 3.0 m \times 2.1 m, as shown in Figure 1. The conditioned outdoor air was fully mixed with ultrapure CO₂ (\geq 99.99% purity) and then sent into the chamber. The exhausted air in the chamber was discharged by a fan to external atmosphere. The air temperature was controlled by the heating and cooling units. The fresh air supply rate was constantly set at 250 m³/h by the volume regulator, with which the human bioeffluent concentrations were expected to be moderate to low during the tests. The dosing rate of pure CO₂ was controlled by the flowmeter and valve opening to achieve different CO₂ concentrations.



Figure 1. Schematic diagram of the environment chamber.

Three CO₂ exposure conditions were tested [9]: a baseline exposure with concentration at 1500 ppm (referred to as low CO₂ condition), and the exposures to concentrations at 3500 ppm and 5000 ppm that were achieved by dosing pure CO₂ to supply air (referred to as medium and high CO₂ conditions, respectively). The high CO₂ condition was based on the current 8 h occupational limit and the safety requirements by the IRB for human-oriented experiments. The low CO₂ condition was based on the fact that the CO₂ concentrations are typically higher than 1500 ppm in enclosed spaces such as aircraft cabins [5] and submarines [12]. The medium CO₂ condition was set between the low and high concentration conditions.

The CO₂ concentration was measured by a T6615 sensor (measurement range: 0–10,000 ppm; measurement error: \leq 75 ppm or \pm 10%; sampling interval: 1 min) that was installed near the participants at a height of 1.2 m in the test area. The measured CO₂ concentrations under the three conditions were 1626 \pm 306 ppm, 3562 \pm 259 ppm, and 5087 \pm 318 ppm. The concentrations of VOCs, CO, and NH₃ under the three exposure conditions were 105–108 ppb (SD < 4), 36–38 ppb (SD < 1), and 17–18 ppb (SD < 1), as measured by a CPR-KA air quality analyzer (measurement range: 0–10 ppm (VOCs), 0–50 ppm (CO), 0–30 ppm (NH₃); measurement error: \leq 5% full scale; sampling interval: 2 min). This indicated that the confounding effects of other air pollutants were well controlled by the constant fresh air ventilation.

The air temperature and relative humidity were maintained at 25 °C and 65% by the air-conditioning units. The temperatures during the tests were 24.6 ± 1.7 °C, as measured by a LX8013 thermo-hygrometer (measurement range: -20 °C–60 °C; measurement accuracy: ± 0.5 °C). The predicted mean vote (PMV) was estimated to be between -0.5 and 0.5 [9], which indicated that the thermal environment in the experimental chamber was neutral. Participants were also allowed to adjust their clothing to ensure they were thermally comfortable during the experiment. In sum, the confounding effects of other environmental factors were controlled to study the effects of additional pure CO₂ exposure on cognitive abilities.

2.3. Cognitive Tests

The participants performed six computer-based cognitive tests sequentially under each exposure condition. The performance metrics of the tests were used to evaluate five basic cognitive abilities of perception, attention, short-term working memory, risky decision-making, and executive ability. The details are described as follows:

(1) Reaction time (RT) tests (perception)

The RT tests [22,23] (duration: 7 min) consist of a simple RT test, discriminative RT test, and choice RT test. In the RT tests, symbols were presented in the center of the screen. The participants were asked to look at the screen and to press the corresponding response buttons on keyboard immediately when they saw the target symbols. Table 2 lists the symbols displayed, target symbols, and response buttons. The accuracy of the simple, discriminative, and choice RT tests are referred to as ACC_{sim} , ACC_{dis} , and ACC_{cho} , respectively. The correct response time (CRT) for the three tests are referred to as CRT_{sim} , CRT_{dis} , and CRT_{cho} , respectively. The higher accuracy and shorter CRT indicate better perception ability.

Table 2. Details of the reaction time tests.

