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Research Article

Field Investigations on Subjective Perception, Physiological Responses, and Cognitive Performance under Increasing CO_2 Concentration in an Underground Confined Space

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The objective of this research was to explore the impacts of heightened CO_2 concentrations on human health and wellness in an underground confined space. A total of 180 participants were subjected to CO_2 concentrations ranging from 1000 to 10000 ppm within a confined underground environment. The study assessed not only subjective perceptions and physiological responses but also cognitive performance, integrating novel measures such as emotion, skin conductance (SC), and heart rate variability (HRV). The findings demonstrated a notable variation in thermal sensation votes (TSV) and perceived air quality acceptability with the change in CO_2 concentration. A significant increase in total mood disturbance (TMD) of 1.5 units was observed at a CO_2 concentration of 8500 ppm, compared to 1000 ppm. Cognitive performance remained consistent for concentrations below 8500 ppm; however, a substantial alteration was noted at 10000 ppm. In terms of task difficulty, numerical calculations were perceived to require 0.74 units more effort than letter searches. As CO_2 concentration exceeded 7500 ppm, significant variances were noted in physiological parameters such as diastolic blood pressure (DBP), heart rate (HR), LF/HF, MF/HF ratios, PNN 50, and frequency domains of HRV (LF, MF, and HF) in comparison to the parameters at 1000 ppm. At 8500 ppm, the LF and HF parameters were found to be 780 and 452.3 units, respectively, higher than at 7000 ppm. These findings suggest that high humidity, low temperature, and elevated CO_2 concentrations collectively contribute to the significant human stress responses. This study is of interest as there are limited reported researches on the air quality in underground confined space.

1. Introduction

The growing emphasis on sustainable energy utilization has accelerated the development and utilization of underground spaces, such as subways, underground shopping centers, and gymnasiums, which often accommodate large populations. In wartime, these areas might be transformed into isolated and protected spaces. The enclosed nature and poor ventilation of these spaces lead to rapid increases in CO_2 concentration, humidity, and bioeffluent levels [1]. In such confined environments, CO_2 levels can surpass 10000 ppm, with instances recorded of up to 25000 ppm in underground coal mine refuges, and in some extreme cases even 30000 ppm [2]. It is important to note that the comprehensive environmental assessments and perceptual shifts within these underground environments markedly differ from those of surface structures [3].

To study the effects on perception and cognition in these confined underground spaces, Li et al. [4] conducted surveys and field measurements across 249 representative cities in China. They uncovered substantial discrepancies between the average thermal sensation and the predicted mean vote (PMV), as calculated from practical measurement data. The research in [5] demonstrated varying comfort levels in comparison to ordinary environments, attributing this variation to distinct psychological and physiological responses under extreme conditions. Researchers like Lan et al. [6], Zhang et al. [7], and Pan et al. [8] highlighted that subjective perceptions are greatly influenced by psychological responses. Alterations in lighting, activity areas, and living conditions in underground spaces can induce feelings of nervousness, depression, and restlessness, resulting in psychological fluctuations that greatly diverge from surface environments. It remains uncertain whether thermal sensations, physiological responses, subjective perceptions, and cognitive performance undergo significant changes in these confined underground settings.

CO_2 serves as a reliable indicator of required outdoor air supply rates [9]. According to Li et al. [4], underground engineering environments tend to enhance cold sensations while diminishing warm ones, in contrast to predicted mean vote (PMV) values. Moreover, the actual thermal sensation deviates notably from the expected with the combined influence of high CO_2 concentration and humidity [3]. Dong et al.'s [10] isolation experiments in confined underground spaces demonstrated a tendency for CO_2 concentration to skew PMV values. Concurrently, cognitive performance appears to deteriorate with increasing CO_2 levels, likely a result of inadequate ventilation. This decline has been observed in numerous psychological examinations targeting academic performance [11, 12] and attention span [13, 14] which were negatively affected by lower ventilation rates.

Cognitive performance impairment was reported at CO_2 levels of 3000 ppm [15], while decision-making abilities were compromised at levels as low as 1000 ppm [16, 17]. However, studies by Liu et al. [18] and Zhang et al. [19–21] suggested that a CO_2 concentration of 3000 ppm does not affect the subjects' performance in neurobehavioral tests and multitasking examinations. Rodeheffer et al. [22] proposed that acute CO_2 exposure at levels of 600, 2500, or 15000 ppm had no impact on submariners' decision-making performance. The exact mechanism by which CO_2 levels influence perception and whether they affect human thermal sensation via emotional and acute reactions remains uncertain. Field studies have consistently linked elevated CO_2 concentration with subjectively assessed acute health symptoms [16, 23] and perceived air quality (PAQA). Symptoms such as headaches, eye irritation, and respiratory issues have been reported by occupants in buildings where CO_2 levels were below 5000 ppm [4, 24].

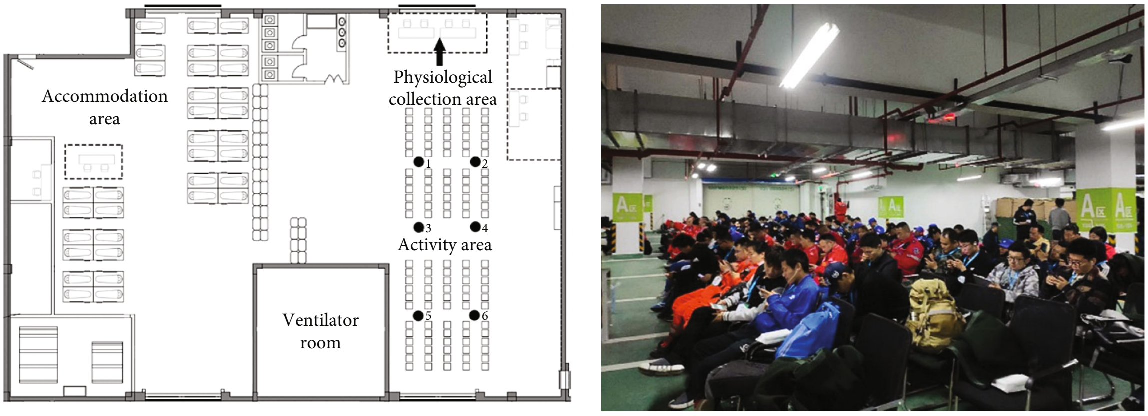
These studies feature observed reactions influenced by multiple factors, not solely attributable to CO_2 effects. To isolate the influence of bioeffluents, pure CO_2 was introduced into the laboratory [25]. Physiological responses to high concentrations of pure CO_2, such as exposure from 50000 to 150000 ppm for 10 to 20 minutes [26, 27], were studied, with some reports indicating initial adverse effects of CO_2 at levels around 12000 ppm [28]. Zhang et al. [21] used a high air supply rate to control bioeffluents, establishing a reference exposure condition of 5000 ppm CO_2. They discovered that a 2.5-hour exposure to pure CO_2 did not intensify reported health symptoms. Zhang et al. [21] also suggested extending exposure time to better understand CO_2's impact on the human body. Vehviläinen et al. [29] examined blood CO_2 concentration and found that physiological compensatory mechanisms could maintain stable blood CO_2 concentrations during the initial hours in high CO_2 environments. They postulated that CO_2's potential adverse effects might necessitate longer exposure periods. However, the mechanism and physiological impact of CO_2, particularly in underground confined spaces, remain largely unclear.

To summarize, while numerous studies have examined CO_2 concentration effects in artificial climate laboratories, there has been a paucity of field research investigating large-scale populations in underground confined spaces. Lengthier exposure durations may be needed to scrutinize high CO_2's impact on human responses. The effect of increasing CO_2 concentration on human response in underground confined spaces is not well understood, and the relationship between physiological parameters and cognitive performance in such spaces has not been sufficiently explored. This study, therefore, is aimed at conducting a field experiment in an underground confined space to examine the varying threshold of CO_2 acceptability and explore the effects of CO_2 concentration on subjective perception, physiological responses, and cognitive performance. Further, the impact of prolonged exposure to CO_2 will be discussed, exploring the relationship between physiological responses and acute reactions. This study will augment existing evidence on the effects of increased CO_2 levels on human responses, particularly by incorporating measurements of emotion, skin conductance, heart rate variability, and more, to enhance our understanding and improvement of human health and well-being in underground confined spaces.

2. Methods

2.1. The Underground Confined Space. The experiment was conducted on April 26, 2019, within an underground confined space situated in East Taihu Ecological Park, Suzhou, China (Figure 1). This space, with an overall building area of 900 m^2 and a refuge zone spanning 600 m^2, is divided into an activity area, accommodation area, and physiological collection zone. The structure reaches a height of 3.5 meters and a depth of 15 meters. A constant temperature and humidity conditioning system allows the control of air temperature and relative humidity. Ventilation devices, equipped with a high-efficiency particulate air (HEPA) filter and activated carbon absorbent, facilitate indoor air circulation while keeping levels of biological contaminants, such as VOCs and $PM_{2.5}$, minimal during the experiment. For safety, an alarm function and protection system were installed within the underground confined space.

2.2. Experimental Conditions. Li et al. [4] investigated the thermal environment of underground buildings in China and found the upper limit of humidity in air-defense staff shelters to be 85%. Indeed, the relative humidity often exceeds 80% [1, 3] in such underground confined spaces. Additionally, due to long-term burial underground, the air temperature in underground spaces tends to be close to the ground temperature of the respective region. Given these findings, accurately simulating these environmental conditions is vital when considering individuals seeking refuge during emergencies. Therefore, the experimental control



(a)

(b)

Figure 1: The layout of the experimental underground confined space (a) and an interior view of the same space (b).

variables were set to reflect these actual environmental parameters of underground spaces, specifically maintaining a temperature and humidity of 19°C and 80%, respectively. The experiment was conducted in a completely sealed underground confined space where other physical environmental parameters were controlled and kept stable. The CO_2 concentration naturally escalated from 1000 ppm to 10000 ppm due to the metabolic CO_2 produced by the subjects. The ceiling limits of CO_2 concentration in coal refuge chambers are 10000 ppm [30], and the World Health Organization sets the CO_2 concentration during sealed operation of underground spaces at 1000 ppm [31]. In this study, CO_2 levels at specific increments (1000 ppm, 3500 ppm, 5500 ppm, 7000 ppm, 8500 ppm, and 10000 ppm) were selected as exposure conditions to examine human responses at regular time intervals. The monitored environmental parameters are outlined in Table 1.

