Effects of elevated carbon dioxide levels on response speed in cognitive test

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Abstract. To explore the associations of exposure to carbon dioxide with adults' response speed, 69 participants were invited to participate in the experiment conducted in an environmentally controlled chamber. Participants were exposed alone in three separate sessions, each lasting one hour, with a fixed ventilation rate, temperature and relative humidity level and the CO_2 levels fixed at 600ppm, 1500ppm and 2100ppm, respectively. A validated neurobehavioral test battery, the Behavioural Assessment and Research System (BARS) was used to assess participants' cognitive performance, and response times were collected. Response speed was assessed in ten different tests. After adjusting for potential confounders (age, gender, and education), results showed no significant differences in eight out of the ten neurobehavioral tests. For the Selective Attention test, participants responded faster (lower response time) under CO_2 levels of 2100ppm compared to 600ppm (adj.β-coef. -17.57, 95% CI (-29.45, -5.68), p-value=0.004). For the Progressive Ratio Test, participants' response times significantly decreased with CO_2 levels increased. Results indicate no statistical link between CO_2 levels and response speed, with only two out of ten comparisons being significant.

1 Introduction

Human exposure to indoor carbon dioxide has grown over time due to climate change, which has led to a rise in the CO_2 concentration level of ambient air, while ventilation rates have been substantially decreased for energy-saving goals. High concentrations of carbon dioxide have been associated with an increased risk of sick building syndrome among building occupants and a decline in human performance [1]–[3]. Carbon dioxide has served as a biomarker of indoor air quality since the 19th century, and its concentration level has long been used to guide ventilation practices. However, carbon dioxide itself started to gain attention in an emerging number of studies investigating whether there is a direct impact on humans in the indoor environment, especially on cognitive performance [4]–[18].

The findings are controversial and inconsistent. Adverse effects of carbon dioxide on cognitive processes have been reported by some lab studies [4], [5], [7], [8], [11], [16], [17], [19] with fixed ventilation rates and studies [13], [14], [18], [20]with varying ventilation rates. In contrast, some studies found no statistically significant effects on cognitive performance during exposures of university students for 4.25h to CO_2 levels of 500, 1000 and 3000ppm with a fixed ventilation rate of 33.3L/s per person keeping bioeffluents sufficiently low [12] and during exposures of submariners for 2.5h to CO_2 levels of 600, 2500 and 15000ppm [15] with varying ventilation rates. With adjusting ventilation rates during the experiment, the concentration of other indoor pollutants might also be affected and contribute to the decrement of cognitive performance.

Response speed was widely used in previous studies as one of the key parameters to measure people's cognitive performance. Among the studies which found significant effects of CO_2 on cognitive performance, some did not find significant effects of exposures to elevated CO_2 levels on response speed [17], [18], some studies found that response speed significantly increased in some cognitive tasks under higher concentrations [20], and some showed decreased response speed under higher CO_2 levels [6]–[8], [13], [21].

The conflicting outcomes between the studies may come from the diverse cognitive performance assessment methods used in the experiment, different subjects, varied ventilation rates and disparity in the experimental procedure. The sensitivity, validity and cognitive load of different test tools might have affected the results. Some studies used relatively simple tasks like text typing, arithmetical calculations and proof-reading [4], [8], [12]; Kajtár [4] did not find significant decrements in performance until he increased the workload with a more challenging text in the second series of exposure. Tu [8] reported significant findings on cognitive performance for response speed; significant decreases were found in text typing when CO_2 levels increased from 8000 ppm to 12000 ppm. Several studies that used validated test batteries to assess participants' cognitive performance during the exposures found significant effects [6], [16], [17], [20]. In contrast, Maniscalco's [9] study utilised a test battery Attentional Performance and showed no effects on cognitive performance at CO_2 levels as high as 20,000 ppm. Ahmed [20] reported that response speed increased at higher CO_2 levels, although Zhang [6] observed the reverse result, and Snow [17] found no effect on response speed. Four studies conducted in the United States used Strategic Management Simulation (SMS) to test participants' higher-order decision-making based on different proposed scenarios [5], [11], [15], [18]. Two of the four investigations indicated significant effects of carbon dioxide on cognitive performance with fixed ventilation rates. However, Rodeheffer found no effects with varied ventilation rates throughout the exposure, even at high CO_2 levels of 15000 ppm. Most SMS studies did not report results of response speed. Scully reported no significant main effect on overall speed; however, the overall speed at 1200 ppm was significantly slower than at 600 ppm and 2500 ppm.

