Study on human responses under different CO\textsubscript{2} concentration and illuminance in underground refuge chamber

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Abstract. Due to insufficient ventilation and absence of daylight, underground confined environment will be dim and occurred with high CO\textsubscript{2} concentration. It is essential to clarify the combined effects of high CO\textsubscript{2} concentration and illuminance on human responses in confined spaces. Twenty-four subjects were exposed to different combinations of illuminance and CO\textsubscript{2} concentrations in an underground climate chamber, with thermal responses, physiological responses and acute health symptoms being investigated.

Results show that: at CO\textsubscript{2} level of 12,000 ppm, heart rate (HR), diastolic blood pressure (DBP) and ratings of acute health symptoms (dizziness, agitation and depression) increased significantly when illuminance level was up to 500 lux. However, no similar results were observed at a CO\textsubscript{2} concentration of 8000 ppm. Additionally, thermal sensation votes (TSV) increased significant with increasing illuminance level, regardless of CO\textsubscript{2} concentration being 8000 or 12,000 ppm. Similar result was obtained for the change of thermal comfort votes (TCV) at CO\textsubscript{2} level of 12,000 ppm. However, TCV result for illuminance level of 100 and 500 lux did not show a significant difference at CO\textsubscript{2} concentration of 8000 ppm. This indicated that the combined effects of illuminance and high CO\textsubscript{2} concentration lead to different human responses.

1. Introduction

Underground spaces are an essential element in modern urban. As the second space of urban development, it is fully developed and utilized. Underground spaces, such as underground shopping mall, subway station and air-defense basements, were semi-opened or confined spaces. These spaces were hot and humid when using [1]. Moreover, there may be other shortcomings in the underground environment, such as insufficient ventilation and the absence of daylight [2,3]. For example, CO\textsubscript{2} levels in underground coal mine refuges can be as much as 25,000 ppm [4] or even 30,000 ppm. These disadvantages might constitute risk factors for adverse health outcomes, and cause different human physiological responses and thermal responses.

To date, studies of thermal responses have mostly focused on the air temperature, radiation temperature, humidity and air velocity of the underground environments [5]. However, very few studies of light and CO\textsubscript{2} concentrations on human responses were reported. In underground confined space with a crowded population, CO\textsubscript{2} levels can exceed 10,000 ppm. The study conducted by Zhang et al. [6-8] recorded no significant change in perceived air quality and acute health symptoms when exposed to CO\textsubscript{2} levels of 5000 ppm. These results were consistent with those by Liu et al. [9], who founded that CO\textsubscript{2} concentrations up to 3000 ppm did not cause significant changes in thermal sensation, physiological responses and subjective ratings. Recently, Li et al.[10] investigated the combined effect of increased temperature, relative humidity and CO\textsubscript{2} concentration on human responses. The result showed that...
thermal sensation votes and thermal acceptability changed significantly when the CO\textsubscript{2} level was up to 12,000 ppm at RH of 85%.

Providing a comfortable light environment to occupants of the underground spaces was essential to improving health and comfort. The study carried out in subway stations [11] showed that an average of 100 lux was barely acceptable to passengers, while the higher intensity of illumination would create a more comfortable indoor environment. Studies by Teramoto et al. [12], Kim et al. [13], and many others [14,15] show that subjects felt cooler in dim light and warmer in bright light. These were consistent with those by Kim et al.[16], who also founded that the change of illuminance had no significant impact on subjects’ thermal comfort. Another study by Kim et al. [17] suggested that subjects’ diastolic blood pressure was lower for bright light (2500 lux) exposure than dim light (50 lux) exposure, while the heart rate was no significant effect by illuminance. However, a majority of studies were conducted in aboveground environments. High-humidity of the underground confined environment might be ignored. Whether the humid environment combined with higher CO\textsubscript{2} concentration and illuminance would lead to different human responses is not completely clear. It is also unknown how the combined effect of illuminance and high CO\textsubscript{2} concentration in an underground confined space will affect the thermal responses, physiological responses and acute health symptoms.