Tests	Displayed Symbols	Target Symbols	Response Buttons
Simple RT	▲ a		"J"
Discriminative RT	▲; ■ ^b ; • ^c	A	"J"
Choice RT	▲; ■; ●	▲; ■; ●	"J" (▲); "F" (■); Space bar ("•")

a. The target symbol was a red triangle. b. The target symbol was a red square. c. The target symbol was a red circle.

(2) Speed perception test (perception)

In the speed perception test [24] (duration: 7 min), a ball moved uniformly and randomly from different directions into the center area of the screen covered with a gray circle. When the ball entered the gray circle, the participants were asked to make a key response when they predicted that the ball reached the center point of the screen. The deviation rate of the predicted position from the center point was used to measure the human perception ability to estimate the speed of a moving object, and the smaller deviation rate indicated better performance.

(3) Visual search (VS) test (attention)

In the VS test [25,26] (duration: 5 min), the participants were asked to find the target character ("L" in red) against other visual distracters ("L" in black and "T" in red). They pressed the "F" button when found the target character, or pressed the "J" button if not. Six performance metrics were calculated to evaluate human attention ability, including the accuracy and average CRT for all trials (referred as ACC_{total} and CRT_{total} , respectively), the accuracy and average CRT for trials with the report of target character (referred as ACC_{report} and CRT_{report} , respectively), the false alert rate, and the missing report rate. The higher accuracy, shorter CRT and lower false/missing report rate indicated stronger attention ability.

(4) 2-back test (short-term working memory)

In the 2-back test [27,28] (duration: 7 min), a sequence of characters was presented one by one in the central area of the screen. Additionally, for each character, the participants needed to judge whether the current character matched the previous second character, and responded as soon as possible by pressing the "F" or "J" button ("F"—matching; "J"—not matching). The *ACC* and the average *CRT* were used to evaluate the short-term working memory ability. The higher *ACC* and shorter *CRT* indicated better short-term working memory.

(5) Balloon analogue risk test (BART) (risky decision-making)

Thirty trials were set for the BART [29,30]. In each trial, the participants could earn credits by clicking the "F" button to pump the balloon up on the screen. Each click incrementally inflated the balloon and credits were added to a count-up counter. However, the earnings for the trial would be lost if the balloon exploded. Specific information regarding the balloon's breakpoint determination was not given to the participants. The participants could decide to stop pumping the balloon by clicking the "J" button at any time prior to the explosion, and collect the credits earned in the trial. The participants were also informed that the total earned credits could be redeemed as cash rewards. The average number of pumps on unexploded balloons, the critical response time of pumps on unexploded balloons (the response time of the last inflation decision) were used to evaluate the risk decision-making ability. The higher number of pumps indicated the greater risk-taking propensity, and the longer response time indicated the more hesitant decision-making.

(6) Stroop test (executive ability)

In the Stroop test [31,32] (duration: 2 min), the words "RED" or "GREEN" appeared in the central area of the screen, randomly shown in red or green. The participants were asked to press the "Z" button when the color of the word was red, and to press the "/" button when the color of the word was green, regardless of the meaning of the words. Six metrics were used to evaluated human executive ability, including the accuracy and average CRT for all trials (referred as ACC_{total} and CRT_{total} , respectively), for the trials with consistent word color and meaning (referred as ACC_{con} and CRT_{con} , respectively), and for the trials with inconsistent word color and meaning (referred as ACC_{incon} and CRT_{incon} , respectively). The higher accuracy and shorter CRT indicated the stronger executive ability.

2.4. Experimental Procedure

The participants took part in practice sessions before the experimental sessions to reduce the potential learning effect of the cognitive tests. They received detailed visual instructions for each cognitive test from the experimenters during the initial practice session. Then they were asked to practice twice a day for three days during the later practice sessions. During the experimental sessions, the fifteen 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 during the same time

period on three consecutive weekdays. During each exposure condition, RT tests, speed perception test, VS test, 2-back test, BART, and Stroop test were conducted in succession with a total rest interval of approximately 13 min, as shown in Figure 2. The participants were instructed to try their best to complete the cognitive tests, with their dominant hand using a laptop that was placed on the table in front.



