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The effect of inhaled air temperature on thermal comfort, perceived air quality, acute health symptoms and physiological responses at two ambient temperatures

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Abstract

We explored the importance of inhaled air temperature on thermal comfort, perceived air quality, acute non-clinical health symptoms, and physiological responses. Sixteen subjects stayed in a stainless-steel chamber for 90 min. They experienced four conditions with two inhaled air temperatures of 22 and 30°C and two ambient temperatures of 22 and 30°C in a 2 × 2 design. They wore breathing masks covering their mouth and nose to control the inhaled air temperature; the air was provided from an adjacent twin stainless-steel chamber. The subjects evaluated thermal conditions and health symptoms on visual-analogue scales. Skin temperature and electrocardiography were recorded. Whole-body thermal sensation and skin temperature did not change when the temperature of inhaled air was changed. Perceived air quality was significantly improved when subjects sat in the chamber at 30°C and inhaled air with a temperature of 22°C; under these conditions lip and throat dryness were significantly reduced. The lower inhaled air temperature increased time-domain heart rate variability indicators and decreased heart rate and the LF/HF ratio, suggesting that the parasympathetic nervous system was activated and the sympathetic nervous system was suppressed.

KEYWORDS
inhaled air temperature, perceived air quality, physiological response, sick building syndrome, thermal sensation

1 | INTRODUCTION

ASHRAE Guideline 10–2011[1] states that acute non-clinical health symptoms, also called Sick Building Syndrome (SBS) symptoms, decrease and perceived air quality improves when the temperature and relative humidity of inhaled air decrease. This statement is based on the results of many studies, some of which are summarized below.

Most of the studies were conducted with a personalized ventilation (PV) system. Gwosdow et al.[2] investigated human physiological and subjective responses when the inhaled air was 27, 30, 33, and 36°C and relative humidity was 47% and 73% RH; the results indicated that perceived air quality decreased when the air temperature increased above 30°C. Fang et al.[3] exposed subjects to different combinations of temperature and humidity from 18 to 28°C and 30% to 70% RH; the perceived air quality decreased with increasing temperature and humidity of inhaled air, while the perceived odor intensity did not change; a linear relationship between perceived air quality and the enthalpy of air was found. Toftum et al.[4] showed that the inhaled air was rated as warmer, stuffier, and less acceptable with higher air temperature and humidity. They found that the acceptability of the air was linearly correlated with enthalpy, confirming the results of Fang et al.[3,5] The hypothesized underlying mechanism was that evaporative and convective cooling of the mucous membranes in the upper respiratory tract results in improved perception of air quality. Kaczmarczyk et al.[6] studied five different personalized ventilation devices delivering air at 20°C at two background temperature levels (23 and 26°C) and two background air quality levels (high and low). All personalized ventilation devices significantly improved perceived air quality. Kaczmarczyk et al.[7] in another study investigated the effect of air supplied at a temperature of 26°C to the breathing zone by a personalized ventilation system while the background temperature was 20°C. Thermal comfort was improved in this condition. Melikov et al.[8] investigated thermal comfort in warm and humid environments (26 and 28°C at 70% RH) with personalized ventilation (24°C at 40% RH) and a thermally comfortable environment (23°C and 40% RH) without personalized ventilation. Supplying air by personalized ventilation improved perceived air quality and thermal sensation and decreased the intensity of SBS symptoms compared to the condition without personalized ventilation. Maula et al.[9] measured fatigue, thermal comfort, and health symptoms in an environment at 29.5°C with and without a cooling jet. Thermal comfort was improved, and indoor air was perceived as fresher with the jet. Pallubinsky et al.[10] investigated the effect of face cooling (22.7°C) at an ambient temperature of 32.3°C. Face cooling improved thermal comfort. Zhang and Zhao[11] observed that thermal acceptability was improved more by face cooling than by chest or back cooling through a local cooling vent. They proposed that the upper boundary of the acceptable room temperature range could be shifted from 26 to 30.5°C with face cooling. Zhang[12] put participants in cool (20°C) and warm (30°C) environments and used a ventilation sleeve providing inhaled air at 36.5 and 37.5, and 23°C for 10 min. The subjects disliked warm inhaled air. When the inhaled air was warm, the subjects overall comfort decreased in a cool environment, while the cool inhaled air improved comfort in a warm environment.

A few studies of uniform thermal environments also explored the effect of inhaled air temperature on perceived air quality and thermal comfort. Berglund et al.[13] showed that the air was perceived as less stuffy and more acceptable when cool and dry. In a later experiment, Fang et al.[5] confirmed that perceived air quality improved and was assessed as less stuffy (more fresh) when the air temperature and humidity decreased; this effect prevailed for several hours.