2.3. Experimental Classification. Designing experiments with either a within-subject or a between-subject approach requires careful consideration of "validity," "causality," and "statistical power" [32]. For this study, a between-subject design was adopted due to its superior external validity. In order to mitigate the influence of individual differences on the experimental results, an ample number of subjects were enlisted. We used G*Power 3.1.9.7 software to determine the minimum sample size needed for the study, with the preset statistical test power set at $1\text{-}\beta = 0.8$ and the significance level at $\alpha = 0.05$. Typically, a moderate effect size is preset [33]; for this study, we utilized the effect size based on productivity measurements provided by Lan and Lian [34]. The minimum required sample size, calculated using these parameters, is presented in Table 2.

The choice of effect size is dictated by the compelling nature of the statistical results. The effect size for the neurobehavioral tests was calculated using the numerical data from previous studies, thereby expediting the determination of sample size [34]. For instance, as shown in Table 2, the total sample size for HRV data is a minimum of 48 (8 per group), with this study measuring 10 subjects per group. Furthermore, given the uncertainty surrounding the effect size of Electroencephalography (EEG), we measured 10 subjects per group. Additionally, considering the substantial individual differences in both HRV and EEG, a within-subject design was employed for these measurements.

2.4. Subjects. We randomly recruited 180 subjects, consisting of 132 males and 48 females. These subjects were evenly distributed across different CO_2 exposure conditions, with each condition comprising 30 subjects (22 males and 8 females). The demographic data, including gender, age, height, and weight of the participants, is presented in Table 3. The average BMI values of each group are shown in Table 1. Notably, to mitigate the potential influence of age on the experiment, environmentally sensitive individuals such as the elderly and females were equally allocated across all groups. Prioritizing health and safety, we ensured that all subjects were nonsmokers and free from chronic illnesses. They reported no medication use during the experiments and no history of cardiovascular disease. Subjects were instructed to abstain from spicy food, alcohol, strong perfumes, and strenuous activities the day prior to and on the day of the experiment. To minimize bias and the possibility of over-reporting symptoms, all participants received a medical assessment and a comprehensive manual before entering the underground confined space. Additionally, all participants signed informed consent forms. Before the experiment commenced, all volunteers underwent a thorough physical examination. The underground confined space also housed 20 experimenters and medical staff during the study.

2.5. Field Experimental Procedure. The experiment spanned 13 hours, from 8 a.m. to 9 p.m., wherein 180 subjects and 20 support staff were naturally isolated in an underground confined space. During the preparatory phase, participants were instructed to enter the designated area and adjust their attire for thermal comfort within a 30-minute window. After a 30-minute acclimatization period, all experimenters conducted and completed cognitive performance, subjective performance, and physical measurements at 9 a.m. (condition I: 1000 ppm, 180 subjects). These results served as the reference level for the experiment. Three hours later, when

Table 1: Mean values and SD of the physical parameters inside the underground confined space.

Tested conditions	1	2	3	4	5	6
Temperature (°C)	18.6 ± 0.3	18.7 ± 0.2	18.8 ± 0.2	19.1 ± 0.3	19.2 ± 0.2	19.0 ± 0.1
CO_2 level (ppm)	1017 ± 116	3542 ± 192	5485 ± 159	6989 ± 142	8468 ± 119	9965 ± 99
Relative humidity (%)	79.4 ± 0.6	80.5 ± 0.5	79.3 ± 0.6	81.3 ± 0.6	82.5 ± 1.0	83.5 ± 1.0
Illuminance (lux)	135 ± 16	132 ± 23	137 ± 18	135 ± 15	134 ± 19	135 ± 20
BMI	21.6 ± 2.4	23.26 ± 2.9	22.39 ± 2.8	21.83 ± 2.87	22.19 ± 2.67	22.70 ± 3.15

Table 2: Effect size of three types of productivity measurement.

Measurements	Items	Partial eta squared	Effect size	Total sample size
Neurobehavioral tests	Number calculation	0.204	0.506	60
	Letter search	0.038	0.200	330*
Physiological measurements	HRV	0.259	0.591	48
	Galvanic skin (GSR)	—	—	—
	EEG	—	—	—
Subjective perception	Well-being	0.302	0.658	36
	Motivation	0.103	0.339	120
	Emotion (POMS)	0.138	0.400	90

The total sample size was calculated by G*Power software based on statistical test power was $1\text{-}\beta = 0.8$, and the significance level was $\alpha = 0.05$. The term of letter search by "*" was not analyzed to date because of insufficient sample size.

Table 3: Participants' information (mean (min–max)).

Participants' information	Values	
Participants	Male: 132	Female: 48
Age	35.3 (19-56)	36.5 (19-55)
Height (cm)	173.3 (157-183)	163.1 (153-170)
Weight (kg)	70.8 (48-100)	52.1 (45-67)
Clothing insulation (Clo)	1.0	1.0
Activity level (Met)	1.3	1.3

the CO_2 concentration had reached 3500 ppm, a second group conducted the same measures (condition II: 3500 ppm, 30 subjects). This pattern was maintained, testing a group whenever the CO_2 concentration reached a certain level at the same time intervals, while the remaining subjects stayed sedentary. The order sequence of the cognitive performance items was altered in subsequent experiments.

Cognitive performance measurement involved all subjects taking numerical calculation and letter search tests, which were about 10 minutes in duration and given without feedback. Subjective performance measurement required participants to self-evaluate their effort, emotional state, acute health symptoms, and thermal responses using questionnaires, also a 10-minute activity. Physical measurements, including SPO_2, HR, and blood pressure, were taken over an approximately 10-minute period. Notably, due to the limitations of quantitative measuring devices and an effort to minimize individual variances, 10 ECG and EEG testers were randomly selected from the first group. In subsequent experiments, these subjects were exposed to all experimental conditions without any changes. Throughout the experiment, subjects were primarily sedentary in the activity area. They were not permitted to leave the underground confined space, and all measurements were conducted therein. Figure 2 delineates the detailed experiment protocol.

Before the experiment, subjects were briefed about the process. To mitigate the effects of fatigue, they were required to have adequate sleep in the residential area. In the week leading up to the formal experiment, ventilation and harmful gas detection were thoroughly conducted in the underground confined space. Comprehensive ventilation was also executed three days prior to the experiment.

2.6. Experimental Measurements and Questionnaires. The study measured environmental parameters, including temperature, humidity, $PM_{2.5}$, illuminance, O_2, and CO_2, at five-minute intervals. The reported values represent the average measurements of 6 sensors placed at different locations within a confined underground space. These positions are situated at a height of 0.8 m above the ground level. The specific locations are depicted in Figure 1. Table 4 outlines the measuring range and accuracy of the instruments used in the study. To evaluate the subjects' cognitive performance, numerical calculation and letter search tasks were implemented. The letter search was a visual task requiring the participant to quickly identify the presence or absence of a target letter within a string of 10 letters. This task, consisting of 80 stimuli, necessitated selective attention operations and the efficient identification of stimuli [35]. Recorded metrics included response time, number of hits, false alarms, correct rejections, and misses. Numerical calculation was a mental arithmetic test measuring both speed

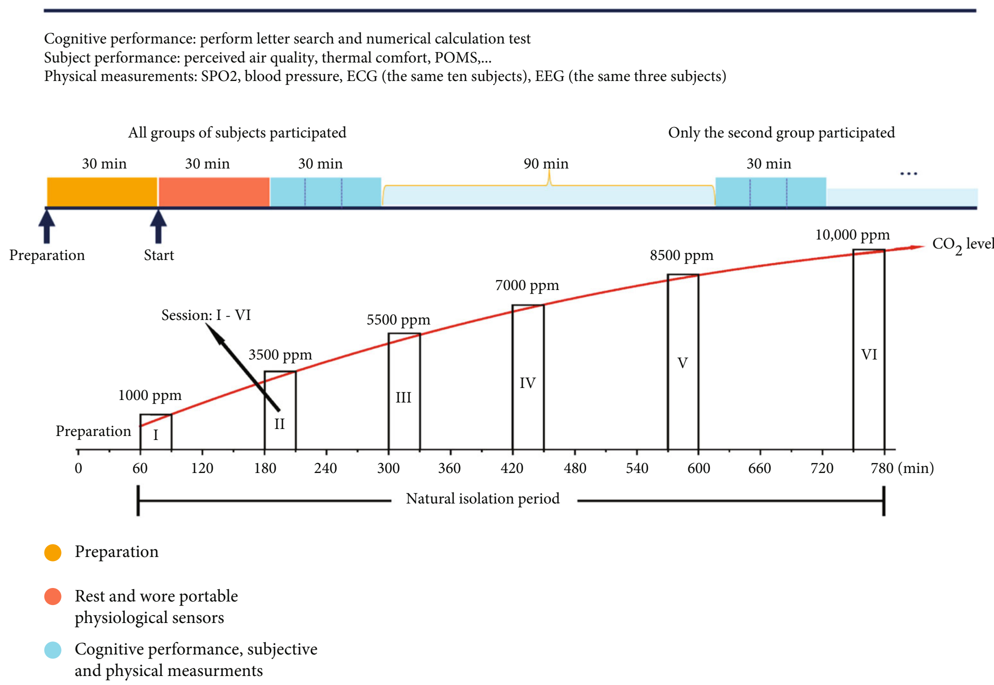


Figure 2: Experiment protocol.

