The effect and influence of personalised ceiling fans on occupants' comfort and physiological response

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Abstract: Personal environmental control systems (PECS), such as fans, have been widely implemented as an effective strategy to increase energy efficiency and occupants' satisfaction with indoor environmental conditions. This paper explores significant differences between thermal sensation votes and participants' physiological responses when using personal ceiling fans. In an experimental study in summer of 2018, 45 participants were exposed to two thermal conditions (28°C and 31°C) and different airflow speeds and directions in a climate chamber that simulates a typical office environment. Indoor environmental, psychological and physiological responses (skin temperature and heart rate) were recorded during the entire session. We tested differences in physiological responses between different demographic, contextual groups and airspeed levels. Results showed that at 31°C, participants had a significantly higher distal skin temperature and that airspeed helped reduce proximal skin temperature. Overweight participants showed a significantly lower proximal skin temperature than average weight participants. Heart rate results yielded statistically significant differences between age groups. Besides, findings suggest that skin temperature follows indoor temperature changes. By increased airspeed, physiological adaptations can be stimulated to restore comfort. Overall, personal ceiling fans are an effective cooling solution that can target occupants' body parts and individual characteristics to increase their comfort.

Keywords: skin temperature; heart rate; personal comfort system; thermoregulation; thermal comfort

1. Introduction

The study of personal environmental control systems (PECS) has gained relevance in recent years, as they can improve occupants' satisfaction with the indoor environment and potentially increase energy savings in buildings. PECS targets occupants' proximity by conditioning only the occupied zone of the building space; hence, there might be less energy consumption than systems that condition the entire building volume, such as air conditioning systems. As a type of PECS, the use of fans has been widely implemented, as the cooling effect of the air movement increases occupants' thermal comfort and acceptability range in moderately warm thermal conditions. Furthermore, localised convective cooling of transitional spaces and work areas by ceiling or desk fans represents a way to enhance comfort recovery (Zhai et al., 2019).

The study of PECS is sustained in the paradigm that shifting thermal comfort toward a wider temperature range might stimulate the thermoregulatory system and not only achieve comfort but improve occupant's health (Ivanova et al., 2021; Luo et al., 2022). For instance, mild cold exposure can increase the human body's daily energy expenditure, contributing to maintaining a healthy weight and improving glucose metabolism. On the other hand, heat exposure can improve cardiovascular functioning after hot water immersion, decrease systolic blood pressure, and improve glucose metabolism (Ivanova et al., 2021). On the contrary, maintaining a stable indoor climate design could decrease the body's thermal resilience, in other words, the ability of the body to adjust to non-neutral conditions (Luo et al., 2022).

The human thermoregulation system responds to various indoor climate conditions through skin temperature adjustments and other physiological responses to keep the body core temperature within narrow temperature limits (Rawal et al., 2020). Skin temperature acts as one and an important sensor of the human body's thermoregulatory system (ASHRAE, 2017). Local skin temperature results from the complex balance between metabolic heat production, heat dissipation to the environment and tissue temperature (Binek et al., 2021). Differences in skin temperature could arise from body composition, health status, metabolic rate, circadian rhythm and ambient temperature (Neves et al., 2017). The underlying adaptive mechanisms to restore comfort are (a) behavioural, (b) physiological and (c) psychological adaptation. While minimising the availability of behavioural adaptation, physiological responses may occur. For instance, PECS can minimise thermal discomfort of targeted body parts which may activate thermoregulation. Very few studies have investigated the human body's physiological response to an increased airspeed due to the use of ceiling fans.

Luo et al. (2022) studied 18 participants between 18 and 40 years old in a climate chamber in autumn and winter. They tested two main scenarios (PECS and no PECS) and the indoor air temperature ranging from 17°C to 25°C. Results showed that skin temperature follows the same increasing pattern as the indoor air temperature. Distal and head skin temperature were significantly affected when using PECS, but this was not the case with torso skin and underarm-finger temperature gradient. Significant differences in lower limb temperature between 10 male and six female highly trained subjects were observed by Binek et al. (2021) under resting conditions but not during exercise. Regarding heart rate, Luo et al. (2022) reported no apparent relation with the indoor environment temperature ramp from 17°C to 25°C. However, there was a small but significant increase in hand skin blood flow and a significant increase in the average heart rate by 2.2 BMP ($p < 0.001$).