Figure 2. Experimental procedure of the cognitive tests.

2.5. Statistical Analysis

Generalized additive mixed effect model (GAMM) analyses [8–11,13,33] were performed using the open-source statistical package R version 3.6.1 (R Project for Statistical Computing, Vienna, Austria) to study the associations of cognitive test performance metrics with CO₂ exposure concentrations, treating the participant as a random effect, as shown in Equations (1) and (2). The level of statistical significance was set at p < 0.05.

$$y = \beta_1 + \beta_2 (\text{Medium CO}_2) + \beta_3 (\text{High CO}_2) + b + e$$
(1)

$$y = \beta_1^* + (-\beta_2(\text{Low CO}_2)) + \beta_3^*(\text{High CO}_2) + b^* + e^*$$
(2)

where *y* is the cognitive test performance metric; β_1 and β_1^* are the fixed intercepts; β_2 and β_3 are the fixed effects of medium CO₂ and high CO₂ compared to low CO₂, respectively; β_3^* is the fixed effect of high CO₂ compared to medium CO₂; *b* and *b*^{*} are the random effects of individual differences between participants; and *e* and *e*^{*} are the residuals.

3. Results

The detailed GAMM results of the CO_2 effects on the cognitive test performance metrics (Table S2) are presented in Table S1. Additional plots shown in Figures 3–7 depict the variations of these performance metrics under different CO_2 conditions.



Figure 3. Cont.



Figure 3. Performance metrics of the RT tests and the speed perception test under different CO₂ conditions. (**a**) Accuracy of the RT tests. (**b**) Response time of the RT tests. (**c**) Average deviation rate of the speed perception test.



Figure 4. Performance metrics of the VS test under different CO₂ conditions; * (p < 0.05), ** (p < 0.01). (a) Accuracy. (b) Response time. (c) Missing report rate and false alert rate.



Figure 5. Performance metrics of the 2-back test under different CO_2 conditions. (a) Accuracy. (b) Response time.



Figure 6. Performance metrics of the BART under different CO_2 conditions; * (p < 0.05). (**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.





3.1. Perception

Figure 3 presents the CO_2 effects on the performance metrics of the RT tests and the speed perception test. The overall performance of the simple RT test was the best, followed by the discriminative RT test and the choice RT test. This indicated that cognitive performance was worse with increased test difficulty, regardless of the CO_2 conditions. The performance metrics of each RT tests and the speed perception test were slightly changed with the CO_2 conditions, but the variations were not statistically significant. In sum, elevated CO_2 concentrations did not significantly affect human perception.

3.2. Attention

The CO₂ effects on the performance metrics of the VS tests were depicted in Figure 4. Both the CRT_{total} and CRT_{report} increased significantly with elevated CO₂ concentration from 1500 to 5000 ppm, and the CRT_{report} also had a significant increase when the concentration increased from 3500 to 5000 ppm. It could be inferred that the attention response slowed when exposed to higher CO₂ concentrations. The accuracy metrics were marginally worse under the medium CO₂ condition, as indicated by slightly lower accuracy and higher missing/false report rate, but the differences were not statistically significant.

3.3. Short-Term Working Memory

As shown in Figure 5, no statistically significant difference was observed in the *ACC* and the *CRT* between any two CO_2 conditions, which indicated that elevated CO_2 concentrations had no significant effect on short-term working memory. Nevertheless, the response time was slightly longer under the high CO_2 condition.

3.4. Risky Decision-Making

As shown in Figure 6, the average number of pumps, critical response time, and final response time on unexploded balloons all increased gradually with elevated CO_2 concentration in the BART. The critical response time had a significant increase as the concentration increased from 1500 to 5000 ppm. The results indicated that the participants

slightly tended to make riskier and more hesitant decisions when exposed to higher CO_2 concentrations.