Table 4: Measuring range and accuracy of the instruments used in this study.

Instrument	Testo 425		HUMIPORT	AS8801	TELAIRE	Metrel MI6201
Parameters	V_A (m/s)	T_a (°C)	RH (%)	O_2 (%)	CO_2 (ppm)	Illuminance (lux)
Range	0-20	0-70	10-85	0-30	0-100000	0-20000
Accuracy	±0.03	±0.5	±1.6	±0.1	±50	±0.1

and accuracy. Here, subjects performed operations like addition, subtraction, or multiplication on sets of numbers. The addition task involved summing three two-digit numbers printed in the same vertical column, the subtraction task subtracted three two-digit numbers, and the multiplication task multiplied a three-digit number and a one-digit number [5]. This test included 10 addition tasks, 10 subtraction tasks, and 10 multiplication tasks. The time taken to complete each task and the total number of correct answers served as performance measurements. In both tasks, subjects did not receive any feedback on their performance. Speed and accuracy were considered separate performance metrics. The performance index (PI) evaluated the overall performance, assigning equal weights to speed and accuracy. This was computed by dividing response accuracy by response time (equation) [6].

$$\text{Performance index (PI)} = \frac{\text{response accuracy}}{\text{response time}} = \text{accuracy speed}. \quad (1)$$

This study divided subjective measurements into three categories to facilitate a comprehensive exploration of subjective perception: thermal sensation, self-rated effort, and emotion. Firstly, as CO_2 concentration increases, acute symptoms such as nose dryness, throat dryness, dizziness, fatigue, difficulty concentrating, and sleepiness tend to manifest [17, 29]. This increase also results in a shift of the existing thermal comfort prediction curve [4, 36]. Thus, questionnaires on perceived air quality, thermal sensation, thermal comfort, thermal acceptability, and acute health symptoms were utilized, drawing upon the Thermal Environment Survey of Standard-55 [37], a methodology also employed by Zhang et al. [19] and Li et al. [3]. Secondly, Lan et al. [38] theorized that prolonged exposure might cause cognitive decline, but motivated subjects could maintain efficiency through increased energetic output. Consequently, the study also considered self-assessed effort and neurobehavioral test performance. Lan et al. [38] advocated for including participants' subjective experiences in laboratory-based research. Therefore, to assess the effort related to CO_2 concentration, we recorded self-rated mental effort on a 7-point continuous scale, as suggested by Lan et al. [38]. Thirdly, the profile of mood states (POMS) was used to gauge participants' emotions, encompassing five negative mood states (tension, depression, anger, fatigue, and confusion) and one positive mood state (vigor). The tool, comprising 65 adjectives, such as nervous, tense, careless, and cheerful, was designed to

Table 5: The selection of measurement tools and analysis parameters in this study.

Measurements	Instrument	Project	Index selection	Analysis
ECG	PsyLAB system	HRV	LF, HF, MF/HF	Sympathetic nerve The activity of the vagal nerve Mental workload
		Galvanic skin (GSR)	SC	Emotional arousal
		HR	PNN50	Parasympathetic modulation
EEG	DSI-7-Flex	Rhythm	δ, θ, α, β	Sober and mental relaxation The tension of the cerebral cortex
SPO_2	Cofoe KF-65B	—	—	Supply of oxygen
Blood pressure	Yuwell YX303	—	Systolic blood pressure, DBP	Stress tension

capture the participants' immediate feelings and moods [39]. Each item was scored on a 5-point Likert-type scale, ranging from 0 (not at all) to 4 (extremely). The TMD score, computed by summing the five negative mood scores and subtracting the vigor scores, served as an indicator of overall mood, with higher TMD scores suggesting more negative moods.

Participants' ECG and EEG were recorded using the PsyLAB wireless multichannel physiological system and the DSI-7-Flex wireless EEG system, respectively. The PsyLAB system, utilizing a radio frequency physiological recording technique, can record and detect real-time physiological changes, including ECG and galvanic skin response (GSR). The recorded data was processed, and artifacts were removed via the LAB human-interface environment synchronization platform multivariate data advanced analysis software. The DSI-7-Flex system incorporates 7 ultrahigh impedance active dry sensor interface (DSI) sensors functioning through hair, negating the need for skin preparation or conductive gels. The International EEG Association's 10/20 standard lead system guided the placement of the working electrode [40]. In addition, SPO_2, SC, and blood pressure were measured. Table 5 delineates the measurement tools and analysis parameters utilized in this study.

3. Results

3.1. Subjective Sensation. Table 6 presents a matrix of the results pertaining to participants' emotional ratings. With the increase in CO_2 levels from 1000 ppm to 7000 ppm, participants' tension, fatigue, emotion, and TMD showed a slight but statistically insignificant rise. However, a significant increase ($p < 0.05$) in tension was observed at 8500 ppm, and fatigue and TMD exhibited substantial elevations at 8500 ppm and 10000 ppm compared to the 1000 ppm CO_2 level. Furthermore, participants' vigor was significantly lower at the CO_2 level of 8500 ppm relative to 1000 ppm. The differences in depression, anger, and confusion compared to the 1000 ppm baseline were not statistically significant. Figure 4 depicts the results of subjective assessments of acute health symptoms associated with increasing CO_2 levels. The prevalence of slight dizziness among participants rose from 15% to 28% as CO_2 levels increased from 1000 ppm to 8500 ppm. At this CO_2 concentration, 27% of participants experienced slight to moderate dizziness, although this variation was not statistically significant. Significant differences in the incidence of severe dizziness were observed at 8500 ppm compared to 1000 ppm ($p < 0.05$). Fatigue, nose dryness, and sleepiness also varied significantly at 8500 ppm, 8500 ppm, and 7000 ppm, respectively ($p < 0.05$) when compared to the 1000 ppm baseline. Among the participants, the proportions of severe, moderate, and slight fatigue were 33%, 7%, and 2%, respectively. Furthermore, the prevalence of slight nose dryness increased from 9% to 29%. Meanwhile, the rates of severe, moderate, and slight sleepiness were 6%, 11%, and 49%, respectively. Interestingly, none of the participants reported throat dryness at 1000 ppm CO_2 level. However, as CO_2 levels escalated from 1000 ppm to 10000 ppm, the incidence of slight throat dryness rose from 13% to 28%. This increase became significant at the 8500 ppm ($p < 0.05$) compared to 1000 ppm, with 24% of participants reporting minor throat dryness.

3.2. Cognitive Performance. The results derived from the accuracy of numerical calculation and letter search tasks, as depicted in Figure 5, showed no substantial changes correlated to varying CO_2 levels. Although the mean performance index (PI) for numerical calculation demonstrated a slight decrement with CO_2 levels elevating from 1000 ppm to 8500 ppm, these changes were statistically insignificant. However, a significant decrement of 11.2% in the mean numerical calculation PI was observed when the CO_2 concentration reached 10000 ppm ($p < 0.05$), compared to 1000 ppm. A similar trend was noted for the letter search PI, which displayed a 9.1% decrease in the mean PI at 10000 ppm relative to 1000 ppm.

Figure 6 illustrates the self-rated effort involved in numerical calculations and letter searches corresponding to CO_2 levels. Although participants' self-rated effort in numerical calculations showed a slight increase from 1.85 units to 2.25 units as CO_2 levels escalated from 1000 ppm to 5500 ppm, this increase was not statistically significant. A notable difference emerged at a CO_2 concentration of 7000 ppm compared to 1000 ppm ($p < 0.05$), wherein the mean self-rated effort climbed by 0.61 units. Parallel trends were observed in the variations of self-rated effort needed for letter search tasks. Additionally, significant differences

Table 6: Correlation matrix for the results of emotional ratings.

CO_2 level (ppm)	1000	3500	5500	7000	8500	10000
Tension	2.35 ± 0.76	2.61 ± 1.33	2.54 ± 1.10	2.52 ± 1.13	**2.65 ± 1.14***	2.52 ± 1.01
Depression	4.22 ± 0.55	4.43 ± 0.87	4.25 ± 0.87	4.40 ± 1.01	4.35 ± 1.15	4.35 ± 0.95
Anger	3.12 ± 0.59	3.47 ± 1.07	3.52 ± 1.26	3.37 ± 1.15	3.40 ± 0.84	3.40 ± 0.93
Vigor	2.59 ± 1.26	2.79 ± 1.77	2.87 ± 1.33	2.94 ± 1.24	**2.38 ± 1.35***	**2.30 ± 1.31***
Fatigue	3.05 ± 0.81	3.11 ± 0.85	3.35 ± 0.95	3.38 ± 0.98	**3.72 ± 1.21***	**3.81 ± 1.33****
Confusion	2.47 ± 0.98	2.71 ± 1.43	2.55 ± 1.15	2.65 ± 1.37	2.65 ± 1.28	2.46 ± 1.16
TMD	12.91 ± 1.81	13.37 ± 2.48	13.31 ± 2.72	13.29 ± 2.69	**14.41 ± 2.71****	**14.14 ± 3.02***

Bold numbers indicate pairs of responses that were significantly different. *$p < 0.05$; **$p < 0.01$).

($p < 0.05$) were detected in the mean self-rated effort between numerical calculations and letter searches.