Finally, some researchers look into the ability to include physiological parameters to estimate thermal comfort responses better. Kingma et al. (2017) looked into the physiological thermoneutral zone (TZN) as a proxy to understand the thermal sensation. Some authors (Chaudhuri et al., 2018; Wu et al., 2017; Zhang and Lin, 2020) found a relationship between overall thermal sensation and mean skin temperature and proposed that the latter could predict thermal votes.

Existing research highlights the impact of physiological responses in thermal comfort studies; however, little is known about the cooling effect of the air movement due to ceiling fans in warm conditions. The study hypothesises that human thermoregulation can be moderately stimulated while providing comfort using personal comfort systems and investigates differences between demographics and contextual differences in human physiology.

2. Objective (Hypothesis)

The study focuses on the evaluation of the effect of personal ceiling fans on skin temperature and heart rate differences due to personal (sex, age, BMI), contextual characteristics (daytime, air temperature), and psychological responses (thermal sensation votes) for the given indoor environmental conditions. The main research questions are as follows:

- RQ1: Is there any significant difference in skin temperature (distal and proximal) and heart rate when subjects are exposed to increased airspeed from personal ceiling fans?

- RQ2: Is there any significant difference in skin temperature (distal and proximal) and heart rate when subjects are exposed to different levels of airspeed?
- RQ3: Is there any significant difference in skin temperature (distal and proximal) and heart rate when subjects felt comfortable or uncomfortable based on reported thermal sensation for different levels of airspeed?

3. Methodology

To investigate the above-mentioned research questions, we conducted a 3-weeks experimental study in the test facility LOBSTER in Karlsruhe, Germany (Schweiker et al., 2014) during the summer of 2018.

3.1. Facility and experimental procedure

The facility consists of two office rooms equipped with a personal ceiling fan, which is integrated into an acoustical ceiling panel. Participants took part in a three h 30 minutes sessions in one of the two rooms of the climate chamber, either in a slot between 9:00 and 12:30 (morning) or 13:30 and 17:00 (afternoon). During the first 30 minutes, the participants acclimatised to the given conditions in the room (acclimation phase). After this period, they experienced six different workstation configurations in a randomised order for 20 minutes concerning the ceiling fan position. For each configuration, participants were exposed to a constant fan speed for 10 minutes ('fixed' condition) and afterwards were given the possibility to adjust the fan speed level for the following 10 minutes ('adjustable' condition). They performed office tasks during the whole session, such as reading or working with the computer. The rooms were set with a room temperature of 28°C (50% RH), and a selected number of participants (N = 11) repeated the session another day with a room temperature of 31°C (50% RH). A detailed description of the study and the ceiling fan is explained in Rissetto et al. (2021).

3.2. Participants

Forty-five participants between 18 and 34 (Adult) and 50–70 year (Elderly) (age young 30.67 ± 4.04, age elderly 65.48 ± 6.45; BMI 24.7 ± 3.72 kg/m2) took part of the study. They were asked to wear long trousers, a t-shirt, and closed shoes (M = 0.44 clo-value; SD = 0.12). Table 1 shows the distribution of participants according to their age group, age, body mass index (BMI < 25 kg/m2 = normal and BMI > 25 kg/m2 = overweight) and sex.

Table 1. Participants' distribution according to personal characteristics (age, sex, BMI).

		Age		Subtotal
Sex	**BMI**	**Adult**	**Elderly**	
Male	Normal	8	7	15
	Overweight	3	8	11
	Subtotal	11	15	26
Female	Normal	7	2	9
	Overweight	1	9	10
	Subtotal	8	11	19
	Total	19	26	45

3.3. Materials and data collection

Physiological data. We measured the skin temperature of the single participants in four points with temperature loggers (iButton model = DS1921H; r = 0.125°C; a = +/- 1°C). The proximal skin temperature was measured at the back of the neck and the right shoulder, and the distal skin temperature was measured at the back of the left hand and the right shin. Their heart rate was measured with chest strap sensors (Model: EcgMove 4; r = 12 bit; Input range CM = 560 mV, DM = +/-5 mV). All data was recorded in a 1-minute interval.