Table 1 Effects of exposures to CO_2 on cognitive performance and response speed in previous studies ([a]Ventilation rates used in the studies; [b]Effects of exposures to CO_2 on cognitive performance, where Yes = significant effects, and No = no effects; [c]Effects of exposures to CO_2 on response speed, * means significant difference between the two exposure levels, (+) means response speed increased at higher CO_2 levels, (-) means response speed decreased at higher CO_2 levels)

Information of studies	CO_2 levels (ppm)	Vent.[a]	Cognitive Task	Effect[b]	Response speed[c]
Satish et al., 2012 [5]	600,1000, 2500	24.85 l/s/p	SMS	Yes	
Kajtar et al., 2012 [4]	a.600,1500, 2500,5000 b.600,1500, 3000,4000	120m³/h	Proofread	a. No b. Yes	
Allen et al., 2016 [11]	500, 1000, 1400	18.6 l/s/p	SMS	Yes	
Zhang et al., 2017 [12]	500, 1000, 3000,	33.3 l/s/p	Multiple tasks	No	No effect
Maula et al., 2017 [13]	540, 2260	28.2 and 2.3 l/s/p	Multiple tasks	Yes	Retrieve: 540 vs 2260*(-)
Ahmed et al., 2017 [14], [20]	600, 1000, 1800	Varying Vent.	BARS	Yes	600 vs 1000*, 600 vs 1800* (+)
Rodeheffer et al., 2018 [15]	600,2500, 15000	Varying Vent.	SMS	No	
Allen et al., 2019 [16]	700,1500, 2500	850 l/s	FAA PTS	Yes	
Scully et al., 2019 [18]	600,1200, 2500,5000	Varying Vent.	Cognition + SMS	Yes	No effect
Snow et al., 2019 [17]	830, 2700	Infiltration	CNS Vital signs	Yes	No effect
Zhang et al., 2020 [6]	1500, 3500, 5000	8.68 l/s/p	MATB	Yes	MATB: 1500 vs 3500* (-)
Pang et al., 2021 [7]	1500, 3500, 5000	8.68 l/s/p	PVT+ Cog. tasks	Yes	PVT: 1500 vs 5000* (-)
Cao et al., 2022 [21]	1500, 3500, 5000	8.68 l/s/p	Multiple tasks	Yes	VS, BART, Stroop: 1500 vs 5000* (-)
Zhijun Tu, China, 2021 [8]	8000, 10000, 12000	1.8m³/h	Typing + Addition	Yes	Typing: 8000 vs 12000* (-)
Maniscalco et al., 2021 [9]	770, 20000	340m³/h	TAP	No	No effect

The contradictory results from previous studies stimulated this research project, conducted in an environmentally controlled chamber, to elucidate the effects of carbon dioxide on response speed, using the systematically structured validated test battery Behavioral Assessment and Research System (BARS) [22]. This study investigates the hypothesis that independent of ventilation rates, occupants' response speed increases at higher CO_2 concentration levels.

2 Methods

Participants were invited to participate in the experiment conducted in an environmentally controlled chamber. With a fixed ventilation rate, temperature and relative humidity level, participants were exposed alone to three CO_2 levels. A validated neurobehavioral test battery BARS was used to assess participants' cognitive performance, and their response times were collected. This study was granted low-risk ethical approval (20201027_IEDE_PGR_ETH) by the UCL BSEER Research Ethics Committee.

2.1 Facilities

The study was carried out in a 4.375m wide × 4.55m deep × 3.0m high stainless-steel chamber. The chamber is located within a lab on the ground floor of the building. The chamber can create a typical indoor environment as expected in real buildings with defined parameters (ventilation rates, temperature, and relative humidity). The construction ensures that the chamber volume is tightly sealed when the door is closed.