The objective of this study is to clarify the combined effects of illuminance and CO\textsubscript{2} concentrations on the thermal responses, physiological responses and acute health symptoms by using an underground climate chamber experiments. The impact of high CO\textsubscript{2} concentrations, illuminance and their interactions impact on human responses would be discussed to increase our understanding of the effects. The results are expected to provide a basis for the optimization of the light and thermal environment in underground confined spaces.

2. Methodology

2.1. Facilities

The experiment was carried out in a 2.5×2.3×2.5m (length×width×height) chamber building with stainless steel frame and thick Perspex partition. The air temperature (T\textsubscript{a}) and humidity (RH) were controlled by heater and humidifier, respectively. Light exposure was obtained by placing fluorescent tubes on the ceiling of the chamber. The light intensity was controlled by adjusting a rheostat, which ranges from 50 to 600 lux. The soda-lime adsorption material and molecular sieve oxygen making machine were used to keep the level of CO\textsubscript{2} close to the intended level and average O\textsubscript{2} concentration within 21% ± 1%. In addition, to ensure the security of the people in the chamber, an alarm function and protection system had been installed in the chamber.

2.2. Experimental conditions

Exposure conditions of two CO\textsubscript{2} concentration levels (8000, 12,000 ppm) and three illuminance intensity (100, 300, 500 lux) were established in the chamber, as shown in Table 1. Those were due to the minimum illumination for air defense basement was 100 lux [18], while standard illuminance for Chinese office was 300 lux. The RH was kept at 85 %, which was the upper limit of humidity in air-defense staff shelters in China. The T\textsubscript{a} was set at 24 °C, which was the thermoneutral temperature in the winter of Nanjing [6].

| Tested conditions | 1 | 2 | 3 | 4 | 5 | 6 |
|-------------------|---|---|---|---|---|---|
| CO\textsubscript{2} (ppm) | 8000 | 8000 | 8000 | 12,000 | 12,000 | 12,000 |
| Illuminance (lux) | 100 | 300 | 500 | 100 | 300 | 500 |

2.3. Experimental protocol

The experiment was conducted in two successive days at the end of December 2019. Twenty-four subjects were randomly assigned to two groups each 12. Each group was exposed to combined CO\textsubscript{2} concentration and illuminance from 8:00 to 11:30 in the order shown in Table 1.
During the experiment, the $T_a$ and RH were constant at 24 °C and 85 %, respectively. Each day of the experiment, subjects were exposed to two CO$_2$ concentrations (8000 and 12,000 ppm). At each CO$_2$ concentration exposure, the exposure levels of illuminance were divided into three blocks: 100 lux, 300 lux and 500 lux (Table 1). Each block in the chamber lasted 60min, with intervals of 5min to adjust the light intensity. Before each day of the experiment, subjects had 15 min to change clothes and enter the chamber. During each exposure condition, subjects had 40 min to adapt to the indoor environment, then they filled out questionnaires and took physiological measures in 20 min.

The study conformed with the Ethics Review Board approval.

2.4. Subjects

Twenty volunteered subjects (all males) were recruited to take part in this experiment. Table 2 shown the detail information of the subjects. A week before experiment, subjects were instructed on how to fill out the questionnaires and get familiar with the procedures.

| Table 2 Comfort survey indicators (Mean (Min-max)) |
|-----------------------------------------------|
| Subjects’ information                        | Values       |
| Subjects                                      | Male:20      |
| Age                                           | 21.5 (20-23) |
| Weight (kg)                                   | 70.5 (68-80) |
| Height (m)                                    | 175.1 (171-179) |
| Activity level (Met)                          | 1.0          |
| Clothing insulation (Clo)                     | 0.5          |

2.5. Measurement

The measurement instruments were placed in the middle of chamber at 1 m height. The $T_a$, RH, CO$_2$ concentrations were measured with Testo 425 (measurement range 0-70 °C, accuracy ±0.5 lux), HUMIPORT (measurement range 10-90 %, accuracy ±0.1 %), and TELAIRE (measurement range 0-100,000 ppm, accuracy ±50 ppm), respectively. The lighting intensity was measured with Metrel MI6201 (measurement range 0-20,000 lux, accuracy ±0.1 lux) and the O$_2$ level was measured with AS8801 (measurement range 0-30 %, accuracy ±0.1 %). Several physiological measurements were made. They included measurement of heart rate (HR) and SPO$_2$ using a Yuwell YX303, measurements of blood pressure using a Kofoe KF-65B. The measurable range of SPO$_2$ was 7-100 % and the accuracy was ±0.2 %, the measurable range of blood pressure was 0-300 mmHg and the accuracy was ±3 mmHg.