3.5. Executive Ability

Figure 7 shows that the CRT_{con} increased significantly as the CO₂ concentration rose from 1500 to 5000 ppm. The CRT_{total} was also modestly longer at higher CO₂ concentration level. It can be inferred that the participants spent more effort to execute the Stroop test trials with higher CO₂ exposure. Nevertheless, no clear variation trend was found between accuracy metrics and CO₂ conditions.

In sum, exposure to elevated CO_2 concentrations from 1500 to 5000 ppm had some detrimental effects on attention, risky decision-making, and executive ability, as manifested by a significant increase in response time. Perception and short-term working memory, however, were only marginally affected by the CO_2 conditions.

4. Discussion

The main finding of this study is that the elevated CO_2 concentrations below 5000 ppm did not affect participants' perception and short-term working memory, but had a detrimental effect, reflected as slower response, on their visual attention, risky decision-making, and executive ability. The following sections discuss four aspects of the results.

4.1. Comparison with Previous Studies

Only the findings in the literature on the effects of additional pure CO₂ are compared with our results, because both CO₂ and other air pollutants may contribute to the detrimental impacts on cognition when the target CO₂ concentrations are achieved by manipulating ventilation rates. Figure 8 summarizes the recent findings of impact on the five cognitive abilities by pure CO₂ addition. As shown in Figure 8, the previous studies [6,13,14] found that perception and short-term memory were not significantly affected by the additional pure CO₂ concentration below 3000 ppm, which was consistent with our findings. Our study further extended the concentration limit of nonsignificant effect to 5000 ppm. It is worth noting, however, that perception could be affected by CO₂ concentration much higher than 5000 ppm. For example, Sheehy et al. [34] reported a significantly slower response of choice reaction time test during the inhalation of 5% CO₂ in 50% O₂.

Furthermore, our results indicated that attention, risky decision-making, and executive ability were significantly impaired as the CO_2 concentration increased from 1500 to 5000 ppm. Similarly, a significant detrimental effect of CO_2 exposure on vigilance was also found at concentrations as low as 3500 ppm using the psychomotor vigilance test (PVT) in our previous study [35]. Snow et al. [13] stated that the increase in CO_2 concentration from 800 to 2700 ppm could lead to reduced cognitive flexibility and executive ability, given lack of learning effect, as examined by the shifting attention test and the Stroop test. However, some scholars have also found inconsistent results. For example, Zhang et al. [6] and Liu et al. [14] reported nonsignificant effects on attention using the D2 test and on execution using the Stroop test, which may be because the concentration range they studied was limited to 3000 ppm. This result indicates that the CO_2 effects on cognitive abilities become more significant as the concentration increases.