3.3. Physiological Responses. HRV has been highlighted as an effective measure due to its sensitivity to changes in skin and ambient temperature [41]. Some studies affirm HRV indicators' suitability for evaluating consumers' thermal comfort [42]. Four main spectral peaks of HRV can be distinguished from a 5-minute ECG recording: very low frequency (VLF: 0.003-0.04 Hz), low frequency (LF: 0.04-0.15 Hz), midfrequency (MF: 0.07-0.15 Hz), and high frequency (HF: 0.15-0.4 Hz) [43]. The LF component of HRV is primarily regulated by the sympathetic nerves, and the HF component is solely mediated by the vagus nerve, reflecting the respiratory rate and volume [44]. The MF component is jointly mediated by sympathetic and vagus nerves. Mulder and Vander [45] suggested the MF/HF ratio as a more sensitive metric for mental workload compared to total variance or respiratory fluctuations. It has been proposed that the LF/HF ratio is an effective HRV index [46] and can efficiently measure the balance between the sympathetic and vagus nerves [47]. Several researchers have leveraged the LF/HF ratio to assess thermal comfort [48]. For instance, Zhu et al. [47] established the regularity of the LF/HF ratio under 60 different environmental combinations of temperature, humidity, and air speed through an experiment involving 6 subjects. Lastly, the time-domain measure of HRV was determined by PNN50, a parameter reflecting parasympathetic modulation of the heart [49] and susceptible to stress.

Figure 8 presents the mean variation of ECG indicators in relation to CO_2 levels for 10 subjects. An increase was observed in LF power, HF power, and PNN50 as CO_2 concentrations increased, whereas heart rate, LF/HF ratio, and MF/HF ratio decreased. Significant increases in LF power, HF power, and PNN50 were noted at a CO_2 concentration of 8500 ppm compared to 1000 ppm ($p < 0.01$). Conversely, significant decreases were seen in heart rate ($p < 0.05$), LF/HF ratio ($p < 0.01$), and MF/HF ratio ($p < 0.05$) at the CO_2 concentration of 8500 ppm relative to 1000 ppm. Importantly, all parameters, excluding the LF/HF ratio—which showed a significant difference at 3500 ppm compared to 1000 ppm ($p < 0.01$)—did not exhibit a significant difference when CO_2 was below 8500 ppm.

The SC results, shown in Figure 9, indicate a decrease with increasing CO_2 concentrations. A significant difference was observed at a CO_2 concentration of 10000 ppm compared to 1000 ppm ($p < 0.05$). At a CO_2 concentration of 10000 ppm, the mean SC was 0.41 μs, marking a decrease of 1.0 μs from the 1000 ppm level ($p < 0.05$).

4. Discussion

4.1. What Are the Effects of the CO_2 on Subjective Perception and Cognitive Performance? It could be observed that the TSV and TCV values obtained from the questionnaire investigation varied with rising CO_2 levels. TCV, representing subjects' thermal discomfort, gradually increased with rising CO_2 levels, but without significant difference, corroborating earlier findings [19, 20, 22]. Past studies [4, 10] suggested a biased, yet insignificant, effect of CO_2 concentration on actual TSV, potentially attributable to our experiment's cooler setting, compared to predominantly neutral or warm conditions in previous experiments. Li et al. [4] found that cooler conditions in underground engineering heightened cold sensations while weakening warmth sensations relative to PMV. The insignificant influence of CO_2 on thermal sensation in past research could be due to warmer experimental conditions and shorter exposure durations. Our experiment, with longer exposure durations and cooler conditions than previous studies, yielded more definitive conclusions.

In our experiment, PAQA significantly decreased when CO_2 concentrations exceeded 3500 ppm compared to 1000 ppm. The findings were in consistent with the previous studies. Li et al. [3] observed significant variations with increased CO_2 concentrations ranging from 450 to 5000 ppm under 28°C temperature and 65% RH. Li et al. [3] also reported that PAQA decreased as CO_2 concentrations rose at higher temperatures of 28°C or 33°C. In the present study, no substantial shifts were observed in acute health symptoms upon exposure to CO_2 concentrations below 7000 ppm, a finding consistent with a previous research [19–21]. For instance, Li et al. [3] reported no significant changes in acute health symptoms during exposure to similar CO_2 concentrations. Notably, our study detected significant differences in symptoms like severe dizziness, fatigue, nasal dryness, sleepiness, throat dryness, and memory deterioration at a CO_2 concentration of 8500 ppm (at 19°C and 80% relative humidity) compared to 1000 ppm, aligning with earlier findings [3]. Notably, the PAQA value remained stable for CO_2 concentrations beyond 3500 ppm,

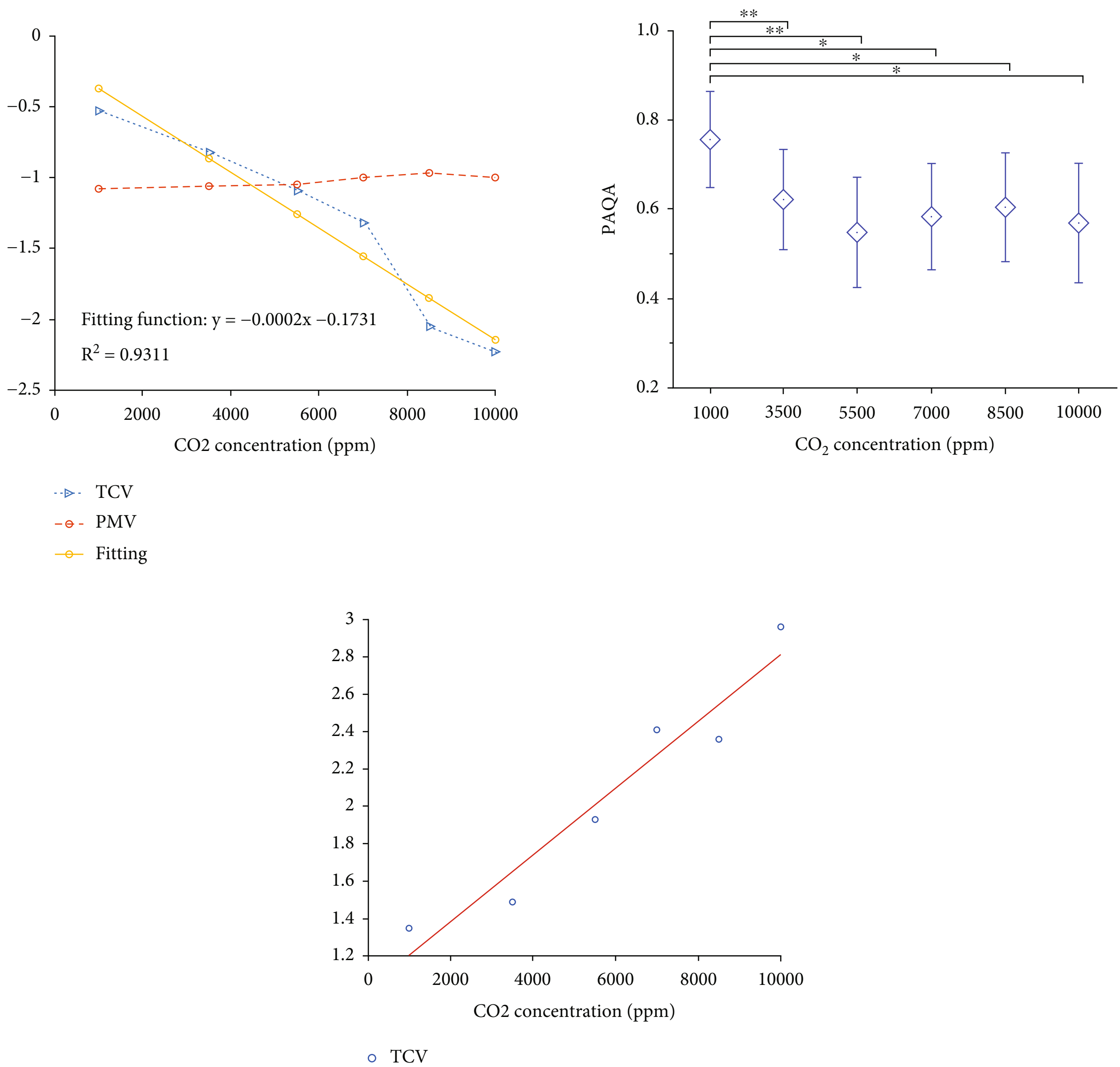


FIGURE 3: Subjective thermal sensation and PAQA of the environment under different CO_2 levels. Figure 3 presents the results for subjective TSV across different CO_2 levels, with the PMV calculated for comparison. There appears to be a crossover between the TSV voting value and PMV within the CO_2 range of 3500 ppm to 5500 ppm. The paired t-test results for TSV and PMV yield a p value of 0.332, which exceeds 0.05, thereby indicating no statistical significance. Conversely, the Pearson correlation coefficient test between CO_2 and TSV reveals a p value of -0.838, indicating a strong correlation ($R^2 = 0.9311$). A notable change in TSV becomes apparent at CO_2 concentrations exceeding 5500 ppm ($p < 0.05$), 7000 ppm ($p < 0.01$), 8500 ppm ($p < 0.01$), and 10000 ppm ($p < 0.01$), compared to the baseline of 1000 ppm. In relation to thermal comfort (TCV), an increase coinciding with rising CO_2 concentration ($R^2 = 0.915$) was observed. However, this trend did not reach statistical significance during the experiment, although the linear regression equation was significant ($p < 0.05$). Similarly, PAQA also demonstrated significant changes at CO_2 concentrations above 3500 ppm ($p < 0.01$), 5500 ppm ($p < 0.01$), 7000 ppm ($p < 0.05$), 8500 ppm ($p < 0.05$), and 10000 ppm ($p < 0.05$), compared to the 1000 ppm baseline. Interestingly, while PAQA exhibited a significant decrease ($p < 0.05$) at CO_2 concentrations below 5500 ppm, the PAQA value appeared to stabilize at 0.6 when CO_2 levels exceeded 5500 ppm.

even at 8500 ppm, suggesting humans may have greater tolerance and adaptability to air quality at lower temperatures.