In previous studies in the indoor environment research area, air with different thermal conditions was presented to subjects using different methods but never directly to the face through a mask.

Practical implications

The findings of this study confirm the importance of inhaled temperature for perceived air quality and health symptoms, providing independent confirmation of previously reported results. Information on the underlying physiological mechanism was obtained. The results indicate that inhaled air temperature does not affect overall thermal sensation. A high inhaled air temperature induces increased physiological stress, suggesting that the upper temperature limit should be lower than 30°C.

These studies used simple exposure conditions that influenced the breathing zone, the facial zone, or the rest of the body and had short exposure times. They mainly focused on human psychological responses and the underlying physiological mechanism was seldom investigated. No physiological responses were measured at different inhaled temperatures. The present study was carried out to fill this gap and provide supplementary evidence on the effects of inhaled temperature on perceived air quality and thermal responses together with information that could be used to determine the underlying mechanisms.

2 | METHODS

2.1 | Approach

The effect of inhaled air temperature on thermal comfort, perceived air quality, acute health symptoms and physiological responses was investigated. Sixteen healthy college students were recruited. Exposures lasted 90 min. Skin temperature and heart rate variability were continuously monitored.

2.2 | Experiment facilities

The experiment was conducted in twin stainless steel chambers[14] located at the Technical University of Denmark, Department of Civil Engineering (now Department of Environmental and Resource Engineering). To separate the inhaled air from the air in the chamber, subjects sat in one of the chambers (Chamber 1) and inhaled air from the other chamber (Chamber 2). They inhaled the air using masks covering their mouth and nose. Medical tubes made of vinyl with an outer diameter of 22 mm were used to deliver the air (Figure 1). The inhaled air was supplied with two pipelines (tubes) which were connected to the two sides of the mask. The exhaled air was exhausted through the hole in the lower part of the mask (Figure 1B). The air was delivered for breathing at a rate that was higher than the minute ventilation (breathing), which is >5–8 L/min during rest; this ensured that the subjects were only breathing the

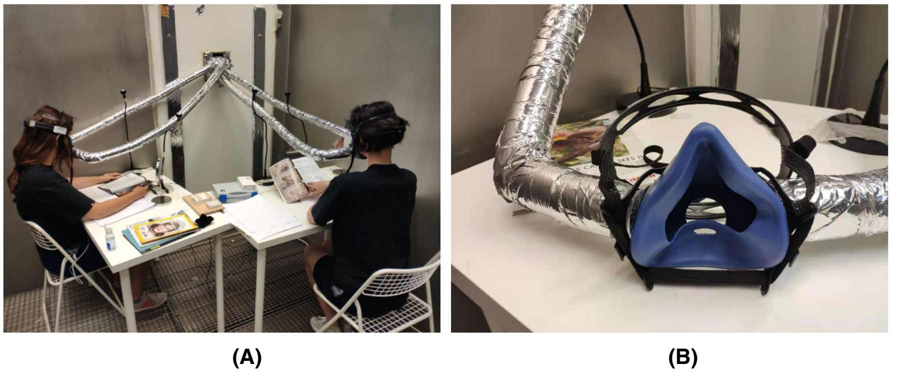

FIGURE 1 (A) Experiment setup and (B) mask structure.

TABLE 1 The information about subjects

Gender	Number	Age	Height (cm)	Weight (kg)	BMI (kg/m^2)	Body surface (m^2)
Male	8	25.0 ± 3.5	175.2 ± 6.1	70.8 ± 7.6	23.1 ± 1.8	1.94 ± 0.11
Female	8	24.7 ± 2.2	165.3 ± 6.7	54.7 ± 3.1	20.1 ± 1.7	1.69 ± 0.07
Total	16	24.8 ± 2.8	170.3 ± 8.0	62.8 ± 10.1	21.6 ± 2.3	1.82 ± 0.16

air delivered to the mask. The exhaled air and the surplus air were rejected through a hole in the bottom of the mask. Considering the flowrate and the diameter of tubes, the speed of the air delivered to the mask was calculated to be about 0.2–0.4 m/s. The tubes were connected to a polyurethane plate tightly mounted on the door passage connecting the two chambers using wooden boards wrapped in aluminium tape.[15] The tubes were well insulated, and the masks were tightly attached to the face of each subject, which ensured that the air that was inhaled maintained the intended conditions. To ensure that the air in the chamber was not contaminated by the air outside the chambers, the chambers were kept at a higher pressure controlled by a pressure controller for each of the two chambers. By changing their set-points, it was possible to control the flow between the chambers. This was confirmed by measurements performed prior to experiments. A pressure difference (5–10 Pa) between the two chambers ensured that all the air inhaled was from the adjacent chamber. During exposure, the subjects were instructed to breathe normally through the masks. Subjects exhaled to the chamber in which they were sitting.