Subjective measurements were carried out using the same questionnaires as were used in the previous study by Li et al.[10]. They consisted of thermal responses and ratings of acute health symptoms. Thermal responses include thermal sensation and thermal comfort. The intensity of acute health symptoms, including: headache, fatigue, dizziness, depression, agitation and sleepiness.

The SPSS 25.0 program was used to compare the data from different cases. The normal distribution data was performed with repetitive measurement deviation analysis, and Wilcoxon Matched Pairs test was utilized to analyze non-normal distribution data.

3. Results

3.1. Result for acute health symptoms

Results for the intensity of acute health symptoms reported by the subjects at different CO$_2$ concentrations and illuminance were shown in Table. 3. When the CO$_2$ concentration was 8000 ppm, the ratings of each acute health symptoms did not change significantly under the different intensity of illuminance. However, significant differences were recorded in the rating of dizziness, agitation and depression between the illuminance levels of 100 and 500 lux at a CO$_2$ concentration of 12,000 ppm (p< .01). Additionally, the ratings of each acute health symptoms were increased significantly with increasing CO$_2$ concentration (p < .05), regardless of illuminance being 100, 300 or 500 lux.
Table 3. Subjects’ ratings of acute health symptoms under different illuminance and CO₂ level

| CO₂ level (ppm) | Illuminance (lux) | Fatigue      | Dizziness    | Headache    | agitation | Depression | Sleepiness |
|-----------------|------------------|--------------|--------------|-------------|-----------|------------|------------|
| 8000            | 100              | 1.38±0.52    | 0.75±0.46    | 0.5±0.76    | 1±0.53    | 0.5±0.53   | 1±0.53     |
|                 | 300              | 1.25±0.46    | 1±0.53       | 0.63±0.74   | 1.38±0.74 | 1.13±0.83  | 1±0.46     |
|                 | 500              | 1.38±0.52    | 1±0.53       | 0.5±0.53    | 1.25±0.89 | 1.13±0.83  | 1.25±0.53  |
| 12,000          | 100              | 2±0.53       | 1.75±0.46    | 1±0.76      | 1.63±1.06 | 1.38±0.92  | 1.63±0.52  |
|                 | 300              | 2±0.53       | 2.13±0.83    | 1.38±1.19   | 1.88±1.25 | 1.88±1.25  | 1.63±0.92  |
|                 | 500              | 2.25±1.04    | **2.25±0.71**| 1.5±1.2     | **2.5±0.76**| **2.5±0.76**| 1.75±1.29  |

Bolded numbers indicate pairs of responses that were significantly different. * (p < .05), ** (p < .01).

3.2. Result for thermal responses

Results for TSV and TCV (Figure 1) showed a significant difference as the level of illuminance increasing from 100 lux to 500 lux at CO₂ concentration of 12,000 ppm. When the CO₂ concentration was 8000 ppm, TSV increased significantly at illuminance level of 500 lux compared to illuminance level of 100 lux (P< .01), but not TCV. In addition, whether illuminance level was 100, 300 or 500 lux, TSV and TCV increased significantly with increasing CO₂ concentration.

3.3. Result for physiological responses

During the experiment, a range of physiological parameters were also measured. Results for systolic blood pressure (SBP) and SPO₂ recorded virtually no change under each experimental condition. At CO₂
concentration of 12,000 ppm (Figure 2a), the DBP was significantly higher at the illuminance level of 500 lux than that of 100 lux (P < .01). However, there was no significant difference in DBP at a CO₂ concentration of 8000 ppm. Similar results were obtained for the change of HR as shown in Figure 2b. In addition, the HR was higher at a CO₂ concentration of 12,000 ppm than that of 8000 ppm, whether illuminance level was 100, 300 or 500 lux.