As shown in Table 6, participants experienced an increase in negative moods and decrease in positive moods at a CO_2 concentration of 8500 ppm. The rise in CO_2 concentration corresponded with a higher probability of acute reactions among participants. In confined underground spaces, the absolute value of TMD could be particularly significant as the negative emotional response may be markedly higher than in surface constructions. Overall, with increasing CO_2 concentrations, subjective perceptions displayed in Table 7, including emotion and thermal perception, showed

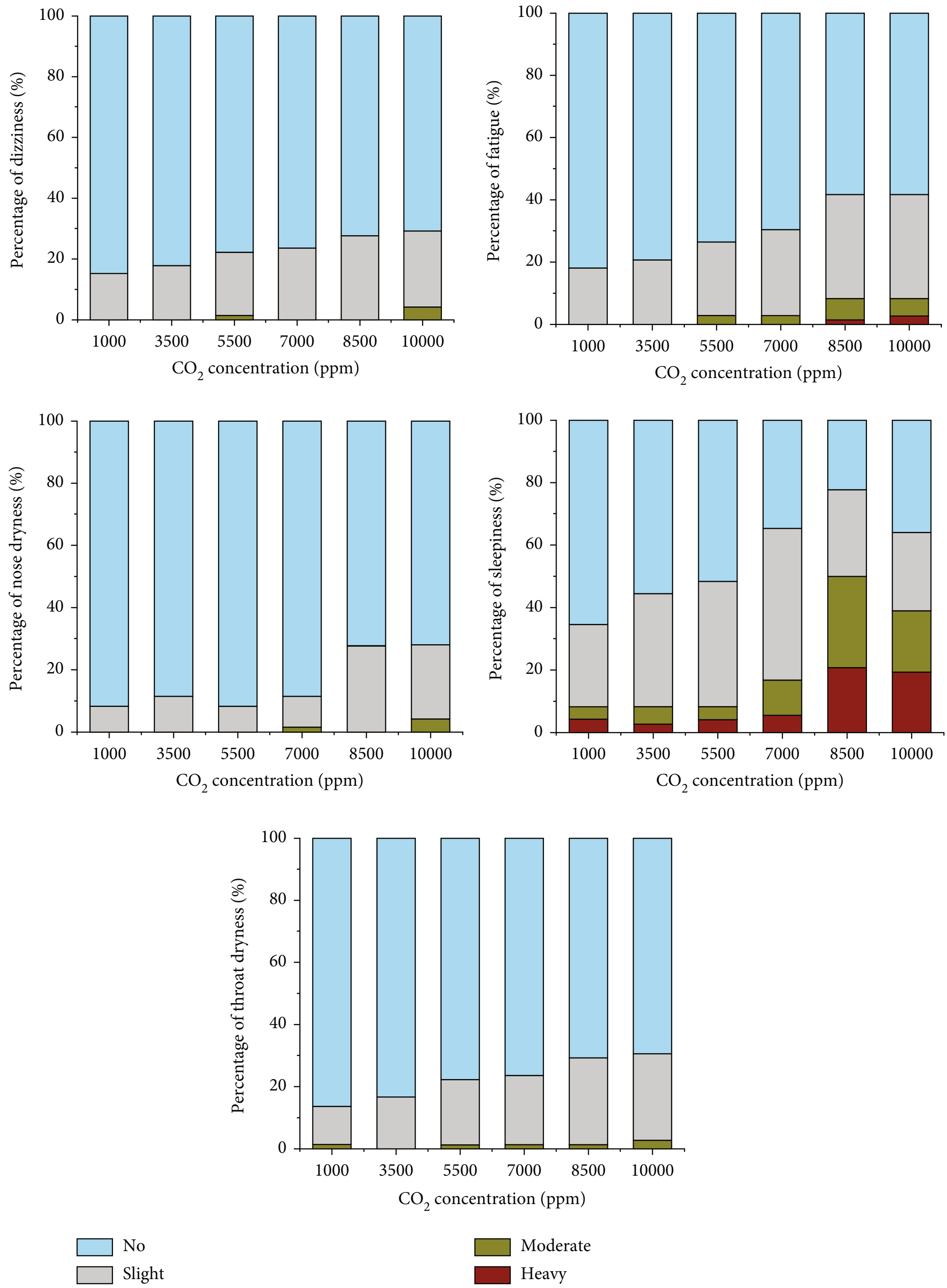


Figure 4: Acute health symptoms with different CO_2 levels.

varying degrees of deterioration. CO_2 concentrations exerted a significant impact on participants' tension, fatigue, and TMD.

As depicted in Figure 5, cognitive performance remained stable with increasing CO_2 concentration, aligning with certain prior studies [22, 50]. In conjunction with the self-rated effort results (Figure 6), it was observed that the self-rated effort value escalated with increasing CO_2 concentration. This suggests that subjects exerted more effort to achieve the same level of efficiency under higher CO_2 concentrations, thereby corroborating the effectiveness of Lan's introduction of the self-rated effort table [41], and this may occur

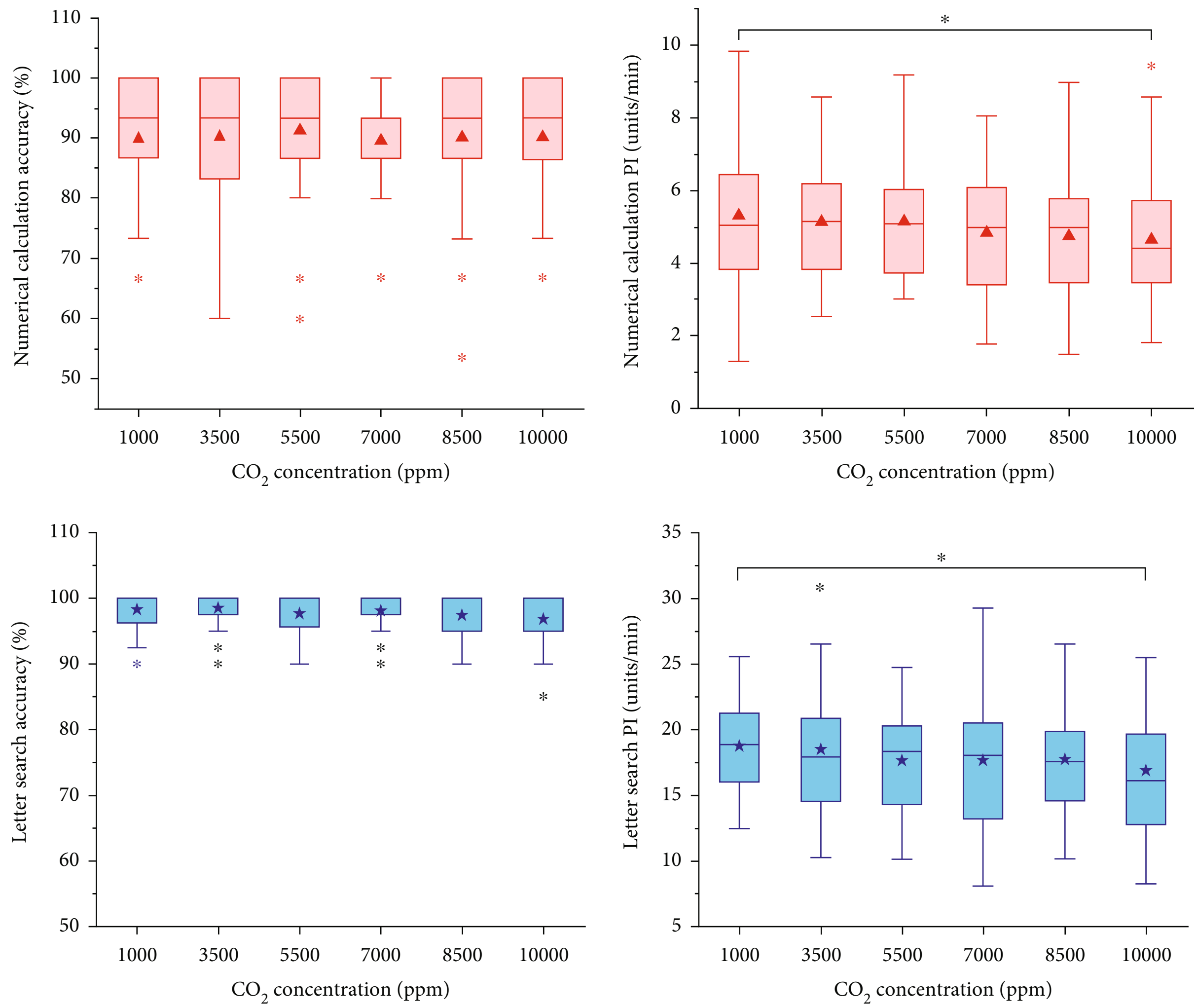


Figure 5: Accuracy and PI of tests with CO_2 levels.

as subjects exert more effort to maintain performance under adverse conditions. Significant differences were also noted in the mean self-rated effort between letter search and numerical calculation tasks. Studies by Satish et al. [17] and Allen et al. [51] revealed that for the same CO_2 concentration, the cognitive performance decreased more significantly during more complex tests. Lan and Lian [34] calculated the effect size of various physiological and psychological measurements from previously published articles or experimental data, establishing that the numerical calculation test has a higher effect size compared to the letter search. Under equivalent environmental pressure, subjects devoted more effort to the numerical calculation task than to the letter search task (Figure 6) because numerical calculations involve more complex information processing. These results suggest that the numerical calculation task has a higher effect size, which is consistent with our findings.

4.2. Discussions on the Relationships and Mechanism between CO_2 and Subjective Perception, Physiological Responses, and Cognitive Performance. The results of the Spearman correlation analysis are presented in Table 7, revealing a significant association between CO_2 concentration and various physiological parameters, including DBP, HF, LF/HF, MF/HF, SC, HR, and PNN50. The changes in the aforementioned physiological parameters reflect the activation of the autonomic nervous system and the impact on the activity levels of the sympathetic and parasympathetic nervous systems when exposed to varying carbon dioxide concentrations in the environment. This is because autonomic activity can trigger corresponding changes in cardiovascular and respiratory functions [52], and variations in sympathetic nerve activity can cause a rise in arterial blood pressure, leading to changes in peripheral vascular resistance [53]. The increase in PNN50, which indicated enhanced parasympathetic nervous system activity, was consistent with the observed increase in fatigue and sleepiness among the participants. Additionally, the observed increase in DBP and decrease in HR represent a relaxation of emotional state among the subjects.