2.3 | Subjects

Sixteen subjects (eight male and eight female) were recruited (Table 1). They were randomly assigned to eight groups of two. They all had been living in Denmark for at least one year before the study. All were non-smokers and healthy as indicated in the survey presented to them upon recruitment. All subjects provided written consent.

The subjects were asked to wear the same clothing during all four exposures, including short pants, short-sleeve shirts, socks, and shoes. The clothing insulation was estimated to be 0.5 clo (ASHRAE 55).[16]

2.4 | Measurements

Air temperature, relative humidity, and CO_2 concentration were monitored during each exposure. The air velocity was maintained at less than 0.05 m/s.

Physiological measurements of skin temperature and heart rate variability were obtained continuously. Skin temperature was recorded every 10 s with iButton sensors (DS1922L-F5#, Maxim Integrated, accuracy: ±0.5°C). They were used to measure skin temperature at each of eight locations: forehead, right upper arm, left forearm, left hand, left chest, right back, right thigh, and left calf. According to ISO 9886,[17] mean skin temperature (T_{mst}) should be calculated as the weighted average of those temperatures as follows:

$$T_{mst} = 0.07T_{forehead} + 0.175T_{right\_scapula} + 0.175T_{left\_upper\_chest} + 0.07T_{right\_upper\_arm} + 0.07T_{left\_lower\_arm} + 0.05T_{left\_hand} + 0.19T_{right\_thigh} + 0.2T_{left\_calf} \quad (1)$$

Heart rate variability (HRV)[18] reflects the time variation between two successive heartbeats. As a marker of autonomic nervous system (ANS) activity, HRV represents human homeostasis.[19] It usually consists of time-domain indices and frequency-domain indices that can be analyzed through heuristically selected statistical and spectral analysis methods. Time-domain HRV indices include Average_RR, SDRR, RMSSD, and pRR_{50} (Table 2). Frequency-domain HRV indices include HF_{norm}, LF_{norm}, and LF/HF (Table 2) where LF_{norm} is

TABLE 2 Description of the parameters describing heart rate variability (HRV)

HRV indices	Description
Time-domain HRV	
Average_RR	Average value of the entire RR intervals
RMSSD	Root mean square of successive RR interval differences
SDRR	Standard deviation of RR intervals
pRR_{50}	Percentage of RR pairs that differ by 50 ms
Frequency domain HRV	
HF_{norm}	Relative power of the high-frequency band (0.15–0.4 Hz) in normal units
LF_{norm}	Relative power of the low-frequency band (0.04–0.15 Hz) in normal units
LF/HF	Ratio of LF-to-HF power

related to the sympathetic nervous system (SNS)[20] while HF is a marker of the parasympathetic nervous system (PNS).[21] LF/HF is the ratio of LF_{norm} to HF_{norm} and indicates the interaction between LF and HF. A portable electrocardiogram (ECG) instrument (CCS-103, Careshine Electronic) monitored heart rate variability (HRV). The electrocardiogram was sampled with a frequency of 500 Hz. The R-R interval values were extracted from the original ECG data. The HRV indicators were calculated for every five-minute period.

Subjects used paper questionnaires to provide responses describing the thermal environment, air quality, and acute non-clinical health symptoms. The responses describing the thermal environment included overall thermal sensation (using the ASHRAE seven-point scale),[22] the acceptability of the thermal environment, thermal comfort, and temperature preference. The intensity of health symptoms was indicated on continuous linear visual-analogue scales (VAS)[23] with the following endpoints: running—dry nose, shortness—easiness of breath, chest tightness—no tightness, throat dry—not dry, mouth dry—not dry, lips dry—not dry, skin dry—not dry, eyes dry—not dry, eyes aching—not aching, headache—no headache, difficult to think clearly—easy to think clearly, dizzy—not dizzy, feeling well—bad, tired—not tired, difficult—easy to concentrate, depressed—not depressed, and alert—sleepy. All of these scales are reproduced in the SI (Figure S1).

2.5 | Experimental conditions and procedure

Each subject was exposed to four conditions: two ambient temperatures (22 and 30°C) and two inhaled air temperatures (22 and 30°C). A 2 ×2 design was used (Table 3). The temperature of 22°C was selected because it is in the middle of the temperature range recommended by EN16798-1 (2020).[24] At this temperature, it was expected that subjects would feel comfortable and slightly cool (PMV = −1.2). The temperature of 30°C was selected to create a significant contrast and a sensation of warmth (PMV = 1.6).

