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An integrated psychological response score of the occupants based on their activities and the indoor environmental quality condition changes

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ABSTRACT

Psychological response based on the indoor environmental quality (IEQ) condition changes and activities of the occupants, can be assessed via indoor air quality (IAQ) satisfaction and thermal comfort. However, it is difficult to analyze both indices at the same time because they are measured on different scales. Therefore, this study aimed to develop an integrated psychological response score of the occupants based on 22 experimental participants' activities and the IEQ condition changes by using the weighted Euclidean distance. For this purpose, the experiment was designed with three scenarios to simulate the IEQ condition changes (i.e., CO_2 concentration and operative temperature) during an 8-h working period. In each scenario, six cognitive tasks that simulate office work were performed to consider the activities of the occupants. A questionnaire survey on IAQ satisfaction and thermal comfort was conducted before and after (i) office work and (ii) IEQ condition changes. As a result, when the operative temperature was changed from 18.70 °C (cold) to 25 °C (neutral), the best psychological response score was calculated as 0.335. In addition, the occupants were more affected by the operative temperature than the CO_2 concentration. It was shown that the mental health status based on IEQ condition, while considering both the indoor air pollutant and indoor climate, could be expressed as a single index. The mechanical system designer and facility manager can design or operate the IEQ condition considering the integrated psychological response score of the occupants, which can be used as an IEQ condition management guideline for mental health.

1. Introduction

As people spend most of their time indoors, there is an increasing interest in indoor environmental quality (IEQ) affecting the mental health status and productivity of the occupants [1–3]. In particular, IEQ management is very important in open-plan offices as they continue to develop [1,4–6]. The mental health of the occupants can be analyzed via psychological response, which can be grouped into indoor air quality (IAQ) satisfaction for indoor air pollutant factors and thermal comfort for indoor climate factors [3,4,7–12]. Industry, government, and academic sectors have tried to define a comfortable range of IEQ conditions considering the psychological responses of the occupants. As a result, many international standards for the health of the occupants were developed in order to maintain a comfortable IEQ condition [3,4,8–12]. In the previous experimental studies, the complex relation between the psychological response and IEQ condition of the occupants with their activities was analyzed as follows (refer to Table 1) [1–4,9–43]: (i) the IAQ satisfaction assessment of the occupants considering the indoor air pollutant factors; (ii) the thermal comfort assessment of the occupants considering the indoor climate and personal factors; and (iii) the IAQ satisfaction and thermal comfort assessment of the occupants considering the indoor air pollutant, indoor climate, and personal factors.

First, several previous studies analyzed the IAQ satisfaction of the occupants considering the indoor air pollutant factors [9,10,13–16]. Aglan [9] developed a model that can predict carbon dioxide (CO_2) concentration that would improve the IAQ of a building. The maximum CO_2 concentration by time was predicted

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Table 1
Review of the IAQ satisfaction and thermal comfort of the occupants.

Occupants' psychological response	[a]IEQ condition factors			Reference
	Category	Sub-category	Unit	
[b]IAQ satisfaction	Indoor air pollutant factor	CO_2	ppm	[9–10,13–16]
		[c]TVOCs	ppm	[13]
		Fine dust	$\mu g/m^3$	[13,15]
Thermal comfort	Indoor climate factors	Indoor temperature	°C	[4,17–35]
		Relative humidity	%	[17–19,21,23–26,28–35]
		Air velocity	m/s	[17,18,21,24–26,28–35]
	Personal factors	Clothing insulation	Clo	[22–26,32,35–37]
		Metabolic rate	Met	[24,26,28,31,32,35,37]
IAQ satisfaction and thermal comfort	Indoor air pollutant, indoor climate and personal factors			[2,3,11,12,38–43]

[a] IEQ stands for the indoor environmental quality.
[b] IAQ stands for indoor air quality.
[c] TVOCs stands for total volatile organic compounds.

by using the model, and the appropriate ventilation rate was suggested by using the maximum CO_2 concentration by time. Hamilton et al. [10] analyzed the benefits of good IAQ and the effects of ventilation and filtration on 112 stakeholders (i.e., owner, facility manager, occupants, mechanical system designer, and consultant) through questionnaire surveys. As a result, a very substantial number of stakeholders did not recognize the benefits of a good IAQ and the effects of ventilation and filtration. They responded negatively to willing-to-pay for improving IAQ. Several studies were conducted in order to determine the IAQ satisfaction of the occupants; however, the thermal comfort (i.e., thermal comfort vote (TCV), thermal satisfaction (TS), thermal sensation vote (TSV) and thermal preference (TP)) should also be considered in analyzing the psychological responses of the occupants.