The precise control of the chamber environment is realised through the Watlow F4T Programmable Controller to achieve defined parameters of temperature, humidity, CO_2 concentration level and ventilation rates. Air circulation is realised through fans with fan speed control. The fresh air is drawn from the building ventilation system and is expelled into the test area through a diffuser. The return air from the chamber exits through the outlet into the building ventilation system. Chemically pure CO_2 is added automatically from the cylinder and well mixed with supply air to reach the desired test levels. Two carbon dioxide monitoring and alarm system are configured for the safety of the chamber environment.

2.2 Participants

Sixty-nine participants were recruited from UCL students through internal email lists, advertisements placed on the university campus and social media, with permission obtained. Thirty-seven females and 32 males were included, with a mean age of 25 ± 4 (mean ± SD) years old. All participants were adults in a healthy state at the time of the experiment, and did not show any symptoms of COVID-19. Recruitment criteria also required that they should be non-smokers without learning disorders.

2.3 Experimental protocols

Participants received a reminder email with an information sheet and instructions for the experiment before the exposure day. The night before the experiment, participants were asked to ensure adequate sleep and avoid intense physical activity for at least 12 hours beforehand. On the day of the experiment, it was advised not to drink coffee, soda, energy drinks, or chocolate and avoid non-essential medications, including caffeine. Additionally, participants were urged not to use perfume or other scent-heavy products.

Every participant visited the chamber at UCL Here East once every month for three months, and there was a four-week interval between the two adjacent experiment sessions. Each session lasted about 70 minutes. Participants were tested alone in the chamber. The first 5 minutes was an introduction to the experiment; participants gave written and informed consent to the participation. After the introduction, the researcher left the chamber and participants were suggested to do some quiet non-work-related activities for 20 minutes to adapt to the chamber environment. At the end of this session, participants filled in the pre-questionnaire to make a self-assessment of the perceived air quality and comfort. Subsequently, participants completed cognitive tests of BARS on the laptop, which lasted for 30-40 minutes. After the test, participants filled in a self-assessment post-questionnaire and left the chamber.

2.4 Experimental conditions

Participants were exposed to three conditions of CO_2 levels at 600 ppm, 1500 ppm and 2100 ppm, in a balanced order. At baseline condition, CO_2 was reduced to the background levels with a high ventilation rate of $108m^3/h$. Higher CO_2 levels were achieved by injecting chemically pure CO_2 into the chamber from the cylinder. The ventilation rate was kept constant in all three conditions, as well as temperature (23˚C) and relative humidity (50%). Noise levels were kept stable and low with noise-cancelling headphones on.

2.5 Measurements

Carbon dioxide concentration levels, temperature and relative humidity levels were monitored continuously with two sensors: a factory-calibrated movable TESTO 480 monitor and a wall-fixed Rotronic sensor linked with the chamber system. Continuous measurements were conducted for TVOC levels with A PhoCheck Tiger monitor and PM levels with a DUST TRAK DRX during the experiment. Lighting intensity was measured with a lux meter Konica Minolta T-10A.

Behavioural Assessment and Research System (BARS) was used to assess participants' cognitive performance, and their response times were collected. The BARS test battery included ten tests: Match to Sample, Continuous Performance Test, Symbol Digit, Tapping, Simple Reaction, Reversal Learning, Selective Attention, Digit Span, Serial Digit Learning and Progressive Ratio Test. Ten tests were arranged in a balanced order for all participants in the experiment to minimise order effects.

2.6 Statistical analysis

Univariable linear mixed-effect models assessed the associations between response speed, CO_2 and the confounding factors of age, gender, and education. The confounders were chosen based on evidence from the literature and are listed in Table 2. To correct for confounding, a multivariable model was performed to compare differences in response time across three conditions, adjusting for the confounding factors. The analysis was performed using IBM SPSS Statistics (version 28.0.0.0), and a p-value<0.05 was considered statistically significant.