The experiment was conducted on weekdays in four successive weeks in September 2019. Each group participated in the experiments from Monday to Friday. Two groups were exposed each day, one from 13:00 to 15:00 and another from 16:00 to 18:00. The practice session was conducted on Mondays to ensure that all subjects were familiar with the experimental protocols and procedures. The order of the exposures was balanced in a Latin-square design.

Each experimental session lasted 120 min, of which 90 min was the exposure in the chamber wearing a mask (Figure 2). Before the exposure, the subjects sat for 15 min in an antechamber for acclimatization. They then entered the chamber and sat there without a mask for 30 min to ensure acclimatization. Sensors for the physiological measurements were attached during this period. Towards the end of the 30 min period, the subject began to respond to questionnaires and the masks were put on. The experimental period began immediately afterwards. Skin temperature and heart rate variability were continuously monitored. Perceived air quality and subjective thermal perception were collected at intervals of 5, 10, and 15 min, respectively, during Phases I, II, and III. The intensity of symptoms was rated at the 0th, 25th, 50th, 75th, and 90th minute of each experimental period. The difference in sampling time between phases was to ensure that we could better monitor potential changes in responses at the outset of each experimental session; it was expected that these changes would disappear over the course of each exposure. The study protocols followed the guidelines of the Declaration of Helsinki.

2.6 | Statistical analysis

The R programming (Rstudio) and SPSS software (IBM SPSS Statistics 22; IBM Corporation, Armonk, NY, USA) were used to perform a statistical analysis. The Shapiro-Wilks test was used to examine the normality assumption. A repeated-measures ANOVA or paired-sample *t*-test was made if the data were normally distributed. Otherwise, a nonparametric test—Wilcoxon's test or the Friedman test as appropriate—was used. The significance level was set to $p = 0.05$ (2-tail). Effect size (ES) was also calculated. For ANOVA, the ES values (η^2) of 0.01, 0.06, and 0.14 indicate, respectively, small, moderate, and large effects while for the *t*-test, the corresponding ES values (Cohen's *d*) are 0.2, 0.5, and 0.8.

TABLE 3 The conditions during experiments, planned (first column) and measured (all remaining columns); means + standard deviations are presented

Planned temperatures (inhaled-ambient)	$T_{22\text{-}22}$		$T_{30\text{-}22}$		$T_{22\text{-}30}$		$T_{30\text{-}30}$	
	Inhaled	Ambient	Inhaled	Ambient	Inhaled	Ambient	Inhaled	Ambient
T (°C)	22.0 ±0.0	22.0 ±0.3	30.0 ±0.0	22.0 ±0.7	22.0 ±0.1	30.2 ±0.2	30.0 ±0.0	30.4 ±0.6
RH (%)	48 ±5	42 ±2	21 ±2	43 ±3	54 ±4	30 ±3	29 ±3	31 ±5
Enthalpy (kJ/kg)	42.5 ±1.9	40.3 ±0.5	52.2 ±2.9	40.4 ±0.5	40.9 ±1.3	50.1 ±3.0	51.2 ±2.3	50.8 ±4.3
CO_2 (ppm)	407 ±6	424 ±19	413 ±6	427 ±33	411 ±6	487 ±71	412 ±7	502 ±38
AH (kg/m^3)	0.127 ±0.011	0.113 ±0.003	0.085 ±0.010	0.113 ±0.004	0.136 ±0.010	0.090 ±0.012	0.095 ±0.010	0.095 ±0.023

3 | RESULTS

3.1 | Thermal environment

The inhaled air was judged as slightly warm (1.0±0.8) when the inhaled and ambient temperatures were 30°C ($T_{30\text{-}30}$) while it was evaluated as slightly below neutral (−0.4±1.0) when the inhaled and ambient temperatures were 22°C ($T_{22\text{-}22}$) (Figure 3). The thermal sensation of inhaled air was significantly affected by the inhaled air temperature ($p<0.001$, $\eta^2 = 0.69$). When the ambient temperature was 30°C, the thermal sensation of inhaled air decreased significantly when the inhaled air temperature fell from 30°C ($T_{30\text{-}30}$) to 22°C ($T_{22\text{-}30}$) ($p<0.01$, $d = 1.05$). When the ambient temperature was 22°C, the thermal sensation of inhaled air increased significantly when the inhaled air temperature increased from 22°C ($T_{22\text{-}22}$) to 30°C ($T_{30\text{-}22}$) ($p<0.05$, $d = 0.59$).