Temperature and airspeed. We also collected with AHLBORN comfort meters located at 1.1 m height and 0.25 m away from the participant's head the following parameters: air temperature (r = 0.01 °C; a = ±0.2 K), globe temperature (r = 0.01 °C; a = ±(0.30 K + 0.005 × T)), relative humidity (r = 0.1%, a = ±2.0%) and air velocity (r = 0.001 m/s; a = ±(3% measured value + 0.01)). Participants' interactions with the ceiling fan during the adjustable condition were collected using a remote controller with a reference level from 0 to 100%. The device was connected to the building management system (BMS), and the fan speeds could be derived from the recorded levels.

Psychological data. Participants completed several questionnaires at different times during the session, including thermal sensation (7-point; *cold* ←→ *hot*), comfort (5-point; *comfortable* ←→ *extremely uncomfortable*), preference (7-point; *much cooler* ←→ *much warmer*), acceptability votes (4-point; *clearly acceptable* ←→ *clearly not acceptable*), perception of air quality and airspeed, among others.

3.4. Data analysis

Data preparation and analysis were conducted with the software environment R Version 4.1.3. Both physiological parameters (heart rate and skin temperature) and airspeed are measured on interval level and therefore assessed using parametric tests. Data normality was tested using Shapiro-Wilk's test, distal skin temperature is normally distributed (W = 0.988, p = 0.071), and proximal skin temperature (W = 0.985, p = 0.025) and heart rate (W = 0.969, p = 0.000) are non-normally distributed. An independent t-test was conducted to test differences between demographics and contextual factors when the studied variables had two groups when data was normally distributed. Furthermore, an ANOVA (F) test was used when the studied variables had more than two groups. Whenever data follows a non-normal distribution, comparisons between two levels were tested using the Mann-Whitney and Kruskal-Wallis (H) for three levels of analysis. Moreover, a paired t-test was conducted to test the significant difference between distal and proximal temperatures. All t-tests were calculated with a significance level of 0.05. Finally, effect sizes are interpreted as small (d = 0.10), medium (d = 0.30), and large (d = 0.50), based on Cohen's suggestions (Cohen, 1988). Table A 1 shows the mean and standard deviation for each analysed group's distal and proximal skin temperature and hear rate scores.

To evaluate the effect of an increased airspeed due to the use of personal ceiling fans in physiological responses, data corresponding to the acclimation period and airspeed below 0.05m/s was discarded from the analysis. To evaluate significant differences in physiological responses between participants' personal (sex, age, BMI) and contextual characteristics (daytime, air temperature) (*RQ1*), we conducted a series of independent-samples t-tests and Mann-Whitney tests to compare the average values of skin temperatures and the average heart rate during the whole session. The effect of different air velocities in participants' physiological responses (*RQ2*) was analysed at three levels of air velocity: Low = airspeed < 0.4m/s, Medium = airspeed between 0.4m/s and 0.8 m/s, High = airspeed > 0.8 m/s. To evaluate significant differences in skin temperature and heart rate between participants who reported thermal sensation for different airspeed levels (*RQ3*), thermal sensation votes (TSV) were classified into two groups: neutral (TSV $\geq 3 \leq 5$) and non-neutral (TSV < 3 and > 5). A correlation between physiological and psychological was performed using Kendall's rank correlation coefficient Tau.

4. Results and discussion

4.1. Differences between personal and contextual characteristics

Error! Reference source not found. shows the results of the t-tests conducted for skin temperature and heart rate to identify differences between personal characteristics (age, sex, and BMI) and between contextual characteristics (daytime and temperature). All groups showed homogeneity of variance for the analysed variables (Table A 2**Error! Reference source not found.**), except for the BMI groups for heart rate scores, which showed inequality of variance across samples. Additionally, we found a significant difference between proximal skin temperature (M = 34.07, SD = 0.89) and distal skin temperature (M = 33.26, SD = 0.68, t (44) = -5.80, p < .001, r = .66, N = 90).