Table 2 Associations of age, gender, and education with cognitive performance in some BARS tests
(MTS- Match to Sample, CPT- Continuous Performance Test, SDT-Symbol Digit, TAP- Tapping, DST- Digit Span, SRT- Simple Reaction)

Test	Potential demographic confounders		
	Age	Gender	Education
MTS [23]	In the adult group, older people have worse performance.		
CPT [24], [25]	In the adult group, older people have worse performance.	Females have slower reaction time.	Improve with education levels.
SDT [26]	In the adult group, older people have worse performance	Females have better performance than males.	Improve with education levels.
TAP [27], [28]	In the adult group, older people have worse performance.	Males have better performance than females.	
SRT [29]	Performance improves with age increases.		
DST [30], [31]	Performance improves with age increases.	Males have better performance than females.	Improve with education levels.

3 Results

Measured conditions in the environmental chamber during exposures are listed in Table 3. The data demonstrate that CO_2 levels at baseline condition were maintained within ± 10%, and CO_2 levels of the other two conditions were maintained within ± 2% of exposure levels. None other measured environmental parameters differed significantly among the target CO_2 levels (see Table 3). Table 4 summarises the sociodemographic characteristics of the participants in this study. Nearly half of the participants were postgraduate students, with the other half from bachelor and PhD students.

Table 3 Measured conditions during exposures in the environmental chamber (mean ± standard deviation)

Con.	CO_2 (ppm)	Temperature (°C)	RH (%)	Ventilation rates (m^3/h)	TVOC ($\mu g/m^3$)	PM (mg/m^3)
1	633 ± 64	23.18 ± 0.03	49.50 ± 1.45	108.08 ± 0.37	110 ± 99	0.0004 ± 0.0007
2	1520 ± 27	23.18 ± 0.03	49.63 ± 0.88	107.97 ± 0.20	116 ± 105	0.0003 ± 0.0006
3	2120 ± 36	23.17 ± 0.04	49.77 ± 0.12	107.93 ± 0.33	105 ± 103	0.0004 ± 0.0006

Table 4 Summary of the sociodemographic characteristics of the participants

Variable		Number of People	Percentage
Age	18-20	8	11.6%
	21-23	20	29.0%
	24-26	17	24.6%
	27-29	13	18.8%
	30-37	11	15.9%
Gender			
	Female	37	53.6%
	Male	32	46.4%
Education			
	Bachelor	19	27.5%
	Postgraduate	35	50.7%
	PhD	15	21.7%

The estimated means for response times for all BARS tests at each CO_2 exposure level are shown in Fig 1. After adjusting for potential confounders (age, gender, and education), results showed no significant differences in eight out of ten tests (Table 5). For six of the ten tests, response time decreased with elevated CO_2 levels, but only two found statistically significant effects. For the Selective Attention test, participants responded faster (lower response time) under CO_2 levels of 2100ppm compared to 600ppm (adj.β-coef. -17.57, 95% CI (-29.45, -5.68), p-value=0.004). For the Progressive Ratio Test, significant effects of elevated CO2 levels on response time were found at 1500ppm (adj.β-coef. -4.80, 95% CI (-8.87, -0.72), p-value =0.021) and 2100ppm (adj.β-coef. -6.10, 95% CI (11.53, 0.67), p-value=0.028).