The overall thermal sensation of subjects was "slightly cool" when the ambient temperature was 22°C and it did not change significantly when the inhaled air temperature increased from 22 to 30°C (Figure 4). When the ambient temperature was 30°C, the subjects felt slightly warm and this sensation did not change significantly when the temperature of inhaled air changed from 22 to 30°C.No statistically significant differences were observed when the inhaled air temperature was changed between 22 and 30°C at an ambient temperature of 22 or 30°C (Figure S2 in the SI).

3.2 | Perceived air quality

Air quality was rated as acceptable in all conditions (Figure 5). However, the acceptability of the air quality when both inhaled and ambient temperatures were 22°C ($T_{22\text{-}22}$) was significantly higher than when both inhaled and ambient temperatures were 30°C ($T_{30\text{-}30}$) ($p<0.05$, $d = 0.77$). The acceptability of the air quality decreased significantly with the inhaled air temperature increased, independently of the ambient temperature ($p<0.01$, $\eta^2 = 0.45$). When the ambient temperature was 30°C ($T_{30\text{-}30}$ and $T_{22\text{-}30}$), the acceptability of the air quality increased significantly when the inhaled air temperature changed from 30°C ($T_{30\text{-}30}$) to 22°C ($T_{22\text{-}30}$) ($p<0.001$, $d = 1.15$). When the ambient temperature was 22°C, the acceptability of the air quality decreased when the inhaled air temperature increased from 22°C ($T_{22\text{-}22}$) to 30°C ($T_{30\text{-}22}$); the effect was borderline significant ($p = 0.06$, $d = 0.56$).

3.3 | Non-clinical acute health symptoms

The intensity of health symptoms indicated by the subjects in all conditions for which significant differences were observed is shown in (Figure 6). The intensity of lip dryness ($p = 0.06$, $d = 0.54$), shortness of breath ($p<0.05$, $d = 0.71$), and difficulty concentrating ($p<0.05$, $d = 0.65$) were lower when both inhaled and ambient temperatures were 22°C ($T_{22\text{-}22}$) compared with when both inhaled and ambient temperatures were 30°C ($T_{30\text{-}30}$). When the ambient

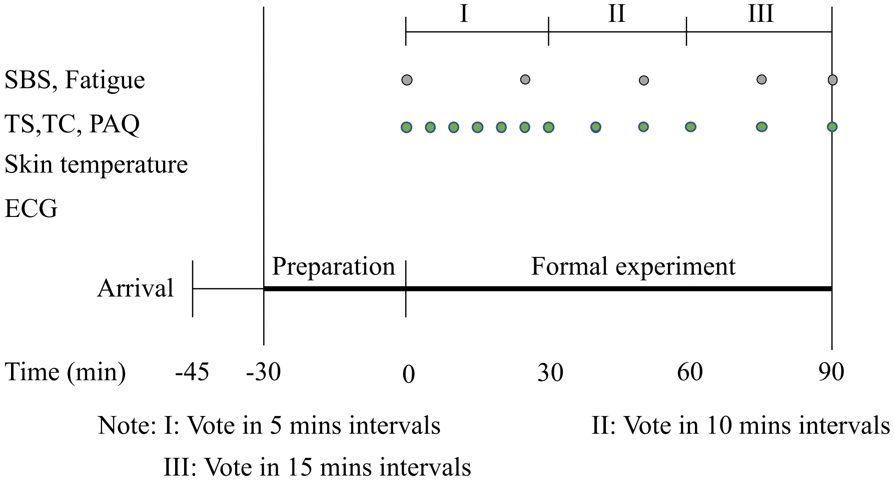

FIGURE 2 Experimental procedure.

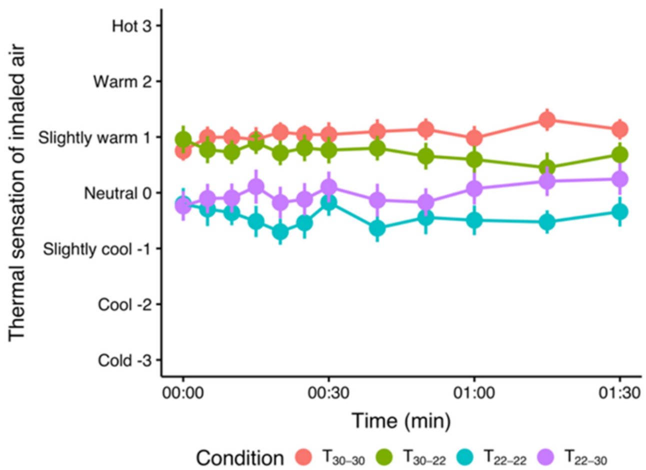

FIGURE 3 The thermal sensation of inhaled air as a function of exposure time and conditions.

