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Thermal comfort and self-reported productivity in an office with ceiling fans in the tropics

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ABSTRACT

Here we present a field study examining the impact of elevated room temperature and air movement on thermal comfort and self-reported productivity. This experiment was performed in three environmental conditions (one with a set-point of 23 °C—a typical set-point used in Singapore—and two elevated (up to 28 °C) room temperature conditions). Occupants had shared control of ceiling fans.

The results show that the most comfortable thermal condition, with thermal sensation closest to neutral, is achieved at a room temperature of 26 °C with operating fans. Increasing the temperature set-point from 23 °C to 26 °C resulted in a significant increase in thermal acceptability (from 59% to 91%), and a 44 kWh/m^{2}yr savings in electrical energy used for comfort cooling. We found that a room's set-point temperature can be increased up to 27 °C without creating a negative impact when controllable air movement is provided compared to an environment with a set-point of 23 °C. Thermal satisfaction is significantly higher in spaces of 26 °C with operating fans, than when the room's temperature is set at the typical 23 °C. Moreover, the relative humidity in the office is decreased from 62% (when the temperature was 23 °C) to 50% when the temperature was 27 °C.

Occupant's self-reported ability to concentrate, be alert, and ability to be productive was comparably high in all conditions. The results indicate that work performance is poorly correlated with room temperature, but increases with greater individual thermal satisfaction.

1. Introduction

Extensive environmental field studies in tropical climates show that most commercial buildings are overcooled [1]. Overcooling not only results in high occupant dissatisfaction, but also in energy waste. Leading causes of this issue are oversized air handling units, which have limited ability to adapt to heat source changes, and dehumidification with supply air [1,2].

Compared to full refrigeration based air-conditioning strategies, an increase in the temperature set-point in hot and humid climates, together with elevated air movement, is a promising solution for increasing occupants' thermal satisfaction and bringing substantial energy savings. Energy simulation analyses of these solutions show projected savings up to 30% [3–6]. Laboratory studies show that elevated air movement at room temperature of 26 °C and above can increase the acceptability of thermal conditions up to 90–100% [7,8]. Thermal comfort in laboratory conditions can be achieved by increased air speed even at the room air temperature of 32 °C and relative humidity of 60% [9–12]. Similar results have been replicated in naturally ventilated buildings with ceiling fans in Brazil [13]. However, to our best knowledge, a field study examining elevated room temperature and air movement provided by ceiling fans in an actual office environment has not been conducted yet. Air movement also appears to compensate the adverse impact of increased temperature on occupants' perceived air quality and cognitive performance [7,12,14,15]. Moreover, results from field surveys show that about 60% of occupants feel as though air movement enhances their ability to work, while about 15% of occupants report that air movement interferes with their work performance [16].

Ceiling fans are both cost-effective and easy to implement (in both new and retrofit environments). Further, fans with direct current (DC) motors have up to 65% higher energy efficiency than alternating current (AC) fans. For standing fans, a change in motors can result in up to three times higher cooling efficiency [17]. Even more, DC motors allow for a wider range of fan speed set-points and emit less noise. Despite these advantages, ceiling fans are most predominantly used within the residential sector. However, several studies have suggested the need for air movement in office spaces. For instance, cross-study analyses of

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ASHRAE field studies and climatic chambers studies examined when air movement is perceived as most desirable and undesirable, and summarized the factors influencing those perceptions [10]. Exploration of other databases, Center for the Built Environment's Occupant Indoor Environmental Quality (IEQ) survey database [16] and ASHRAE RP-1161 dataset [18], has also yielded useful insights into these issues. These extensive datasets indicate that twice as many people prefer more air movement as opposed to it—even when occupants report experiencing cooler thermal sensations. These findings suggest that most air movement tends to be too low in workspaces—forcing occupants to seek personal remedies (such as opening a window or using a personal fan) to increase thermal comfort.

To analyze demand for air movement in warm environments, a series of survey studies were conducted in China [9]. Results showed that 78% of participants frequently use fans at home, even though 68% of those respondents also have installed air-conditioning. Additionally, 70% of respondents report that fans are an acceptable solution for offices. Interestingly, results also highlighted that the main advantages of ceiling fans in the office environment are: an increase in perceived air freshness, increased personal control, prevention of drowsiness, and a lack of risk of overcooling—as can happen with air-conditioning.

In response to findings like those mentioned above, both EN 15251 [19] and ASHRAE 55 [20] standards allow for an increase in a space's temperature with the presence of elevated air movement—even though each standard uses different calculation methods. For instance, according to EN 15251 [19], air velocity can be increased to 0.8 m/s which would compensate for an operative temperature increase by 2.8 °C above comfort temperature at still air. ASHRAE 55 [20] and EN ISO 7730 [21] extend the acceptable range of air velocity with regards to relative differences between both mean radiant and air temperature. Additionally, ASHRAE 55 [20] gives no air speed limit if occupants have the ability to personally control their thermal environment, or if the metabolic rate is above 1.3 met. The current Singaporean standard SS 553 [22] allows for an increase in operative temperature up to 26 °C when an air-conditioning system is in operation, but it also suggests that air movement should be limited to 0.3 m/s.