Second, several previous studies on the thermal comfort of the occupants were carried out in various IEQ conditions based on Fanger's model, which was developed in 1970 [4,17–37]. The predicted mean vote (PMV) and the predicted percentage of dissatisfied (PPD) have been used to measure the thermal comfort of the occupants by using three indoor climate factors (i.e., operative temperature, relative humidity, and air velocity) and two personal factors (i.e., clothing insulation and metabolic rate) [22,23]. The PMV-PPD model has been utilized by various nations and international standard organizations as a standard [23,24]. In the previous studies, the questionnaire survey was conducted in order to present the thermal comfort of the occupants according to the change of indoor climate and personal factors. Cheong et al. [17] measured the thermal comfort of 189 subjects in an air-conditioned lecture room through objective measures, computation fluid dynamics modeling, and questionnaire survey. According to the questionnaire survey, the PMV and PPD of the experimental participants were expressed as −0.93 and 20.6%, respectively. Therefore, the indoor air temperature should be raised to 25.84 °C for the thermal comfort of the occupants. Ning et al. [37] analyzed not only how much the indoor climate factor was affected by climate change in the cold districts of China, but also how this affected the thermal comfort of the occupants. To this end, they performed experiments by dividing the process into five stages from autumn to spring, and conducted a survey on the thermal comfort of the experimental participants. By comparing the PMV and mean TSV, they found that the indoor thermal environment varied according to season, and the mean TSV was constantly greater than the PMV. As a result, various studies were conducted in order to determine the thermal comfort of the occupants. However, the IAQ satisfaction should also be considered in analyzing their psychological responses.

Finally, several previous studies analyzed the psychological responses of the occupants considering both IAQ satisfaction and thermal comfort [2,3,11,12,38–43]. Xue et al. [3] conducted a survey on 482 residents of high-rise residential buildings in order to analyze the effect of IEQ condition on the overall environmental satisfaction of the occupants. Reynold et al. [12] defined the physical, mechanical, and environmental factors that affect IEQ condition in six large office buildings. They considered indoor air pollutant factors (i.e., TVOCs, formaldehyde, acetaldehyde, and CO_2 concentration), indoor climate factors (i.e., operative temperature and relative humidity), noise, and light as IEQ parameters. As a result, the IEQ parameters were significantly correlated with each other, and there were differences in psychological responses between the male occupants and female occupants based on the IEQ condition. As mentioned above, there have been studies that analyzed the psychological responses of the occupants considering both IAQ satisfaction and thermal comfort. However, only a few studies have been conducted that syntagmatically analyzed the psychological responses of the occupants according to the IEQ condition changes.

Overall, psychological responses according to the IEQ condition changes and activities of the occupants can be assessed by using IAQ satisfaction and thermal comfort, but it is difficult to analyze both indices at the same time because they are measured on different scales. Therefore, this study aimed to develop an integrated psychological response score of the occupants based on their activities and the IEQ condition changes.

2. Material and methods

2.1. Study design

This study is conducted in the following five steps: (i) Experimental condition; (ii) Experimental protocol; (iii) Psychological response measurements of the occupants; (iv) Psychological response analysis of the occupants based on their activities and the IEQ condition changes; and (v) Development of integrated psychological response scores of the occupants based on their activities and the IEQ condition changes.

- *Step 1: Experimental condition*: Three scenarios were designed by simulating the IEQ condition changes during an 8-h working period. Each scenario was classified into an initial IEQ condition and a changed IEQ condition according to the IEQ condition. Scenarios 1 and 2 were designed to measure the psychological responses of the occupants when the operative temperature was changed, while scenario 3 was designed to measure the psychological responses of the occupants when the CO_2 concentration was changed.