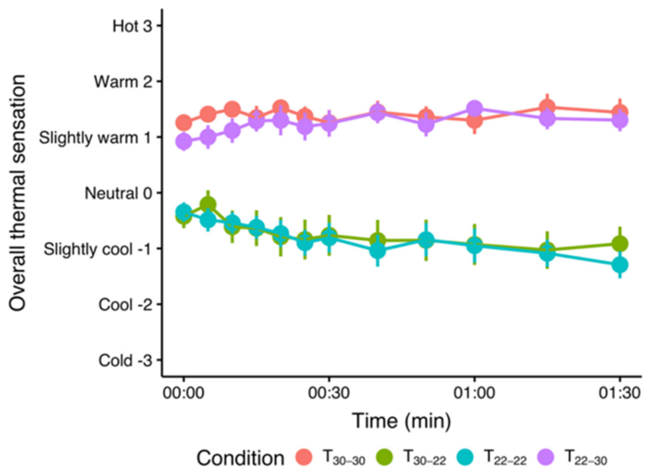

FIGURE 4 The overall thermal sensation as a function of the exposure time and condition.

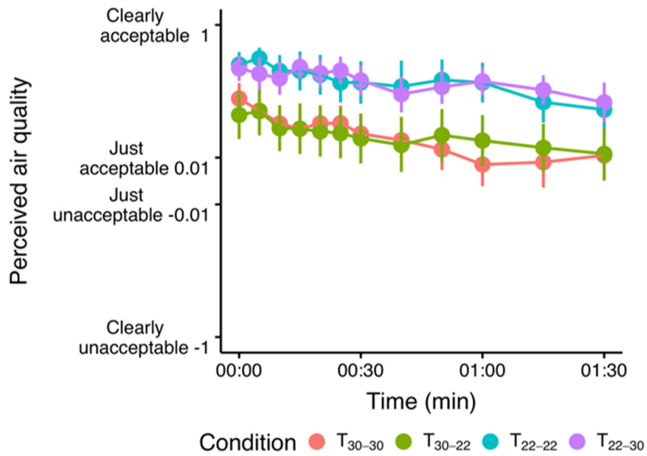

FIGURE 5 Acceptability of air quality as a function of exposure time and condition.

temperature was 30°C, the intensity of throat dryness decreased significantly when the inhaled air temperature changed from 30°C ($T_{30\text{-}30}$) to 22°C ($T_{22\text{-}30}$) ($p < 0.05$, $d = 0.57$). When the ambient temperature was 22°C, the intensity of lip dryness decreased significantly when the inhaled air temperature changed from 30°C ($T_{30\text{-}22}$) to 22°C ($T_{22\text{-}22}$) ($p < 0.05$, $d = 0.71$).

3.4 | Physiological responses

The mean skin temperature was averaged for the last ten minutes of each exposure, by which time it had reached a stable condition (Figure 7). T_{mst} was significantly higher when the ambient temperature was 30°C independently of inhaled air temperature ($p < 0.001$, $\eta^2 = 0.94$). There were no significant differences in the skin temperature when the inhaled air temperature was changed at an ambient temperature of 22 or 30°C.Heart rate decreased during exposures, reaching a steady-state value after

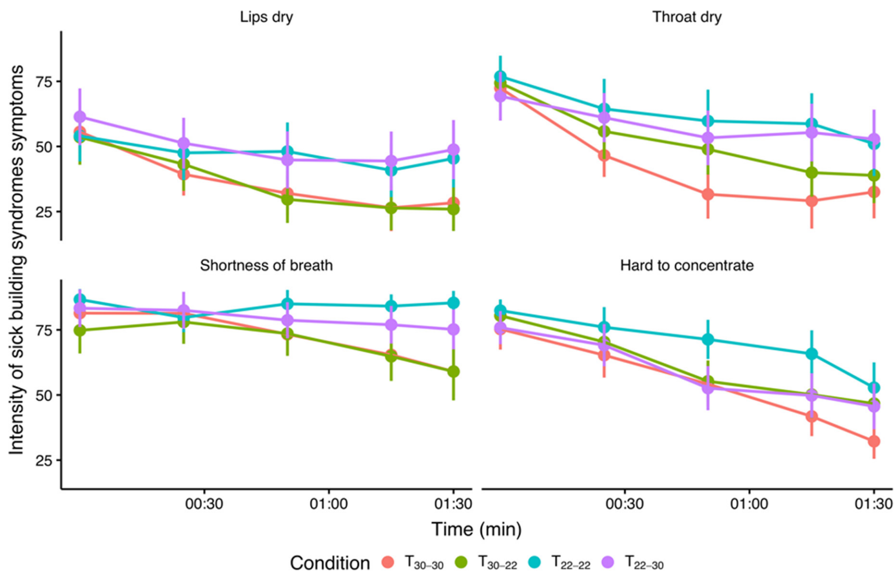

FIGURE 6 The intensity of health symptoms as a function of exposure time and condition.