The LF/HF ratio reflects the relative balance between the sympathetic and vagus nerves. A lower LF/HF ratio is generally associated with proximity to thermal neutrality in thermal adaptation experiments [47]. This study observed that

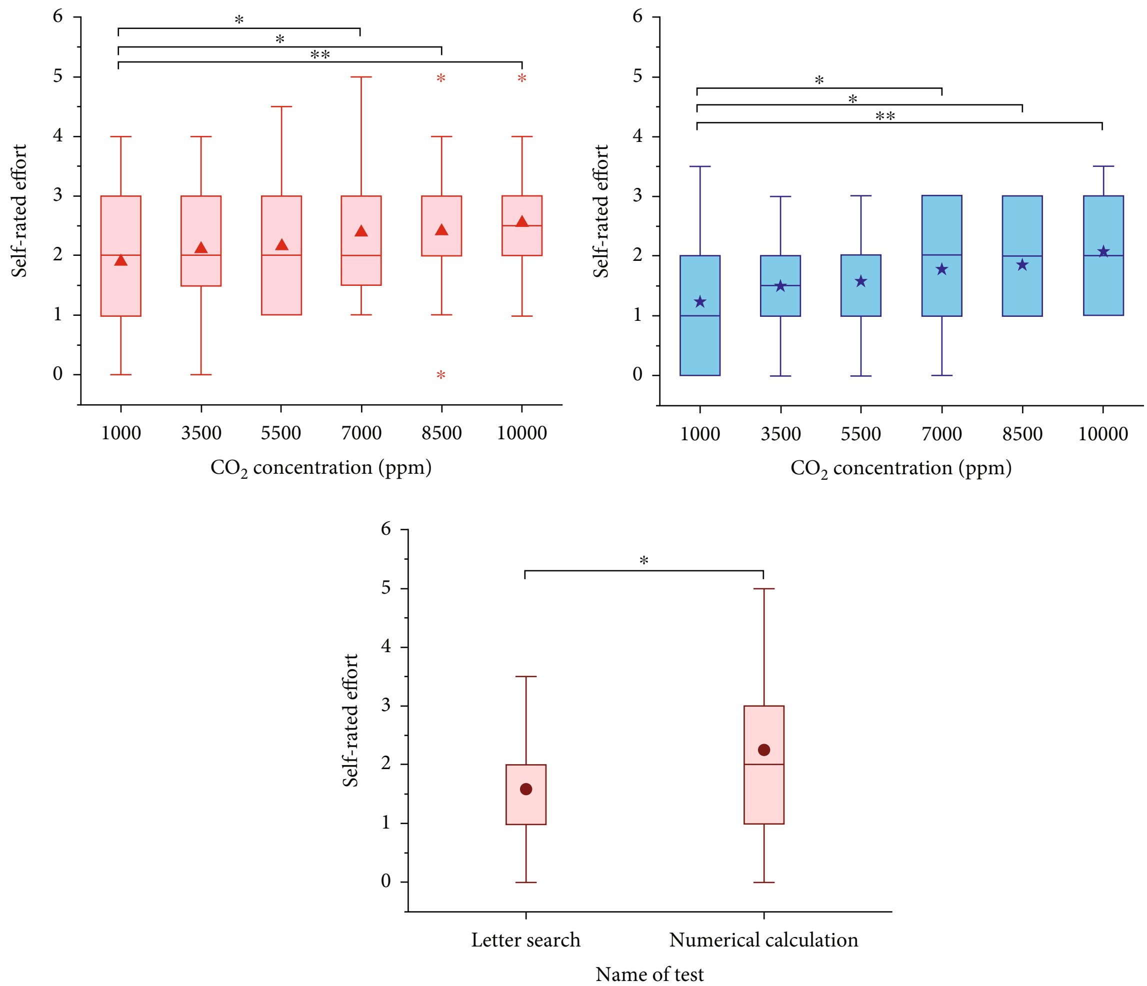


Figure 6: Self-rated effort of numerical calculation and letter search with CO_2 levels; for the assessment of self-rated effort, 0 = very low and 7 = very high.

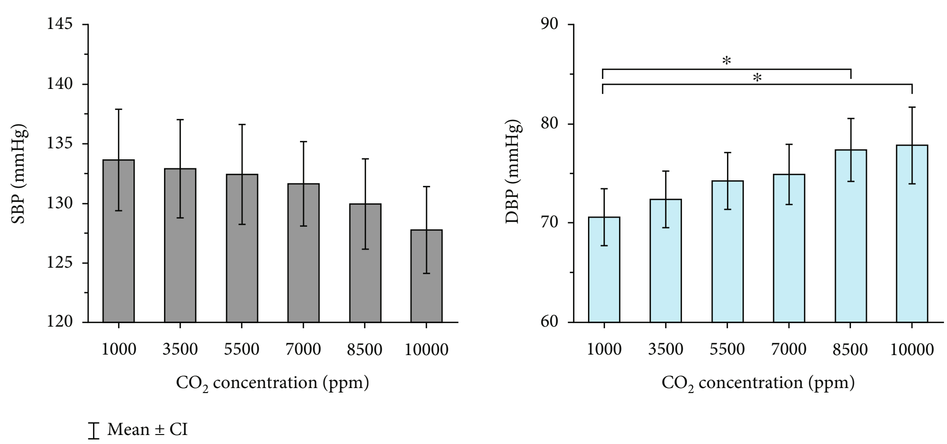


Figure 7: Blood pressure with CO_2 levels.This study evaluated the ECG, galvanic skin response (GSR), and EEG data of 10 participants. Vital physiological metrics such as heart rate, blood pressure, and SPO_2 were measured for all subjects. Figure 7 presents the blood pressure results at various CO_2 levels, indicating a decrease in systolic blood pressure (SBP) with increasing CO_2 concentrations, though these changes lacked significant statistical correlation with CO_2 levels. Conversely, the diastolic blood pressure (DBP) displayed a slight increase as CO_2 levels rose from 1000 ppm to 7000 ppm, with a statistically significant rise at levels above 8500 ppm ($p < 0.05$) and 10000 ppm ($p < 0.05$) relative to 1000 ppm. EEG and SPO_2 measurements remained consistent across all experimental conditions (data not shown).

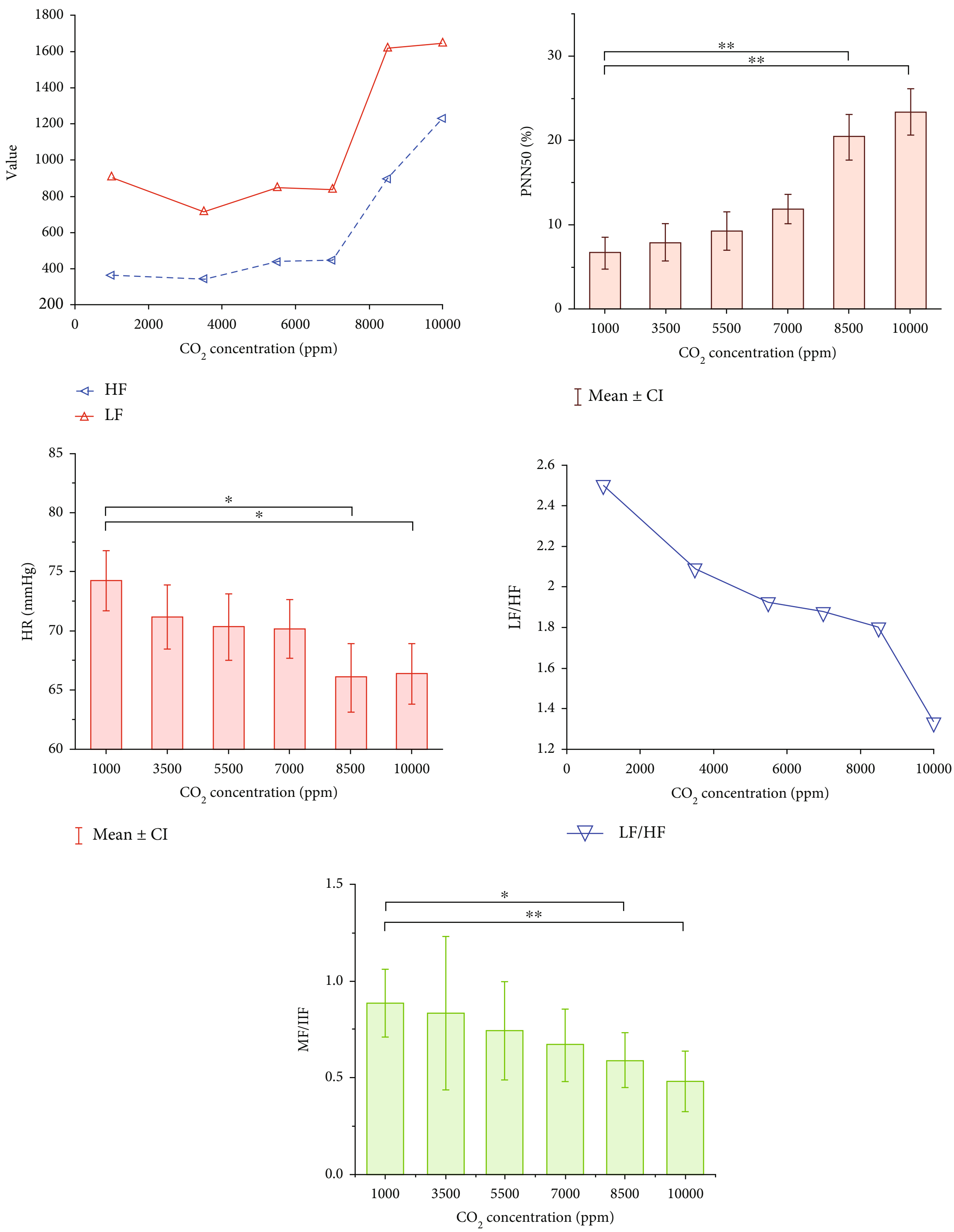


Figure 8: ECG indicators with CO_2 levels.

