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Performance, acute health symptoms and physiological responses during exposure to high air temperature and carbon dioxide concentration

Weiwei Liu [a, b, *], Weidi Zhong [a], Pawel Wargocki [b, **]

[a] School of Energy Science & Engineering, Central South University, Changsha, Hunan, China
[b] International Centre for Indoor Environment and Energy, Technical University of Denmark Denmark

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ABSTRACT

Human subjects were exposed for 3 h in a climate chamber to the air temperature of 35 °C that is an action level, at which the working time needs to be diminished in China. The purpose was to put this action level to test by measuring physiological responses, subjective ratings and cognitive performance, and compare them with responses at temperature of 26 °C (reference exposure). Moreover, CO_2 was increased to 3000 ppm (CO_2 exposure) at 35 °C to further examine, whether this change will have any effect on the measured responses. Compared with the reference exposure, exposure to 35 °C caused subjects to report feeling uncomfortably warm, to rate the air quality as worse, to report increased sleepiness and higher intensity of several acute health symptoms. Eardrum temperature, skin temperature, heart rate and body weight loss all increased significantly at this exposure, arterial oxygen saturation decreased significantly, while the percentage of adjacent inter-beat cardiac intervals differing by > 50 m (pNN50) decreased significantly, indicating elevated stress. The performance of addition and subtraction tasks decreased significantly during this exposure, as well. Increasing CO_2 to 3000 ppm at 35 °C caused no significant changes in responses. Present results reaffirm the selection of 35 °C as an action level, and show that concurrently occurring high CO_2 levels should not exacerbate the hazards.

1. Introduction

High temperatures create major health and safety risks especially to individuals working outdoors, where the effects are difficult to mitigate, e.g. craftsmen on construction sites [1,2] and motorbike riders [3]. Driver vigilance is greatly reduced even at moderate compartment temperatures [4]. Extreme heat events are becoming more frequent, severe and long lasting due to global climate change [5]. People working outdoors will thereby face a severe adverse challenge due to increased, and at times extremely high, outdoor temperatures especially in the summer months.

In China an outdoor temperature of 35 °C is the action level, at which a high temperature yellow warning is issued; at this temperature outdoor workers are required to reduce their working time and to protect themselves from heat stroke (www.cma.gov.cn). It is relevant to examine physiological reactions and cognitive performance, as well as other human responses at this temperature. It is also valid to examine, whether other environmental factors interact with the selected action level for temperature and exacerbate these responses.

Temperatures higher than 35 °C result in a significant increase in core temperature, heart rate and sweat rate. These effects were observed, when subjects were exposed to temperatures ranging from 35 to 50 °C for 80–120 min [6–10]; it is worth mentioning that during the 2 h exposures to 50 °C, the air relative humidity was kept as 40% and the subjects were at complete rest [6]. The exposure to high temperatures decrease also both systolic and diastolic blood pressure. These effects were observed during 4-hour exposures in experiments, which examined the effects of increasing temperature from 20 °C to 34–42 °C [11]. Lu and Zhu [11] showed that oral temperature of 38 °C and dehydration causing body weight loss of 1% should be considered as the physiological limits for the health safety of persons exposed to heat. Temperatures close

* Corresponding author. School of Energy Science & Engineering, Central South University, Changsha, Hunan, 410083 China.
** Corresponding author. International Centre for Indoor Environment and Energy, Technical University of Denmark, Nils Koppels Alle, Building 402, DK-2800 Kongens Lyngby, Denmark.
E-mail addresses: wliu@csu.edu.cn (W. Liu), paw@byg.dtu.dk (P. Wargocki).

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to 35 °C and above cause additionally changes in subjective responses. Holland et al. [12] found that the rise of core temperature to 39 °C (by immersion in 41 °C water) induced a significant decrease in alertness and increased irritability as judged by subjects exposed for 20 min to 35 °C in air. In a study by Tamm et al. [10], subjectively rated fatigue and exertion increased during 1 h exposures, when the temperature increased from 22 °C to 42 °C. Finally, high temperatures reduce also mental performance. Wilkinson et al. [13] observed a significant decrease in the performance of two-digit addition and an improvement in the performance of a vigilance test (subjects listened to a series of tones), when body temperature was maintained at 38.5 °C with ambient temperature at 37 °C for 2 h. Epstein et al. [6] found that percentage of errors in a shooting TV game rose gradually, when the air temperature increased from 24 °C to 37 °C and then to 50 °C; at each temperature the exposure lasted 2 h. The effect observed in their study indicated a deterioration in psychomotor functions caused by the heat load. Hocking et al. [7] found that thermal stress at 35 °C induced deficits in working memory, information retention and information processing, and there was a marked difference in the electrical responses of the brain when subjects were thermally strained. Mohr et al. [8] examined the effect of high air temperature on physical performance during a 90-minute football game. The total distance run by the players and high intensity running (>14 km/h) declined, but the success rate for passes and crosses and peak sprint speed increased at 43 °C compared to 21 °C. The latter was most likely caused by the lower distance of high intensity running and reduced pressure from the opposition on the player in possession. On the other hand, Holland et al. [12] were not able to show that 20-minute exposure to 35 °C after raising the body temperature to about 39 °C (by immersion in water at 41 °C) had a significant effect on the accuracy with which tests examining long-term and short-term memory were performed, or on the accuracy of reasoning tests such as logic problems and two-digit subtraction. This exposure was actually associated with a significant increase in the speed, at which reasoning tests were performed. This result may be explained by a direct effect of temperature on neuronal processes and by the 20-minute exposure at which subjects can maintain a high level of motivation.