Previous studies examining increased temperature set-points and air movement have been performed in laboratory conditions. These types of studies tend to be conducted with short time exposure and are limited to simulated tasks, which are quite simplistic compared to actual employees' responsibilities in an actual workplace. Moreover, they focus mostly on the personally controlled devices, which implementation on a big scale in currently dominating open-space offices is questionable. The current study aims to assess the impact of the use of ceiling fans under shared control and increased temperature set-points, on thermal comfort and self-reported productivity, with workers performing their actual work, in a real office space located in Singapore.

2. Methods

2.1. Facilities and measuring equipment

A case study was conducted for six weeks at the Robert Bosch (SEA) Pte Ltd building. To our best knowledge, it was an only commercial company (not related to fan industry) in Singapore that decided to install ceiling fans in its office space and agreed to perform prolonged questionnaire study. Participants worked in two open-space office rooms (WxLxH: 8.0 m × 8.0 m x 4.2 m) and in a private room separate from the main open-spaces (3 m × 4 m) shown in Fig. 1. The space under examination is localized on the first floor and has a glass façade with a south-west orientation.

Within the space, a mechanical ventilation system delivers required air-conditioned outdoor air to the occupants. Separate fan coil units (2 units of Carrier 40LM070 with a total cooling capacity of 12.8 kW per room) control the room's temperature set-points. DC motor ceiling fans (Haiku I-Series 60 in., BigAss Solutions, US) provide elevated air movement within the space. Fans are installed in an array of 3 m × 4 m at the height of 3.5 m from the floor. The maximum power consumption of the installed fans reaches 30 W per fan; however, the fan power consumption related to the speed set points usually used by occupants is no greater than 5 W.

Dry-bulb air temperature, operative temperature and relative humidity were measured at workstations in 5-min intervals using a data logger (HOBO U12-012, Onset, US) with an accuracy of ± 0.35 °C, ± 0.25 °C and ± 2% *RH* respectively (measuring range: −20–70 °C and 5–95% *RH*). We used grey sphere sensors to directly measure the operative temperature [23]. The temperature sensors were calibrated before measurement.

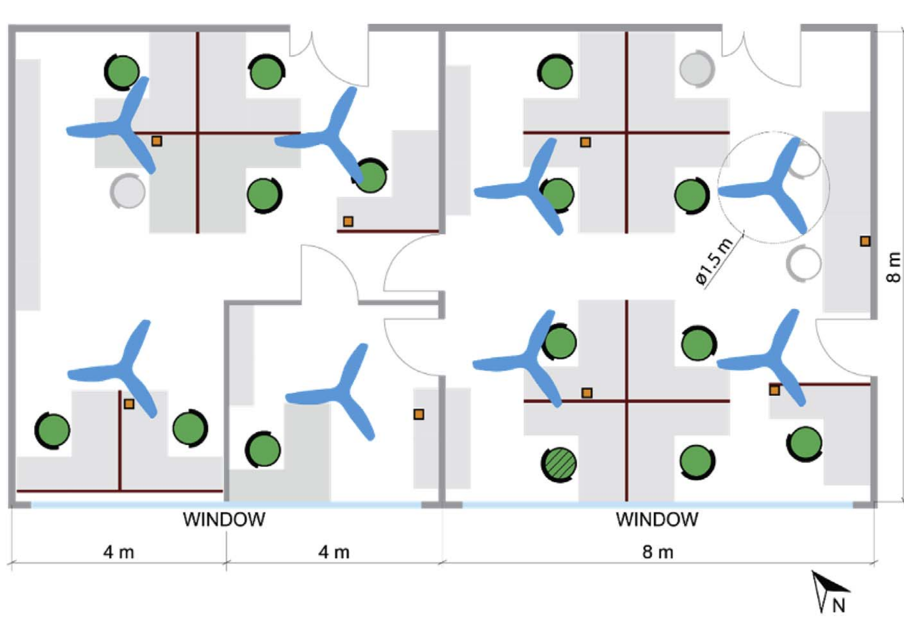

Fig. 1. Plan view of the studied office space. Green seats represent occupants participating in the study (occupant marked with dashed lines submitted invalid generic questionnaire), grey seats occupants who refused to participate and white empty seats. Ceiling fans (1.5 m (60 in.) in diameter) are marked in blue. Orange squares show positions of sensors monitoring dry-bulb and operative temperatures, and relative humidity. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)