4. Discussion

Acute health symptoms reported by the test subjects can be significantly affected by CO₂ concentration. These findings were consistent with the previous results reported by Li et al. [10]. In our study, at CO₂ level of 12,000 ppm (Table 3), the rating of dizziness, agitation and depression were significantly higher at illuminance level of 500 lux compared with illuminance level of 100 lux (p < .01). However, similar results were not obtained at a concentration of 8000 ppm. It should be noticed that the average votes of those acute health symptoms were “moderate”. These results indicated that under higher CO₂ level condition, the increase of illuminance aggravated the subjects’ complaints of acute health symptoms.

Previous results by Kim et al. [17] showed that the change of illuminance has significantly effect on TSV, but not on TCV. Similar results to these investigations were recorded in our study when illuminance increased from 100 to 500 lux (Figure 2), at a concentration of 8000 ppm. However, significant changes in TCV of the subjects were recorded when the CO₂ concentration was 12,000 ppm. It should be noted that the average TSV and TCV were 0.93 and 0.78 units higher at a CO₂ concentration of 12,000 ppm than CO₂ concentration of 8000 ppm. Hence, this difference might be due to the significant deviation of thermal comfort level from thermal neutrality at a CO₂ concentration of 12,000 ppm. Those suggested that subject felt cooler in dim light (100 lux) and warmer in bright light (500 lux), and the increase of light intensity significantly increased thermal discomfort under higher CO₂ level.

When the CO₂ concentration was 12,000 ppm (Figure 3), significant increase in subjects’ HR were recorded with increasing illuminance, which confirmed the findings proposed by [19]. Similar result was obtained for the change of HR. However, at CO₂ concentration of 8000 ppm, HR and DBP results for illuminance level of 100 and 500 lux did not show a significant difference. These results indicated that under higher CO₂ concentration condition, the DBP and HR were higher for bright light exposure.

When the illuminance was 100 lux (Figure 2), TSV and TCV were significantly higher at a CO₂ concentration of 12,000 ppm than that of 8000 ppm. Similar results were obtained for conditions at an illuminance of 300 and 500 lux. Moreover, HR (Figure 3b) was increased significantly with increasing CO₂ concentration. While, DBP was almost unchanged between CO₂ concentration of 12,000 and 8000 ppm. This showed that CO₂ concentration has significant effect on HR, TSV and TCV, but not on DBP.

5. Conclusions

The purpose of this study was to explore human response in underground confined spaces with a crowded population. Twenty-four subjects were exposed to various combinations of illuminance and CO₂ concentrations for 210 min in an underground climate chamber; human responses were investigated and discussed. The conclusions drawn from this study are:

(1) When the CO₂ concentration was 12,000 ppm, the HR, DBP and ratings of acute health symptoms (dizziness, agitation and depression) were significantly higher at illuminance of 500 lux than illuminance of 100 lux. However, those did not show a significant change between illuminance of 500 and 100 lux at a CO₂ concentration of 8000 ppm. These results showed that subjects’ acute health symptoms, DBP and HR were significantly increased for bright light exposure at a higher CO₂ concentration.

(2) Results for TSV showed a significant increase with increasing illuminance, regardless of CO₂ level being 8000 or 12,000 ppm. However, TCV did not change significantly between the illuminance level of 100 and 500 lux at CO₂ level of 8000 ppm. Significant change was recorded at CO₂ level of 8000 ppm. It indicated that the subject felt cooler under dim light, and increase of illuminance led to a significant increase in thermal discomfort at higher CO₂ concentration.
(3) Compared with CO$_2$ level of 8000 ppm, the ratings of each acute health symptoms, TSV, TCV and HR were significantly higher at a CO$_2$ level of 12,000 ppm. This showed that increase in CO$_2$ level would cause severe human responses.

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