Building and Environment 145 (2018) 96–103

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Physiological response of building occupants based on their activity and the indoor environmental quality condition changes

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ARTICLE INFO

Keywords:
Physiology response
Work stress
Indoor environmental quality
Human health
Homeostasis
Hypertension

ABSTRACT

This study aimed to analyze the physiological response (i.e., blood pressure) of building occupants based on the 22 subjects' activity and the Indoor environmental quality (IEQ) condition (i.e., carbon dioxide (CO_2) concentration and operative temperature) changes. The experiment was designed with three scenarios to simulate the IEQ condition changes. In each scenario, six cognitive tasks that simulate office work were conducted by the subjects to determine their activity that cause work stress. The paired-t test was conducted to analyze the building occupants' physiological response by scenario. As a result, with a low CO_2 concentration (below 1000 ppm), the subjects maintained homeostasis well under work stress. It was difficult to maintain homeostasis, however, with a high CO_2 concentration (above 2000 ppm): When the subjects were under work stress, they showed different responses compared to those of the seated state. Homeostasis was affected by stress, according to the IEQ condition changes. The unacceptable condition and work stress were particularly dangerous for the hypertensive (i.e., above 140 mmHg systolic blood pressure) subjects. For the maintenance of homeostasis of occupants, a low CO_2 concentration (below 1000 ppm) should be kept, and work stress above a certain level should be avoided. The building's mechanical system designer and facility manager can manage the IEQ condition considering the building occupants' physiological responses, which can be used as an IEQ condition management guideline for health.

1. Introduction

As people spend most of their time indoors, there has been a growing interest in indoor environmental quality (IEQ), which affects the physical status of building occupants [1–5]. The physical status of the building occupants can be analyzed based on their physiological responses, which can now be more easily measured thanks to the recent relevant technological advances [6,7]. Physiological responses can be divided into the heart rate, blood pressure (BP), and body temperature, and can be evaluated by determining how well the building occupant can maintain homeostasis against external stimuli [2]. All living things live in complex dynamic equilibrium, and this equilibrium is called homeostasis. External stimuli cause the body to reestablish homeostasis and to ultimately reach allostasis. However, failure to reestablish proper allostasis may lead to defective-homeostasis, which may have a detrimental effect on humans, both short-term and long-term. There can also be a harmful effect on individuals when the homeostasis system overreacts or underreacts [2]. Thus, the maintenance of homeostasis can be used as an index for evaluating the health of building occupants [8–12]. In other words, failing to maintain homeostasis will bring negative effects on the human physiology and health [13–16]. Previous relevant studies have analyzed the physiological responses based on specific IEQ conditions and work stress, in which the factors can be divided into three main categories (see Table 1) [1,17–20]: (i) the indoor air quality factor; (ii) the indoor climate factor; and (iii) work stress.

- *Indoor air quality factors*: The indoor air quality factors have a considerable effect on the physiological responses of the building occupants, and of these factors, the CO_2 concentration is one of the main factors [21]. CO_2 can enter from outside but is emitted mainly by the metabolism process of the subjects and equipment use. Zhang et al. [5] found end tidal CO_2 increase with a high CO_2 concentration. Kajtár and Herczeg [22] found that a high CO_2 concentration

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https://doi.org/10.1016/j.buildenv.2018.09.018
Received 1 July 2018; Received in revised form 9 September 2018; Accepted 10 September 2018
Available online 12 September 2018
0360-1323/

Table 1
Reviews of researches using physiological response.

Category	Reference	Physiological response
i) Indoor air quality factors (CO_2 concentration)	[5]	$ETCO_2$[a]
	[22]	HR[b], DBP[c]
	[23]	Breathing, BT[d]
	[8]	Respiratory
	[25]	SBS[e]
	[4]	SDNN[f]
	[12]	Salivary cortisol
	[20]	SBP[g], DBP[c]
ii) Indoor climate factors (Air temperature Humidity)	[1]	BP[h], HR[b]
	[3]	Skin blood flow, BP[h]
	[19]	BP[g], HR[b], BT[d]
	[11]	Skin humidity
	[27]	Skin humidity
	[28]	α amylase
	[29]	Sweat
	[9]	Shiver
iii) Work stress (Office work Cognitive task Work load)	[32]	HR[b], SC[i]
	[31]	Heat flux, ECG[j]
	[37]	sIgA[k]
	[10]	sIgA[k]
	[28]	sIgA[k]
	[39]	sIgA[k]
	[17]	BP[h], HR[b]
	[18]	BP[h], HR[b]
	[40]	HR[b]
	[41]	HR[b]

Note: $ETCO_2$[a] stands for end tidal CO_2; HR[b] stands for heart rate; DBP[c] stands for diastolic blood pressure; BT[d] stands for body temperature; SBS[e] stands for sick building syndrome; SDNN[f] stands for standard deviation of normal to normal intervals; SBP[g] stands for systolic blood pressure; BP[h] stands for blood pressure; SC[i] stands for skin conductivity; ECG[j] stands for electrocardiogram; sIgA[k] stands for salivary secretory immunoglobulin A.