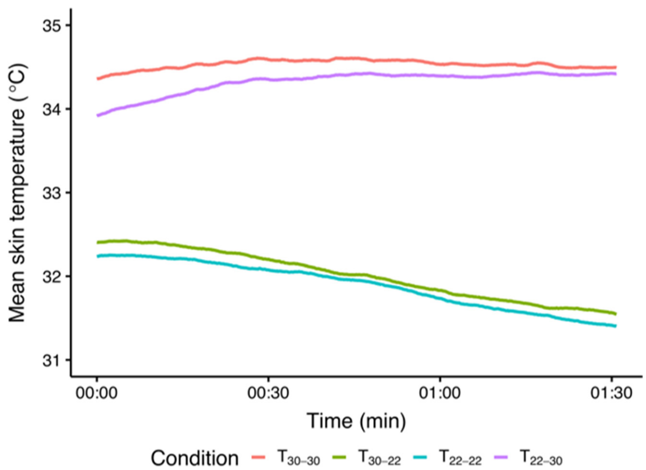

FIGURE 7 Skin temperature as a function of exposure time and condition.

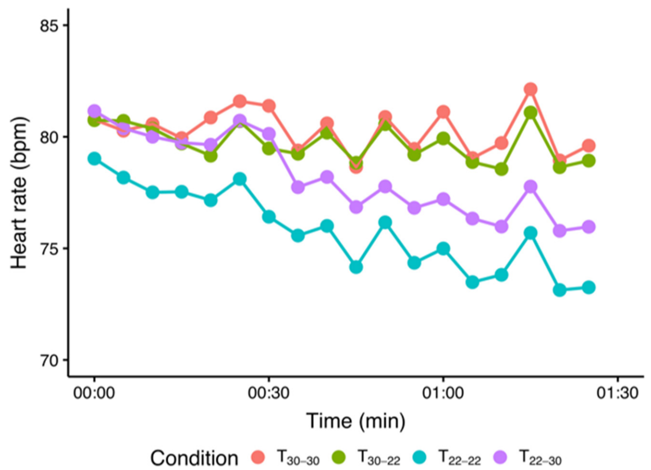

FIGURE 8 Heart rate as a function of the time of exposure and condition.

about 80 min (Figure 8). Heart rate when both inhaled and ambient temperatures were 22°C ($T_{22\text{-}22}$) was significantly lower than that when both inhaled and ambient temperatures were 30°C ($T_{30\text{-}30}$) ($p < 0.05$, $d = 0.78$). Heart rate was significantly lower with lower inhaled air temperature ($p < 0.05$, $\eta^2 = 0.31$). There were differences in the heart rate at an ambient temperature of 22°C—it was significantly lower when the inhaled air temperature was 22°C ($T_{22\text{-}22}$) than when it was 30°C ($T_{30\text{-}22}$) ($p < 0.05$, $d = 0.71$). When the ambient temperature was 30°C, heart rate decreased when the inhaled air temperature changed from 30°C ($T_{30\text{-}30}$) to 22°C ($T_{22\text{-}30}$), but this effect did not reach formal statistical significance ($p = 0.1$, $d = 0.46$). The fluctuations in heart rate could be caused by responding to questionnaires.

We show pRR50 and LF/HF here while all other HRV parameters are shown in the SI (Figure S3). pRR50 decreased significantly ($p < 0.05$, $\eta^2 = 0.34$) while LF/HF increased significantly ($p < 0.05$, $\eta^2 = 0.37$) as the inhaled air temperature increased, independently of the ambient temperature (Figure 9). When the ambient temperature was 30°C, LF/HF decreased significantly ($p < 0.05$, $d = 0.75$) and pRR50 increased non-significantly ($p = 0.2$, $d = 0.35$) when the inhaled air temperature changed from 30°C ($T_{30\text{-}30}$) to 22°C ($T_{22\text{-}30}$). When the ambient temperature was 22°C, LF/HF tended to increase ($p = 0.1$, $d = 0.47$) and pRR50 decreased significantly ($p < 0.05$, $d = 0.69$) when the inhaled air temperature increased from 22°C ($T_{22\text{-}22}$) to 30°C ($T_{30\text{-}22}$).