Table 2. Central tendency comparison for skin temperature (distal and proximal) and heart rate measurements between independent groups (sex, age, BMI, time of day and temperature).

	Sex	Age	BMI	Time of day	Temperature
Skin t° distal	t (37.34) = 1.50 p = 0.141 M = 33.08 (f); 33.39 (m)	t (31.41) = -0.52 p = 0.608 M = 33.32 (y); 33.21 (e)	t (39.89) = 1.81 p = 0.08 M = 33.42 (n); 33.07 (o)	t (42.96) = -0.56 p = 0.578 M = 33.31 (m); 33.20 (a)	t (15.43) = -5.02 **p < 0.01**** M = 33.05 (1); 34.00 (2)
Skin t° proximal	W = 185 p = 0.159 M = 34.43 (f); 33.88 (m)	W = 196 p = 0.249 M = 34.30 (y); 33.88 (e)	W = 373 **p < 0.01**** M = 34.38 (n); 33.57 (o)	W = 284 p = 0.492 M = 33.96 (m); 34.35 (a)	W = 137 p = 0.198 M = 33.92 (1); 34.42 (2)
Heart rate	W = 278 p = 0.487 Mdn = 73.19 (f); 75.11 (m)	W = 157 **p = 0.039*** Mdn = 77.78 (y); 72.79 (e)	W = 227 p = 0.581 Mdn = 72.97 (n); 75.59 (o)	W = 215 p = 0.398 Mdn = 77.00 (m); 73.82 (a)	W = 168 p = 0.861 Mdn = 73.86 (1); 74.46 (2)

Note: The following abbreviations correspond for each group: Sex = f: female, m: male; Age = y: young, e = elderly; BMI = n: normal, o: overweight; Time of day = m: morning, a: afternoon; Temperature = 1: 28°C; 2: 31°C.

Results showed that heart rate values were significantly higher for younger participants than for the elderly group, with a medium effect size (d = -.31). At the same time, no differences were found in the skin temperature between groups. Reported psychological responses of the participants were previously analysed (Rissetto et al., 2021), and results showed that younger participants evaluated the temperature as significantly less comfortable, expressed a preference for a cooler temperature and found the temperature less acceptable than older participants. Besides, participants with normal weight showed higher proximal skin temperature than participants with overweight during the session, with a large effect size (d = -.42). However, there were no differences between heart rate scores and comfort votes between BMI groups.

Although Rissetto et al. (2021) showed that female participants perceived the temperature as significantly hotter and less comfortable, we found no statistically significant differences in skin temperature or heart rate values between female and male participants.

Differences in skin temperature between women and men have been previously assessed, as in Wu et al. (2017), who found no statistically significant difference between groups in the hand skin temperature for warm thermal sensation votes at an average air velocity of 0,2 m/s and 26°C indoor temperature. We analysed differences in the average air speed between sex groups, and no significant difference was observed (t (40.71) = -0.84, p = 0.408).

We found statistically significant differences in distal skin temperature between the temperature sessions (d = .79), showing higher levels of distal skin temperature when participants experienced the warmer temperature condition (31°C). At 31°C, participants reported the temperature conditions as significantly warmer and less comfortable. Even though studies showed that temperature changes could induce changes in the heart rate (Lan et al., 2011), we found no differences between thermal conditions. Differences in results could be explained as the mentioned study compared neutral to warm changes, while participants experienced only warm indoor conditions in our study. Besides, Rissetto et al. (2021) showed that afternoon participants perceived the temperature as higher, evaluated the temperature and air velocity as less comfortable and chose a higher selected level of fan speed; in the present study, physiological responses did not significantly differ between daytime sessions.

4.2. Effect of airspeed levels for different thermal sensation votes and temperature settings

Table 3 summarised the differences in physiological responses between air speed levels. RQ2 needs to be rejected in this analysis. In this first analysis, the level of airspeed seemed not to influence physiological adaptations, as no significant differences were found for skin temperature, neither proximal nor distal, and heart rate between the different levels of airspeed.

Table 3. Central tendency comparison for skin temperature (distal and proximal) and heart rate between air speed groups.