	Results summary	Main findings
 Perception Continuous performance test, four-part continuous performance test Visual reaction time RT tests, speed perception test (our study) 	Ambient CO_2 5000 ppm Snow et al. (2019) 830 vs. 2700 ppm Liu et al. (2017) 1000 ppm 380 vs. 3000 ppm This study * 1500 vs. 3500 vs. 5000 ppm 1000 vs. 5000 ppm	• No significant effects on perception.
 Short-term memory Digit spanmemory test Continuous performance test, four-part continuous performance test Digit-span memory, visual learning memory 2-back test (our study) 	Ambient CO₂ 5000 ppm Zhang et al. (2017) 500 vs. 1000 vs. 3000 ppm 500 vs. 1000 vs. 3000 ppm 1 Snow et al. (2019) 1 Liu et al. (2017) 1 380 vs. 3000 ppm 1 This study * 1 1500 vs. 3500 vs. 5000 ppm 1	 No significant effects on short-term memory.
 Attention D2 test Continuous performance test, Shifting attention test D2 test Psychomotor vigilance test VS test (our study) 	Ambient CO ₂ 5000 ppm Zhang et al. (2017) 500 vs. 1000 vs. 3000 ppm Snow et al. 2019) (→ (shifting attention*)→ 830 vs. 2700 ppm Liu et al. (2017) → Bang et al. (2021) * 1500 vs. 3500 vs. 5000 ppm This study * 1500 vs. 3500 vs. 5000 ppm	 Significantly adverse effects on attention observed in Snow et al. (2019) and Pang et al. (2021) and our study. No significant effects on attention observed in and Zhang et al. (2017) and Liu et al. (2017).
 Decision-making SMS test SMS test SMS test BART test (our study) 	Ambient CO ₂ 5000 ppm Satish et al. (2012)* 600 vs. 1500 vs. 2500 ppm Allen et al. (2016)* 550 vs. 945 vs. ↓ 1400 ppm Rodeheffer et al. (2018) 600 vs. 2500 vs. 15000 ppm This study * 1500 vs. 3500 vs. 5000 ppm	 Significantly adverse effects on decision-making ability observed in Satish et al. (2012) and Allen et al. (2016) and our study. No significant effects on decision-making ability observed in Rodeheffer et al. (2012).
Executive ability Stroop test Stroop test Stroop test Stroop test Stroop test (our study) 	Ambient CO ₂ 5000 ppm Zhang et al. (2017) 500 vs. 1000 vs. 3000 ppm ↓ Snow et al. (2019)* 830 vs. 2700 ppm Liu et al. (2017) 380 vs. 3000 ppm This study * 1500 vs. 5000 ppm	 Significantly adverse effects on executive ability observed in Snow et al. (2019) and our study. No significant effects on executive ability observed in Zhang et al. (2017) and Liu et al. (2017).

Figure 8. Results summary of additional pure CO₂ effects on the five cognitive abilities. * Studies with statistically significant (p < 0.05) changes in performance metrics [6,10–14,35].

The main negative effect on cognition observed in this study is delayed reaction, which is consistent with the summary of Du et al. [36] that indicated accumulation of CO_2 and other indoor pollutants could reduce the reaction speed of various cognitive tests but leaves the accuracy unaffected. The difficulty of a test determines its capability for observing changes in cognitive performance metrics. Therefore, the nonsignificant effect on performance metrics was possibly due to the relatively low difficulty of the cognitive tests we used, most of which were accomplished with accuracy rates higher than 95%. In contrast, the SMS test let subjects experience the management of a business strategy in a

competitive business environment, which is more difficult than other cognitive tests used in the reviewed literature. As assessed by the SMS test, the increased CO_2 exposure from 550 to 1400 ppm could result in a 50% reduction in cognitive function scores [11]. This supports that the speculation that the effect of CO_2 exposure on cognitive performance could be more pronounced with increasing task difficulty and workload.

4.2. Potential Mechanism Underlying the Cognitive Performance

The underlying mechanism of CO_2 affecting cognition may be the interaction between passive protection and subjective adaption. With the elevation of CO₂ concentrations, passive protection triggered by physiological regulation, such as the increase in sympathetic activity and deep breath [37,38], would reduce arousal levels and lead to further cognitive decline. This will increase the need for extra mental effort and arousal level to accomplish cognitive tests. According to the fight-or-flight response theory [39], a state of physiological arousal occurs when the human body perceives stress caused by an unfavorable environment. In this case, people will devote more energy to maintaining their cognition through subjective adaption, which helps to counteract the detrimental effect of elevated CO_2 concentration on cognitive performance. The increased arousal level could maintain cognitive performance, but may sacrifice cognitive speed to some extent. As demonstrated in this study, the accuracy metrics of the Stroop test and the VS test were not affected by increasing concentrations, but at the expense of slower responses. The participants also tended to be more hesitant in making risky decisions in the BART at higher concentration. The response times of tests for perception and short-term memory tests were not significantly affected, probably because less additional mental effort was required. In sum, the detrimental effect of high CO₂ concentration on cognitive performance may be induced by passive protection, and then be alleviated when subjective adaption is activated. It can also be inferred that the accuracy metrics may be significantly reduced if the difficulty level or CO2 concentration further increases, when subjective adaption is not sufficient to meet the demands of extra mental work.

