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Workplace productivity and individual thermal satisfaction

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ABSTRACT

This study examines the relationship between individual thermal satisfaction and worker performance. Field measurements and a questionnaire survey were conducted within an organization participating in the COOL BIZ energy conservation campaign. A subjective experiment was also conducted in a climate chamber with eleven Japanese male subjects, testing five scenarios combining operative temperature (25.5 °C and 28.5 °C), clothing (with and without suits), and cooling items (desk fan, air-conditioned shirt, mesh office chair). From the individual analysis, actual air temperature in the COOL BIZ office was poorly correlated with self-estimated performance, whereas perceived thermal satisfaction correlated well with self-estimated performance ($R^2 = 0.944$, $p < 0.001$). The results of the subjective experiment indicate that performance during simulated office work (i.e. multiplication and proof reading tasks) increased with greater individual thermal satisfaction ($R^2 = 0.403$ and 0.464, $p < 0.001$). The finding that perceived thermal satisfaction of occupants is reflected in objective measurement of office work performance has practical implications for the evaluation of thermal satisfaction in real offices as a means to boost workplace productivity.

1. Introduction

There is an extensive body of research on comfort and satisfaction in indoor environments, which includes a strong focus on directly relating elements of indoor environments with workplace productivity. However, there is no clear evidence that employee satisfaction with the indoor environment is associated with improved productivity. The main aim of this study is to examine the relationship between individual thermal satisfaction and worker performance.

In Japan, building-related carbon dioxide emissions, or the sum of the “commercial” and “residential” sectors, account for nearly one-third of the total emissions, and show the greatest increase. In order to reduce emissions from the “commercial” sector, the COOL BIZ campaign [1] has been promoted by the Japanese government since the summer of 2005, which involves raising the preset temperature for cooling, and modifying the business dress code in offices during summer. The issue of energy conservation has been more actively addressed in Japanese offices after the Great East Japan Earthquake of 2011 [2]. The most well-known catchphrase of the COOL BIZ campaign is “28 °C,” which is the upper limit to invoke cooling, set by the “Act on Maintenance of Sanitation in Buildings” [3]. The effect of removing jackets and ties was reported to be equivalent to lowering air temperature by 2 K [4]. The Energy Conservation Centre, Japan (ECCJ) reported that 1.2% of the annual energy consumption of an HVAC (heating, ventilation, and air conditioning) system can be saved by raising the temperature set point during summer from 26 °C to 28 °C. Since the annual primary energy consumption of a typical office building in Japan is 2225 MJ/($m^2 \cdot yr$), the reduction under the COOL BIZ campaign was estimated to be 26.7 MJ/($m^2 \cdot yr$) [5]. Although the effect was estimated in terms of energy conservation, there was no recognition of the effect of raising air temperature by 2 K on worker performance.

Several studies have reported the effects on work performance of a moderately warm environment, corresponding to a COOL BIZ office. Tanabe et al. [6] tested the effect of moderately hot environments at 25 °C, 28 °C, and 33 °C on office work performance via a subjective experiment. The effect differed between task types and was inconsistent, while there was a clear trend of greater mental

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fatigue with higher temperature. Witterseh et al. [7] conducted a subjective experiment to test the combined effect of thermal (22 °C corresponding to thermally neutral, 26 °C corresponding to slightly warm, 30 °C corresponding to warm) and acoustic environments (35 dBA and 55 dBA with extra recorded noise) over an exposure period of 180 min. In the conditions without noise, there was no significant difference in the performance of simulated office work at different temperatures. In terms of the effect of thermal discomfort, the subjects who felt too warm (pooled results at both 26 °C and 30 °C) made 56% more errors during a mathematical addition task. Lan et al. [8] investigated the effects of thermal discomfort on health and human performance by testing two conditions at 22 °C and 30 °C with twelve subjects. Task performance decreased when the subjects felt warm at 30 °C than when they felt thermally neutral at 22 °C. Tanabe et al. [9] performed a field survey at a call center in Japan to investigate the effect of indoor air temperature on call response rate. The results showed that raising indoor air temperature by 1.0 K from 25.0 to 26.0 °C was associated with a 1.9% reduction in call response performance. Following a detailed review of the literature, Seppänen et al. [10] proposed an equation relating indoor air temperature and relative performance of office work. In this equation, performance decreases with increasing indoor temperature higher than 21.8 °C.