	Normality	Central tendency	Test	p-value	Effect size
Skin t° distal	W = 0.988, p = 0.303	M = 33.3 (l), 33.3 (m), 33.2 (h)	F (2, 203) = 0.178	0.774	0.18
Skin t° proximal	W = 0.982, p = 0.303	M = 34.1 (l), 34.1 (m), 34.0 (h)	F (2, 124) = 0.147	0.048	0.05
Heart rate	W = 0.969, p = 0.303	Mdn = 73.8 (l), 75.8 (m), 74.6 (h)	H (2) = 0.570	0.752	-0.03

Note: The following abbreviations correspond for air speed groups = l: low, m: medium, h: high.

Results of a correlation showed that the expressed sensation votes during the session were significantly related to the distal skin temperature (τ = 0.16, p < .01) and the proximal skin temperature (τ = 0.22, p < .001). These results align with previous studies that found a linear relationship between overall thermal sensation and upper extremity skin temperature (Wu et al., 2017). Assuming a relationship between thermal sensation and skin temperature, we analysed the effect of different levels of airspeed on skin temperature for different thermal sensation groups and temperature configurations. **Error! Reference source not found.** shows the results of the performed t-test.

Table 4. Central tendency comparison for skin temperature (distal and proximal) measurements between thermal sensation groups and thermal conditions for different air speed levels.

	Level	Airspeed and sensation	Airspeed and temperature
Skin t° distal	Low	t (25.3) = -2.29, **p = 0.030***, d = .41 C = 61 (n), 19 (nn); M = 33.2 (n), 33.7 (nn)	t (15.6) = -4.65, **p = 0.000***, d = .762 C = 35 (1), 10 (2); M = 33.1 (1), 34.0 (2)
	Med	t (8.22) = -1.46, p = 0.181, d = .454 C = 29 (n), 8 (nn); M = 33.2 (n), 33.7 (nn)	t (12.4) = -4.63, **p = 0.000***, d = .796 C = 28 (1), 9 (2); M = 33.1 (1), 34.1 (2)
	High	t (5.44) = -1.96, p = 0.103, d = .643 C = 52 (n), 6 (nn); M = 33.1 (n), 34.0 (nn)	t (16.2) = -5.12, **p = 0.000***, d = .787 C = 35 (1), 10 (2); M = 33.0 (1), 34.0 (2)
Skin t° proximal	Low	t (31.7) = -2.29, **p = 0.029***, d = 0.376 C = 61 (n), 19 (nn); M = 34.0 (n), 34.5 (nn)	t (19.1) = -1.35, p = 0.193, d = .295 C = 35 (1), 10 (2); M = 34.0 (1), 34.4 (2)
	Med	t (9.60) = 0.103, p = 0.920, d = .033 C = 29 (n), 8 (nn); M = 34.1 (n), 34.1 (nn)	t (18.4) = -1.75, p = 0.096, d = .379 C = 28 (1), 9 (2); M = 33.9 (1), 34.5 (2)
	High	t (7.21) = 3.160, **p = 0.015*,** d = .762 C = 52 (n), 6 (nn); M 34.0 (n), 34.9 (nn)	t (18.9) = -1.06, p = 0.301, d = .237 C = 35 (1), 10 (2); M = 34.1 (1), 34.3 (2)

Note: The following abbreviations correspond for each group: Thermal sensation = nn: non-neutral, n: neutral; Temperature = 1: 28°C, 2: 31°C.

RQ3 is partially supported. Regarding thermal sensation votes, participants who voted neutral thermal conditions showed statistically significant lower distal and proximal skin temperature (0.5°C difference), when the air speed was below 0.4m/s, compared to participants voting feeling warmer (non-neutral). On the other hand, a 0.9°C difference between participants voting neutral and non-neutral is not significantly different when the airspeed is above 0.8m/s for distal skin temperature. This could be interpreted as at low fan speed values, the cooling effect of the airflow was not sufficient to restore comfort, slightly increasing participants' skin temperature, consequently reporting warmer thermal conditions. Although thermal conditions were perceived differently at elevated fan speeds (medium and high), it seems that participants did not require to thermoregulate their bodies, as the cooling effect provided by the fan airflow was higher. However, at airspeeds higher than 0.8 m/s, participants who voted neutral showed lower proximal skin temperature than participants who voted non-neutral thermal conditions. A possible explanation could be the direct cooling effect of the airspeed on the skin temperature in the upper body parts (shoulder and neck), which allowed a higher reduction of the skin temperature in some participants (neutral group), consequently leading them to perceive the indoor conditions as neutral. Although the effect sizes for the different tests are either medium or large, the sample size of the non-neutral group is relatively small, which could lead to different results.