4.3. Exposure Limit for CO₂ Concentration in Workplaces

ASHRAE recommends that indoor CO_2 concentrations should be maintained at or below 1000 ppm to ensure adequate ventilation for acceptable indoor air quality. The current 8 h permissible exposure limit is 5000 ppm as regulated by the Occupational Safety and Health Administration (OSHA) and the American Conference of Governmental Industrial Hygienists (ACGIH). However, current indoor CO₂ concentration standards have not taken into account the maintenance or improvement of cognitive function, despite growing evidence pointing to the negative impact of CO_2 on cognitive function. As discussed in this study, exposures to elevated CO₂ concentrations above 1000 ppm have been reported to adversely affect various cognitive abilities, and the effects would become more significant with increasing exposure concentrations and task difficulty. Specifically, the findings of our study suggest delayed responses could occur during the CO_2 exposure at a concentration of 5000 ppm, when performing the cognitive tests of visual attention, risky decision-making, and executive ability. Slow reaction (lapse) has been considered as one of the most important factors leading to human error accidents [40]. Therefore, the current occupational exposure threshold of 5000 ppm may not meet the requirements for rapid response and operational safety in workplaces, especially for those enclosed environments (e.g., submarines, cockpits, space stations), where staff members are routinely exposed to high concentrations of CO₂. To prevent human error accidents due to cognitive decline, we suggest formulating more stringent occupational regulations on permissible exposure limits for CO_2 .

4.4. Limitation of This Study

There are several limitations to consider when interpreting the results of this study. A major limitation is the unbalanced order of CO_2 exposures among the participants, because

there was insufficient time to establish different CO_2 conditions in one day. This could lead to potential confounding effects of prior exposures. Another limitation is that the recruited participants were limited to fifteen healthy college-age male students. The sample size was only fifteen as limited by the experimental resource. Because of the relatively small sample size, the statistical power could be lowered [41], which indicates that the effects of *p*-values modestly higher than 0.05 are also worthy of attention. Only college-age male students were recruited, considering the CO_2 effects could be related to the population type and our target population was the operators in high-duty workplace environments. Therefore, a larger and mixed study population would be desirable in future research. In addition, the assessment of human cognitive function was limited by the performance metrics of six cognitive tests, which covered only certain aspects of cognition. The cognitive tests employed in our study were also relatively easy. Therefore, to further study the cognitive abilities from more perspectives, additional cognitive tests of different types and difficulty levels are suggested to be involved. It is possible to observe a greater effect of CO_2 exposure on human cognition as the increase in test difficulty and mental workload.

5. Conclusions

In this study, fifteen participants were recruited to perform six classic cognitive tests under three CO₂ conditions (1500, 3500, and 5000 ppm) to investigate the sole effects of CO₂ exposure on five work-related cognitive abilities. The statistical results showed that perception and short-term working memory were only marginally affected by increased CO₂ concentrations. However, attention, risky decision-making, and executive abilities were significantly impaired at 5000 ppm, as indicated by a significant increase in response time, though leaving the accuracy metrics unaffected. It can be inferred that people have to devote more energy to maintaining cognition through subjective adaption, which helps to combat the cognitive decline caused by elevated CO₂ concentrations, but at the cost of slower cognitive speed. The adverse effects of CO₂ on cognitive performance may even become more pronounced as concentrations and task difficulty increased. The research findings suggest that to meet the cognitive requirements for rapid response and operational safety, CO₂ controls in enclosed workplaces should be more stringent than the current permissible exposure limit.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/atmos13060891/s1, Table S1. GAMM results of the CO2 effects on the cognitive test performance metrics; Table S2. Values of the cognitive test performance metrics.

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