the LF/HF value decreased with the increase of CO_2 concentration, the potential reasons for which lies in that the vagus nervous gets excited, and that the sympathetic nerve functions are restrained under such conditions. The excitation of vagus nervous usually results in vasodilatation, consistent with the observed DBP. In previous thermal comfort experiments, LF/HF is usually considered to be a better indicator for evaluating thermal comfort. Usually, the more the LF/HF value tends to 1, the higher the comfort of the subject [47]. In this experiment, it was observed that when LF/HF tended to 1, the thermal comfort of the subjects was decreased in combination with the TCV questionnaire survey. The

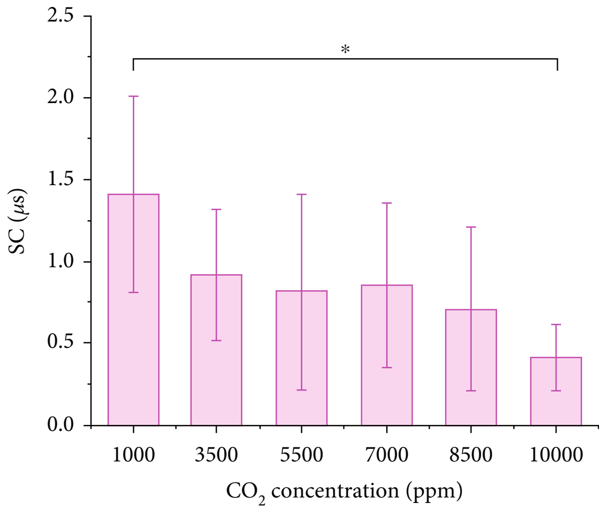


Figure 9: Effect of CO_2 levels on SC.

potential reasons for which lies in environmental stimulation were different, the human body can adapt to the environment by sweating, shaking and so on, in view of the change of ambient temperature. When the subjects were in an environment where CO_2 is gradually increasing, the level of CO_2 in the blood is constantly increasing, that is, the body's lack of CO_2 adjustment capacity. Vehviläinen et al.'s [29] experiment supports this view by demonstrating significant changes in blood carbon dioxide levels in unventilated offices. Moreover, Shin et al. [54] suggested that the LF/HF ratio fails to denote a comfortable condition under colder environments. In studies of thermal comfort that use the LF/HF index, participants undergo a period of thermal adaptation, and the human body employs effective self-regulation mechanisms such as shivering and sweating to mitigate thermal stress. Hence, a lower LF/HF ratio is indicative of thermal neutrality, attributable to the body's adaptation to the thermal environment and the relatively high HF power reflecting vagus nerve activity. The mechanisms underlying how CO_2 concentration activates the vagus nervous are not fully understood.

Additionally, Satish et al. [17] suggested that increased CO_2 concentration could diminish cognitive performance.

A negative correlation emerged between PNN50 and the performance index of the tests, indicating that increased physiological stress could cause a performance decline. Both heart rate and SC decreased with the rise of PNN50. Table 8 presents the correlation coefficient between TMD and other parameters, highlighting a significant correlation between TMD and number calculation PI. This suggests that emotions can impact cognitive performance, a finding that aligns with previously reported results [50].

Correlations between the performance of tests and TMD or total acute health symptoms (TSBS) are exhibited in Table 8. The correlation factors were analyzed using Spearman coefficients. A positive correlation was found between TMD and TSBS, both of which decreased with the increase in letter search performance index (PI) and numerical calculation PI. However, no significant correlations emerged between the accuracy of tests and TMD or TSBS.

Figure 10 presents the impact of subjects' SBP on performance (PI). The subjects' SBP had virtually no significant effect on the accuracy of tests. However, when CO_2 levels reached 7000 ppm or higher, the numerical calculation PI for subjects with lower SBP (90-140 mmHg) was significantly higher than that for subjects with higher SBP (>140 mmHg) ($p < 0.05$). Comparable outcomes were obtained for the letter search PI. Relative to the CO_2 level of 1000 ppm, subjects with higher SBP registered significantly lower numerical calculation PI and letter search PI at CO_2 levels of 7000, 8500, or 10000 ppm.

As presented in Table 7, lower LF/HF yields unpleasant thermal sensation and discomfort. The possible explanation may be that the vagus nervous activities dominated and sympathetic nerve smother when there was a lower LF/HF, which led to the autonomous thermal regulatory activities such as sweating and decrease in heat production and vasomotor function. The possible reason is that thermal regulatory activities such as vasodilation and sweating are primarily controlled by the sympathetic nervous system, but the sympathetic nerve smother. Subjects felt colder and uncomfortable.

4.3. Discussion on the Allowable Value of CO_2 in an Underground Confined Space. Previous studies [55] identified increased mental workload and stress levels resulting from traffic congestion, significantly influencing HR and the LF/HF ratio. Nevertheless, solely utilizing the LF/HF value is insufficient to accurately assess the high stress induced by CO_2. The LF/HF ratio can only provide a single degree of freedom, and the balance of sympathetic nerves requires measurement using a combination of LF/HF with other factors. Von Rosenberg et al. [56] postulated that a novel two-dimensional analysis approach offers superior accuracy and robustness for stress level classification. In light of this, a 2D LF-HF diagram was constructed, demonstrating notable differences in the distribution of LF and HF at various concentrations. Both LF and HF powers jump to a higher level when the CO_2 concentration surpasses 8500 ppm. Increased parasympathetic activity and a decreased heart rate were identified as signs of decreased vigilance, preparing the autonomic system for sleep during active working hours. These results align with the study by Vehviläinen et al. [29] that recorded a significant increase in SDNN and sleepiness at the CO_2 level of 2756 ppm. They also partly concur with previous experiments by Maresh et al. [27] and Bailey et al. [26] which showed that noticeable effects on the respiratory and cardiovascular systems occur at CO_2 concentrations of 10000 ppm. A significant reduction in performance (Figure 6) and SC (Figure 9) was observed when CO_2 concentration reached 10000 ppm, indicating impaired cognitive performance at this concentration.

Physiological responses, such as DBP, HR, and MF/HF, exhibited significant changes when the CO_2 concentration was increased to 8500 ppm compared to 1000 ppm. Furthermore, negative emotions increased significantly with CO_2

Table 7: Spearman correlation coefficient calculation results.

	CO_2	TSV	TCV	PAQA	TMD	NA effort	NA accuracy	NA PI	SPO^2	SBP	DBP	LF	HF	LF/HF	MF/HF	SC	HR
TSV	-1.000**																
TCV	0.943**	-0.943**															
PAQA	-1.000**	1.000**	-0.943**														
TMD0	0.714	-0.714	0.486	-0.714													
NA effort	1.000**	-1.000**	0.943**	-1.000**	0.714												
NA accuracy	0.200	-0.200	0.086	-0.200	0.429	0.200											
NA PI	-0.754	0.754	-0.551	0.754	-0.870*	-0.754	-0.696										
SPO^2	-0.334	0.334	-0.334	0.334	0.091	-0.334	-0.030	0.277									
SBP	-0.657	0.657	-0.429	0.657	-0.829*	-0.657	-0.714	0.986**	0.334								
DBP	1.000**	-1.000**	0.943**	-1.000**	0.714	1.000**	0.200	-0.754	-0.334	-0.657							
LF	0.600	-0.600	0.429	-0.600	0.429	0.600	0.200	-0.667	-0.820*	-0.714	0.600						
HF	0.943**	-0.943**	0.886*	-0.943**	0.543	0.943**	0.086	-0.667	-0.577	-0.600	0.943**	0.771					
LF/HF	-1.000**	1.000**	-0.943**	1.000**	-0.714	-1.000**	-0.200	0.754	0.334	0.657	-1.000**	-0.600	-0.943**				
MF/HF	-1.000**	1.000**	-0.943**	1.000**	-0.714	-1.000**	-0.200	0.754	0.334	0.657	-1.000**	-0.600	-0.943**	1.000**			
SC	-0.943**	0.943**	-0.829*	0.943**	-0.771	-0.943**	-0.486	0.899*	0.334	0.829*	-0.943**	-0.657	-0.886*	0.943**	0.943**		
HR	-0.943**	0.943**	-0.829*	0.943**	-0.771	-0.943**	-0.086	0.696	0.152	0.600	-0.943**	-0.543	-0.886*	0.943**	0.943**	0.886*	
PNN50	1.000**	-1.000**	0.943**	-1.000**	0.714	1.000**	0.200	-0.754	-0.334	-0.657	1.000**	0.600	0.943**	-1.000**	-1.000**	-0.943**	-0.943**

$^{*}p < 0.05$; $^{**}p < 0.01$.

Table 8: Correlations among TMD, total acute health symptoms, and performance.

	TSBS	Letter search		Numerical calculation	
		Accuracy	PI	Accuracy	PI
TMD	0.77**	0.12	-0.32*	-0.07	-0.37*
TSBS		0.09	-0.43*	0.13	-0.39*

*$p < 0.05$; **$p < 0.01$.

concentrations reaching 8500 ppm compared to 1000 ppm. In this perspective, In this perspective, it is reasonable to consider that 8500 ppm is an allowable value of CO_2 concentration in an underground confined space. These findings may suggest a significant change point in the physiological response to CO_2 concentration.