In terms of thermal conditions, participants showed significantly higher values of distal skin temperature when the indoor temperature was 31°C, regardless of the airspeed level. Contrarily no significant difference in proximal skin temperature values was found between thermal conditions. This could be interpreted as a reduction of the skin temperature at warmer thermal conditions was achieved by the cooling effect of the air movement in the proximity of the participant's body, generating no difference in skin temperature between the two temperature conditions. In the case of the distal body parts, an increase in temperature resulted in an increase in skin temperature, in which no skin temperature reduction was possible as no direct airflow was directed to those body parts.

5. Conclusions

This study aims to understand the relationships between human physiology and perceptions of the indoor environment quality when using a personal ceiling fan. The effects of airspeed from and personal control over the fan and personal and contextual characteristics of participants were investigated. The main conclusions are as follows:

- Overweight participants showed a significantly lower proximal skin temperature than participants with average weight, while a higher mean heart value was measured for young participants, showing that body composition and ageing can affect physiological responses under the same indoor environmental conditions.
- Skin temperature corresponds to changes in indoor temperatures. At increasing moderately warm indoor temperatures, participants had a significantly higher distal skin temperature and rated the thermal condition significantly warmer and less comfortable.
- Participants selected a significantly higher air velocity for the warmer condition to restore thermal comfort. When the airspeed was insufficient to achieve thermal neutrality, a thermoregulation process took place in body extremities, increasing the distal skin temperature.
- The effect of the air movement in the proximity of the human body affected the skin temperature of the participants and, consequently, their thermal perception of the environment.

Findings suggest that personal environmental control systems can improve thermal comfort by stimulating human thermoregulation processes targeting specific body parts. Moreover, these systems allow multiple configurations to target individuals' body composition to achieve individual comfort.

Abbreviations

r resolution

a accuracy

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Appendix

Table A 1. Count, mean and standard deviation (sd) for distal and proximal skin temperature and heart rate scores for each analysed group.

Group	Levels		Distal temp. (°C)		Proximal temp. (°C)		Heart rate (bpm)	
		Count	mean	sd	mean	sd	mean	sd
Age	Young	19	33.3	0.8	34.2	0.9	79.9	11.6
	Adult	26	33.2	0.6	33.9	0.9	72.8	8.2
BMI	Normal	24	33.5	0.8	34.5	0.8	75.9	13.1

	Overweight	21	33.1	0.5	33.6	0.8	75.8	6.5
Sex	Male	26	33.4	0.6	33.9	0.8	76.0	8.6
	Female	19	33.1	0.7	34.3	1.0	75.6	12.5
Temperature	28°C	35	33.1	0.6	34.0	1.0	75.7	11.3
	31°C	10	34.0	0.5	34.3	0.7	76.2	6.7
Time day	Morning	23	33.4	0.7	34.2	1.0	77.5	10.1
	Afternoon	22	33.2	0.7	33.9	0.8	74.3	10.5

Table A 2. Levene's test for equality of variance.

	Sex	**Age**	**BMI**	**Time of day**	**Control**	**Tempera-ture**
Skin t° distal	F = 0.01 p = 0.961	F = 2.78 p = 0.103	F = 3.93 p = 0.054	F = 0.02 p = 0.896	F = 0.11 p = 0.736	F = 0.03 p = 0.874
Skin t° proximal	F = 1.19 p = 0.282	F = 0.02 p = 0.894	F = 0.27 p = 0.607	F = 3.36 p = 0.078	F = 0.05 p = 0.820	F = 1.46 p = 0.233
Heart rate	F = 1.36 p = 0.249	F = 2.57 p = 0.116	F = 5.72 **p = 0.021***	F = 0.17 p = 0.685	F = 0.03 p = 0.867	F = 1.50 p = 0.228

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