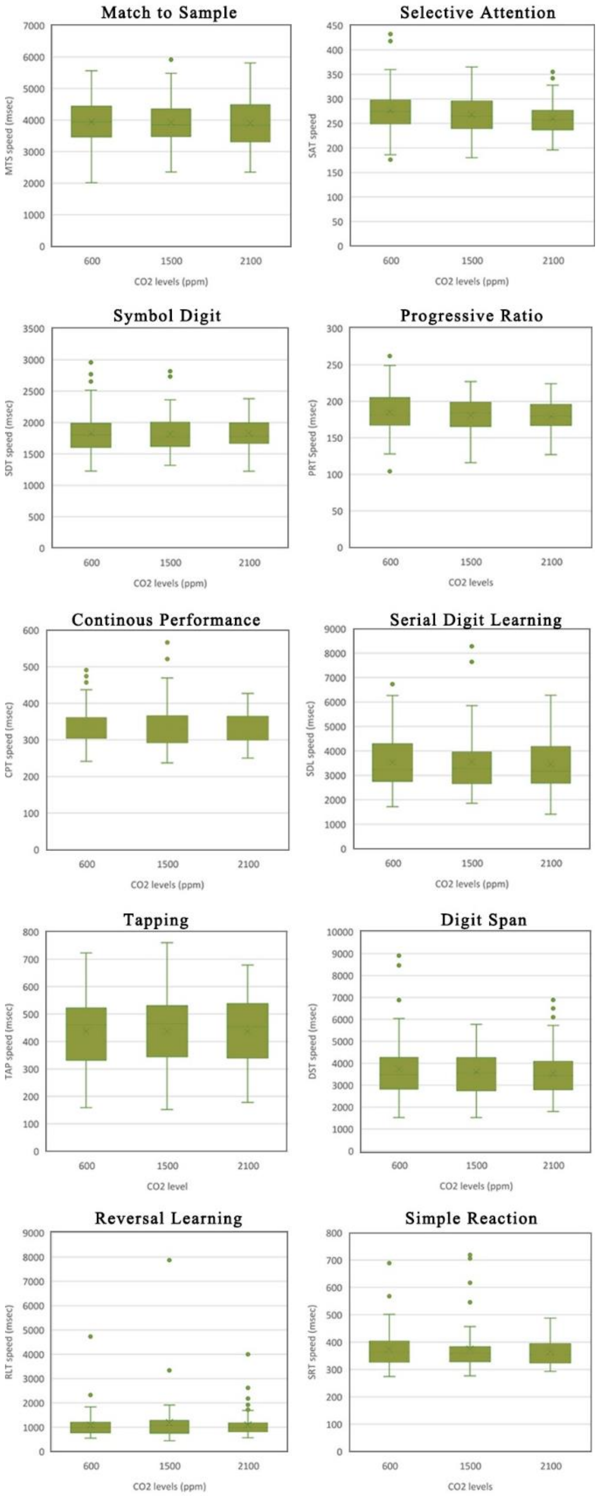

Figure 1 Boxplots of response time in ten BARS tests at three exposure conditions

Table 5 Univariable and multivariable associations of conditions with response speed in ten BARS tests (Con.-conditions; 1- CO_2 levels at 600 ppm, 2- CO_2 levels at 1500 ppm, 3- CO_2 levels at 2100 ppm; MTS- Match to Sample, CPT- Continuous Performance Test, PRT- Progressive Ratio Test, SDT- Symbol Digit, SDL- Serial Digit Learning, TAP- Tapping, DST- Digit Span, SRT- Simple Reaction, SAT- Selective Attention Test, RLT- Reversal Learning)

Con.	Univariable models β- coeff. (95% CI)	p-value	Multivariable models* β- coeff. (95% CI)	p-value
MTS				
1	Ref.		Ref.	
2	-11.06 (-190.66, 168.55)	0.90	-11.06 (-190.91, 168.79)	0.90
3	-36.81 (-256.81, 183.19)	0.74	-36.81 (-254.76, 181.14)	0.74
CPT				
1	Ref.		Ref.	
2	-1.58 (-11.59, 8.43)	0.76	-1.58 (-11.57, -8.41)	0.76
3	-8.58 (-21.55, 4.39)	0.19	-8.58 (-21.46, 4.30)	0.19
PRT				
1	Ref.		Ref.	
2	-4.80 (-8.87, -0.72)	**0.02**	-4.80 (-8.87, -0.72)	**0.02**
3	-6.10 (-11.54, -0.66)	**0.03**	-6.10 (-11.53, -0.67)	**0.03**
SDT				
1	Ref.		Ref.	
2	-6.13 (-59.81, 47.55)	0.82	-6.13 (-59.72, 47.46)	0.82
3	2.04 (-68.37, 72.46)	0.95	-2.04 (-68.09, 72.18)	0.95
SDL				
1	Ref.		Ref.	
2	21.45 (-285.85, 328.75)	0.89	21.45 (-287.20, 330.10)	0.89
3	-70.72 (-433.05, 291.60)	0.70	-70.72(-428.45, 287.00)	0.70
TAP				
1	Ref.		Ref.	
2	-0.33 (-29.94, 29.27)	0.98	-0.33 (-29.89, 29.22)	0.98
3	-1.59 (-38.56, 35.37)	0.93	-1.59 (-38.11, 34.92)	0.93
DST				
1	Ref.		Ref.	
2	-134.68 (-450.27, 180.91)	0.40	-134.68 (-450.38, 181.02)	0.40
3	-193.90 (-558.69, 170.89)	0.30	-193.90 (-556.93, 169.13)	0.30
SRT				
1	Ref.		Ref.	
2	-0.65 (-19.21, 17.91)	0.95	-0.65 (-19.22, 17.92)	0.95
3	-8.97 (-30.22, 12.28)	0.41	-8.97 (-30.19, 12.25)	0.41
SAT				
1	Ref.		Ref.	
2	-8.88 (-18.73, 0.96)	0.08	-8.88 (-18.72, 0.95)	0.08
3	-17.57 (-29.57, -5.56)	**0.004**	-17.57 (-29.45, -5.68)	**0.004**
RLT				
1	Ref.		Ref.	
2	100.26 (-130.39, 330.91)	0.39	100.26 (-130.38, 330.90)	0.39
3	6.81 (-221.50, 235.12)	0.95	6.81 (-220.44, 234.06)	0.95