Carbon dioxide is gradually increasing in ambient air and there is a new evidence that the concentrations below occupational level set at 5000 ppm [14] may influence the ability to make decisions [15,16] although these levels have not been shown to cause negative effects on health or comfort, or result in measurable physiological responses [17,18]. One isolated experiment suggested that exposure to CO_2 at 3000 ppm increased fatigue and reduced wellbeing [19], but no other study supports this observation. Whether levels of CO_2 below 5000 ppm would impair mental performance is not completely clear at the moment. Some studies show that the performance of cognitive tests and tasks examining subjects' ability to perform office work are not affected during exposures to CO_2 (dosed from cylinder to otherwise clean environment with low exposures) below 5000 ppm [20–22] and some studies have shown that negative effects are first seen at levels as high as 12,000 ppm [23] and even higher, up to 60,000–70,000 ppm [24]. On the other hand, some recent studies have shown that the performance of proof reading is negatively affected by exposure to CO_2 at 4000 ppm [19] and that exposure to CO_2 at levels as low as 1000 ppm can reduce the ability to take decisions [15,16]. In certain cases, e.g., in a welding factory, green house and in mines, elevated CO_2 can occur together with high temperatures. Consequently, it is important to determine whether exposure to high CO_2 levels would modify the effects of exposure to high temperature, and whether it would intensify the observed effects. This question has not yet been examined: the Authors of the present paper were not able to find any study in the published literature that examined the combined effects of temperature and pure CO_2.

The objective of the present study was to supplement the existing evidence on the effects of elevated air temperatures on humans in particular by extending the experimental protocols by adding measurements of oxygen saturation, end-tidal CO_2, stress biomarkers and neurobehavioral tests of cognitive performance, as well as by examining whether increased concentration of CO_2 at elevated air temperature would have any modifying effect on the measured responses. The results are expected to facilitate decisions and recommendations aiming to protect the workers during events with high temperatures.

2. Methods

2.1. Approach

Twelve subjects, two persons at a time, were exposed for 3 h in the climate chamber to the air temperature of 26 °C and 35 °C at CO_2 level of 380 ppm and to the air temperature of 35 °C at CO_2 level of 3000 ppm. The three exposure conditions were experienced in balanced order. They performed different cognitive tests, rated their acute health symptoms and assessed the environmental conditions. Their physiological reactions were monitored.

2.2. Facilities

The experiment was conducted in a climate chamber (Fig. 1), one of the twin climatic chambers located at Technical University of Denmark (DTU) [25,26]. The size of the chamber is $3.6 \times 2.5 \times 2.5\ m^3$; the volume of the chamber with its recirculation ducts is 30 m^3. The chamber is ventilated by 100% outdoor air through a perforated floor and the air is exhausted through outlets in the ceiling. The air temperature and humidity are controlled by the specially designed air-conditioning system. To achieve good mixing, the air in the chamber is recirculated at an exchange rate of >10 h^{-1}.

Three workstations were set up in the chamber. They were used by the subjects and the experimenter during exposures. Each consisted of a table, a chair, a desk lamp and a laptop.

2.3. Experimental conditions

Three indoor environmental conditions were established.

In Condition 1 (reference condition designated T26), the air temperature in the chamber was set at 26 °C.The temperature of 26 °C was selected because this is the lower limit of air-conditioning temperature in public buildings as specified by the Chinese government during summer, if both thermal comfort requirements and energy conservation are taken into account.

In Condition 2 (exposure condition designated T35), the air temperature in the chamber was set to 35 °C. A temperature of 35 °C was selected because this is the threshold for high temperature yellow warning in China (see Introduction).

In Condition 3 (CO_2 condition designated T35C3000), the air temperature in the chamber was kept at 35 °C and the concentration of CO_2 in the chamber was increased to 3000 ppm by adding pure CO_2 of a high quality (99.99%) from a pressurized cylinder. The concentration of 3000 ppm was selected to match the concentration studied by Zhang et al. [20,21], and because it was higher than the concentration in the experiments by Satish et al. [15] and Allen et al. [16], while still lower than occupational exposure limit of 5000 ppm.

In all three exposure conditions, the outdoor air supply rate was