resulted in the increase of the DBP and heart rate. Caruana-Montaldo et al. [8] and Chen and Hsiao [23] found that the change in the CO_2 concentration led to respiratory change and that the high CO_2 concentration caused increased respiration and body temperature. Allen et al. [24] found that the cognitive function score of subjects decreased even when the CO_2 concentration was approximately 950 ppm. Apte et al. [25] found that the sick building syndrome has a significant correlation with the CO_2 concentration near 900 ppm. Considering the aforementioned studies, it can be said that even though some studies failed to observe a significant change in the subjects' BP, an increase in the CO_2 concentration resulted in not only an increase in the subjects' respiration but also a physical symptom as well as the change of the subjects' BP.

- *Indoor climate factors*: The indoor climate factors are related to the IEQ factors [26]. Particularly, a change in the operative temperature will cause the following effects on the building occupants' physiological responses. Budd and Warhaft [1], Sun and Zhu [3], and Mäkinen et al. [19] analyzed the changes in the BP and heart rate according to the thermal change and found that when the operative temperature increased, the BP decreased while the heart rate increased. Höppe et al. [11] and Toftum et al. [27] observed the humidity increase on the subjects' skin due to the increase of the operative temperature. Tham and Willem [28] confirmed an increase of α amylase at the moderately cold temperature of 20 °C. Wyndham et al. [29] divided the subjects in their study into male and female subjects to compare their physiological responses according to the thermal change, and the results showed that the female subjects produced less sweat than the male subjects. Cheng et al. [9] analyzed shivering, which occurs with a fall in the operative temperature, and observed that shivering increased at a cold temperature. Considering the aforementioned studies, it can be said that when the operative temperature increases, the skin blood vessels of the subjects become relaxed to maintain homeostasis, and as such, the SBP and DBP decrease.
- *Work stress*: The types of stress of the building occupants of an office building include job stress, work stress, office work, and cognitive tasks [30–33]. Stress affects the autonomic nervous system, and the Excitement of the sympathetic nervous system causes various cardiovascular responses, such as arterial blood pressure rise and abnormal heart rate [34,35]. The continued exposure of subjects to stress can result in autonomic imbalance, which can cause abnormal physiological responses and even the death or disease of the subjects [36]. Mehler et al. [32] discovered that the increase of the office workload would result in the rise of the heart rate and skin conductivity. Haapalainen et al. [31] argued that the heat flux and median absolute deviation of the electrocardiogram might be the most reliable values for distinguishing the level of cognitive load. Evans et al. [10], Henningsen et al. [37], Phillips et al. [38], and Zeier et al. [39] focused on salivary secretory immunoglobulin A (sIgA), an indicator of the status of the immune system, under high stress. In summary, it was shown that high negative stress decreased the sIgA. Ettema and Zielhuis [17] and Fredericks et al. [18] studied the heart rate and BP under mental workload and found that mental workload resulted in the rise of the BP and heart rate. Lenneman et al. [40] and Thackray and Pearson [41] showed that the heart rate was increased by stress. It has also been shown that general stress excites the sympathetic nerves [42]. The aforementioned studies showed that work stress excites the sympathetic nervous system, which causes the BP to rise as the subjects need to maintain homeostasis.

Overall, the building occupants' physiological responses are affected by the indoor air quality factors, indoor climate factors, and work stress, but it was difficult to analyze all indices at the same time in previous studies. Therefore, this study aimed to analyze the physiological responses (i.e., BP) of the building occupants based on their activity and the IEQ condition changes by fixing one by one, in order to confirm healthy and acceptable IEQ condition.

2. Materials and methods

Kim et al. [43] develop an integrated psychological response score based on building occupants' activity and the IEQ condition changes. A questionnaire survey on IAQ satisfaction and thermal comfort was performed before and after (i) office work and (ii) IEQ condition changes. As the operative temperature was changed from cold to neutral, the psychological response score was enhanced. In addition, the building occupants were more affected by the operative temperature more than by the CO_2 concentration. In this study, more comprehensive research, focused on the building occupants' physiological responses, was carried out as a follow-up to the research of Kim et al. [43].

This study was conducted in the following four steps: (i) establishment of experimental conditions; (ii) preparation of the experimental protocol; (iii) measurement of the physiological responses of the subjects; and (iv) analysis of the physiological responses of the subjects based on their activity and the IEQ condition changes.

2.1. Step 1: establishment of experimental condition

In this study, the IEQ condition changes in normal office hours were divided into three scenarios. To investigate the effect of the IEQ condition changes on the subjects' physiological responses, the CO_2 concentration, an indoor air quality factor, was varied, and the operative temperature, an indoor climate factor, was adjusted. To design the experimental conditions, this study collected real-time office monitoring data, and referred to international standards, and the experimental conditions in previous studies [44–50]. In February and August