In addition to indoor air temperature, many of previous laboratory studies that focused on the effect of thermal comfort on worker performance considered other elements of thermal environment. Wyon et al. [11] conducted a subjective experiment that provided two ensembles of clothing (1.15 clo and 0.60 clo) that allowed subjects to adjust the indoor temperature according to their preference in each condition. Several types of simulated office tasks were performed during 2.5 h of exposure; however, no significant difference was observed between the conditions. Witterseh [12] exposed subjects to test conditions (duration 173 min); clothing was adjustable to maintain thermal neutrality at 22 °C and 25 °C, and clothing was fixed to feel slightly warm at 22 °C. Subjects made significantly fewer errors during a mathematical addition task at 25 °C than at 22 °C. Fang et al. [13] found no significant difference in performance when subjects were exposed to conditions of 20 °C/40%RH, 23 °C/50%RH and 26 °C/60%RH for 280 min. The subjects were allowed to adjust their clothing so that they were thermally neutral (0 ± 0.5) in these conditions. The decline in performance when exposed to different temperatures was not significant when the thermal perception of the subjects was within the comfort zone. Willem [14] exposed 96 Singaporean subjects to temperatures of 20 °C, 23 °C, and 26 °C for 245 min. Average thermal sensations reported by the subjects at these conditions were −1.8, −0.9, and +0.5, and were comparatively colder than votes by European subjects reported by Witterseh et al. [7]. This might indicate that the origin or the habitual climate of subjects can influence their thermal sensation. Performance during a proof reading task was significantly better at 20 °C and 26 °C than at 23 °C; and typing speed was faster at 20 °C than at 23 °C and 26 °C [14]. From the review of the previous literature, it is clear that there are no effects on performance at neutral thermal conditions, whereas the effects are inconclusive at non-neutral conditions. As de Dear et al. [15] concluded from an extensive literature review, the effects of thermal comfort on task performance and productivity remain ambiguous due to diverse definitions of the productivity metric.

Huizenga et al. [16] conducted a questionnaire survey at 215 buildings in the US, Canada, and Finland, and reported that satisfaction with workstation temperature was strongly correlated with self-assessed productivity. Unfortunately, no further attempt has been made to relate satisfaction with thermal environment to office work performance.

In this study, a field survey was conducted to investigate thermal environment in an office at which the workers were responsible for promoting the COOL BIZ campaign. A questionnaire survey was conducted to evaluate the effect of thermal satisfaction on productivity. Then, a subjective experiment was conducted in a climate chamber to evaluate the effect of improving thermal satisfaction (by introducing cooling items) on the performance of simulated office work.

2. Field survey in COOL BIZ office

2.1. Methods

2.1.1. Investigated office

The field survey was conducted in an office on the 23rd floor of a 26-story office building that was constructed in 1983 in Tokyo, Japan. The office, as shown in the floor plan in Fig. 1, was split into two rooms on the east and west sides of the building, and covered a floor area of 530 m^2. Forty-eight workers are based in the east room and sixty-eight in the west. During the COOL BIZ campaign from June 1 to September 30, the cooling temperature in the office was set at 28 °C and the workers were encouraged not to wear suit jackets and ties. Operation of the HVAC system started at 09:30 and lasted until 19:00 during this survey.

2.1.2. Measurement of the thermal environment of the office

The thermal environment of the office was measured from July 23 to September 30, 2007. The measured points are indicated in Fig. 1. Air temperature and relative humidity were measured at 36 points in the office with RSW-20S (Espec) thermo-recorders positioned 0.6 m above the floor. Vertical air temperature profile was measured at the perimeter and the interior in the east room with an RTW-30S (Espec) thermo-recorder positioned at 0.1 m, 0.6 m, 1.1 m, 1.7 m, and 2.1 m above the floor. Supply air temperature of the HVAC system was measured at 8 points in the office (RTW-30S). Supply air temperature of the fan-coil unit (FCU) was measured at 6 points (RTW-30S). All measurement intervals were 10 min.

2.1.3. Questionnaire survey

A questionnaire survey was conducted in three periods: July, August, and September. In each period, three pairs of questionnaires for the “Beginning” and “End” of the working day were distributed to and collected from 105 workers. The “Beginning” questionnaire consisted of present health status, assessment of indoor environment, and subjective fatigue symptoms [17]. The “End” questionnaire assessed indoor environment during the working hours, self-estimated performance, mental workload, concentration on work, motivation for work, usage of cooling items, and subjective fatigue symptoms. The scoring schemes for thermal satisfaction and self-estimated performance are shown in Fig. 2. The cooling items used in the office included a personal paper fan, a personal electric fan on the desk, a shared electric fan on the floor, and/or a dehumidifier.

2.2. Results

2.2.1. Measurement of thermal environment in the office

The mean indoor air temperature of the office during operation of the HVAC system was approximately 28 °C, which was the set temperature point for cooling; however, the temperature varied with location and time. As an example of a typical summer day, the planar temperature distribution at 12:00 on August 8 was obtained by bilinear interpolation, as shown in Fig. 3. The indoor air temperature tended to be higher in areas with high density of heat sources, such as workers and electrical appliances. Fig. 4