*Model adjusted for age, gender and educational background

4 Discussion

Our findings diverged from those anticipated by earlier studies that demonstrated adverse effects of CO_2 on response speed and were consistent with those that reported no effects. Although six of ten tests exhibited a trend of increase in response speed, only two reported significant differences between conditions.

Compared with most studies which found adverse effects on cognitive performance, our study used a relatively lower CO_2 level, independent of ventilation rates. It aims to examine the effect at levels close to people's daily life scenario, as in Building Bulletin 101, 1500 ppm is the recommended threshold, and 2100 ppm corresponds to a minimum threshold value for a ventilation rate of 3l/s/p [32]. The drastic increase in exposure conditions compared with baseline conditions tended to be more likely to exhibit the effects of CO_2 on people. While in similar exposure conditions to Satish et al. [5] of 600, 1000 and 2500 ppm, as well as to three of four conditions in Scully's study [18] of 600, 1200, 2500 and 5000 ppm, both were utilising SMS test and found significant effects on cognitive performance, but Scully et al. report no main effect on response speed. This difference may be attributed to the different cognitive loads of SMS and BARS test batteries. SMS is a highly demanding test battery, and compensatory mental effort may be limited; hence, the effects of CO_2 might be observed at low concentration levels. But this difference did not affect response speed, as neither our research nor Scully's revealed the main effects on response speed.

Our findings of the Selective Attention test and Progressive Ratio align with past research utilising the BARS test battery [20], in which significant increases in response speed were found at CO_2 levels of 1000 and 1800 ppm. As Zhang et al. [12] discussed in their study, arousal level has impact on performance. For simple tests aiming at concentration and attention, performance increases under high arousal, but as the difficulty of tests increases, an inverted-U shape relationship has been reported between performance and arousal, higher arousal leads to decreases in performance, like executive thinking [33]. The increase in response speed in the Selective Attention and Progressive Ratio test could be due to higher arousal associated with elevated CO_2 levels [34]. Selective Attention test is mainly associated with people's attention and the Progressive Ratio test measured individual's motivation and concentration. In these two tests, participants performed better with higher arousal induced by higher CO_2 levels.

Overall, our findings concur with research reporting null effects on response speed exposed to elevated CO_2 levels under fixed ventilation rates [35]. As all participants were chosen from top university students, which were admitted with good academic performance and executive function skills, this homogeneous sample may explain why they had similar performance in the BARS test regardless of changes in CO_2 levels. Future research should explore the relationship between exposure to CO_2 and response speed in a broader population range.

5 Conclusion

This study examined whether carbon dioxide itself has effects on people's cognitive performance, independent of ventilation rates. Statistically significant increases in response speed were found when increasing CO_2 levels from 600 to 2100 ppm in the Selective Attention and Progressive Ratio tests, which could be due to higher arousal level triggered by higher CO_2 levels. However, with only two out of ten tests finding significant effects, the findings suggest no statistical link between exposure to CO_2 levels and response speed.

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