4.4. Discussion on the Limitations of This Study. Despite studying the subjective, cognitive, and physical aspects of personnel in an underground confined space, this study has some limitations. To ensure improved validity and causality, a between-subject design was employed. However, this design does not completely eliminate individual differences, requiring a large sample size, which poses a significant challenge to the experimental procedure. Gender differences were not addressed in this study due to uneven gender distribution. Females have been found to be more sensitive to thermal sensations than males. To simulate long-term isolation, the experiment lasted for 13 hours. Consequently, it is challenging to exclude the cumulative effect of time on the results. Exposure duration, which was significantly related to CO_2 concentration in this experiment, also needs to be further quantified. Additionally, understanding the impact of exposure duration on the health and well-being of personnel in confined underground spaces is essential, particularly for those living underground for extended periods.

To control the metabolic rate within a controllable range, subjects maintained a sitting position, potentially leading to boredom. The CO_2 emission rate of the subjects can be influenced by the intensity of physical activity [57]. However, once CO_2 reaches a certain concentration, it can also have a reverse effect on metabolic rates, thus slowing down the CO_2 emission rate [58, 59]. Since this study did not monitor the subjects' metabolic rate or respiratory parameters and only estimated the average metabolic rate for the time periods using formulas [60], there is a lack of additional support for the counteractive effect of carbon dioxide on metabolic rates. Moreover, previous equations describing the relationship between CO_2 and metabolic rates [60–62] did not take into account the inhibitory effect of CO_2 at certain concentrations on metabolic levels. Both this study and previous experiments have found that when CO_2 concentration reaches a certain level, respiration [63] and lung activity [58] are inhibited, resulting in a slower carbon dioxide production rate. In this study, we controlled the subjects' exercise intensity and respiratory quotient (by providing them with the same breakfast and lunch). However, as CO_2 concentration increased, the subjects' average thermal sensation ratings gradually decreased, indicating a decrease in body heat production. At the same time, the growth rate of CO_2 slowed down, which could imply that CO_2 inhibits metabolic levels once it reaches a certain concentration. The discussion on subjects' metabolic levels in the study was based on the assumption that the subjects' exercise intensity remains constant throughout the sedentary process. However, further research is needed to investigate whether exercise intensity decreases with prolonged sitting time. Understanding the interplay between sedentary behavior, CO_2, and metabolic rates in future studies is crucial for comprehending the physiological effects of sedentary behavior on human metabolism. By investigating how carbon dioxide concentration influences metabolic rates during extended periods of sitting, we aim to shed light on the potential mechanisms underlying the observed changes in respiratory parameters.

Although all participants are required to engage in 2 minutes of standing activity every hour, this emotional state may have influenced the participants' feelings and emotional results, necessitating further analysis of participants' emotional status in isolated environments. Lastly, this study primarily investigated how CO_2 concentration affects the personnel's perspective and physiological responses, with limited measurements of cognitive performance. The underground engineering environment is affected by the comprehensive effects of acoustics, lighting, and thermal environments [10]. The influence of multiple physical fields on the cognitive performance of personnel requires further quantification.

5. Conclusion

This research investigated human responses to underground confined spaces, aiming to enhance human health and well-being. In the study, we exposed 180 participants to heightened CO_2 levels in such a space. Employing both subjective and objective methods, we evaluated the impact of CO_2 concentration on subjective perception, physiological responses, and cognitive performance. This study thus expands the existing evidence of CO_2 concentration's effects on human responses. We drew the following conclusions:

(1) Elevated RH, decreased temperature, and CO_2 concentration significantly deviate the TSV. TSV exceeds PMV between 1000 and 3500 ppm and falls below PMV between 5500 and 10000 ppm. Above 8500 ppm, TSV sees a substantial shift, sitting 0.73 units lower than at 7000 ppm. This suggests that a sub-5500 ppm exposure concentration will feel warmer, while concentrations above 5500 ppm feel colder at 19°C, with an 80% relativity to PMV. Subjects' PAQA votes dropped to 0.54 at a CO_2 concentration of 5500 ppm from 1000 ppm, stabilizing at 0.6 units with a CO_2 increase from 3500 to 10000 ppm. Negative emotions like tension and fatigue remained unchanged at CO_2 concentrations below 8500 ppm. At 8500 ppm, tension, fatigue,

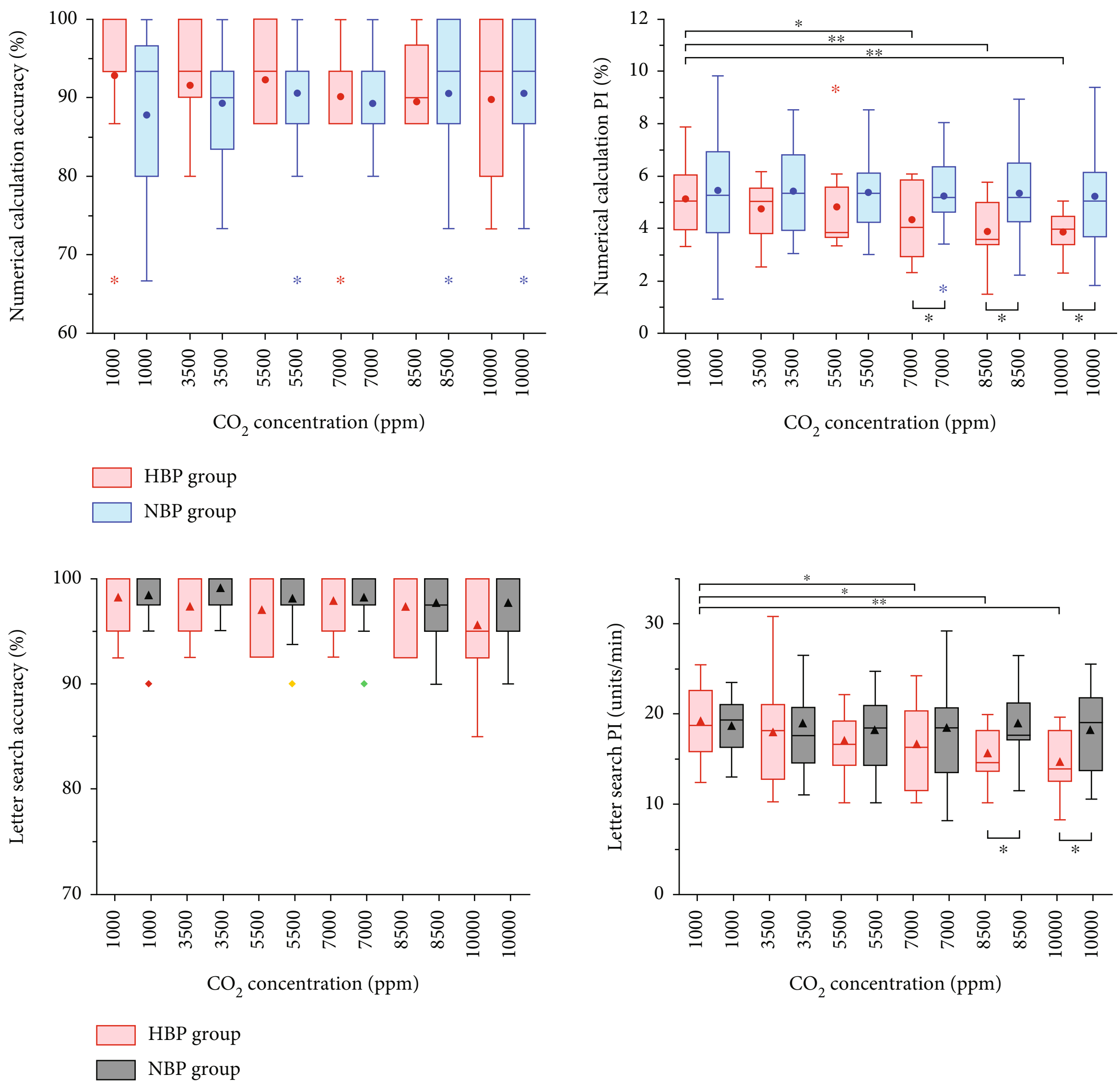


Figure 10: Relationship between SBP and performance (accuracy and PI). Note: NBP: normal SBP group; HBP: high SBP group.

vigor, and TMD were 0.3, 0.65, -0.21, and 1.5 units higher than at 1000 ppm, respectively. This implies a substantial deterioration in emotional state at a CO_2 concentration of 8500 ppm

(2) Throughout the experiment, the subjects' numerical calculation and letter search accuracies, representing cognitive performance, remained relatively constant. At a CO_2 concentration of 10000 ppm, the PI for numerical calculation and letter search fell by 11.2% and 9.1%, respectively, compared to 1000 ppm. Subjects' cognitive performance was mostly unaffected when exposed to an underground confined space for 13 hours at a CO_2 concentration of 10000 ppm. However, we observed a significant increase in the self-rated effort for numerical calculation and letter search when the CO_2 concentration surpassed 7000 ppm compared to 1000 ppm. Subjects exerted more effort in numerical calculations compared to letter searches, with the average self-rated effort for numerical calculation 0.74 units higher

(3) During the experiment, physiological parameters such as DBP, HRV, HR, and SC remained relatively constant with CO_2 concentrations under 8500 ppm. However, significant differences were observed in DBP, LF, HF, PNN50, HR, LF/HF, and mean MF/HF when CO_2 concentration exceeded 7500 ppm compared to 1000 ppm. At 10000 ppm, the LF/HF ratio was 1.17 units lower than at 1000 ppm, and at 8500 ppm, LF and HF values were 780 and 452.3 units higher than at 7000 ppm, respectively. These findings suggest that 8500 ppm is an allowable value of CO_2 concentration in an underground confined space

Data Availability

Data will be made available on request.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

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Supplementary Materials

Table S1: example of numerical calculation task. Table S2: example of letter search task. Table S3: the Brief Mood States Questionnaire. Figure S1: questionnaires of thermal sensation, thermal comfort, thermal acceptability, and acute health symptoms. Figure S2: questionnaires of self-rated mental effort. *(Supplementary Materials)*

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