4 | DISCUSSION

The purpose of the present work was to examine the effects of inhaled temperature and relative humidity on physiological and psychological responses. We wanted to understand the consequences of a difference between inhaled and ambient air temperature and for this purpose we used the masks. Our purpose was not to examine the effect of mask wearing as this has been done in many other studies.[25,26]

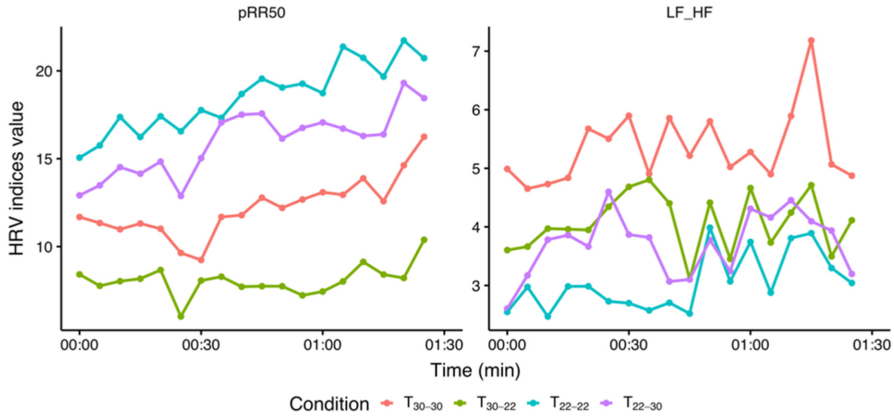

FIGURE 9 Heart rate variability as a function of exposure time and condition.

Previous studies[7,10,11] have shown that facial cooling or heating has a significant impact on overall thermal sensation and comfort. For example, Zhang and Zhao[11] found that the upper limit of acceptable room temperature can be shifted from 26 to 30.5°C by providing some cooling of the face. The present experiment indicates that changing the inhaled air temperature independently of the ambient temperature did not have a significant effect on overall thermal sensation, thermal comfort, thermal preference or thermal acceptability, although it did affect the thermal sensation of the inhaled air as would be expected. The reason for the discrepancy between the present and previous studies is probably that facial cooling directly affects several other local body parts e.g., face, head, and upper chest, while in the present study the air was delivered through a mask. It is logical that cooling both the breathing zone and nearby body regions will change the overall thermal sensation. However, Zhang[12] found that inhaling cool air decreased overall thermal sensation from warm to neutral, which was not found to be the case in the present experiment. The difference may be due to the shorter exposure (10–15 min) or the higher air velocities in the earlier experiment. This discrepancy should be further explored. Core temperature was not measured in the present experiment, as it was not expected to change much in the 90-min exposures. In longer exposures, inhaled air temperature might reasonably be expected to affect core temperature slightly in the same direction as its difference from the ambient temperature.

That changing the inhaled temperature had no effect on overall thermal sensation was further supported in the present study by the measured skin temperature (Figure 7), which did not change when the inhaled temperature was changed. A previous study[10] also found that local cooling in a warm environment did not change mean skin temperature.

As shown in previous studies,[1,27] reducing the temperature of inhaled air improved perceived air quality and the perception of air freshness both under isothermal conditions ($T_{22\text{-}22}$ vs. $T_{30\text{-}30}$) and when the inhaled air temperature was reduced at higher ambient temperatures ($T_{22\text{-}30}$). Improved perceived air quality at lower inhaled temperature has been assumed to be due to cooling of the mucous membranes in the upper respiratory tract[3–5]—inhaled air cools the mucosa when the inhaled air temperature is below mucosal temperature (30°C).[3,28,29] The temperature and water vapor pressure gradients between the respiratory tract surface and inhaled air both apply a cooling effect to the mucous membranes. Unlike the local heating and cooling of other local body parts,[30–33] reducing the inhaled air temperature significantly decreased the thermal sensation of the inhaled air independently of the ambient temperature (Figure 3).

The present study shows that exposure to higher ambient air temperature ($T_{30\text{-}30}$ vs. $T_{22\text{-}22}$) increases the intensity of acute health symptoms, as has been observed in many other studies.[8,27,34] Reducing the inhaled air temperature reduced the intensity of dryness symptoms, as shown in other studies,[4] but not the intensity of neurobehavioral symptoms (such as "difficult to concentrate").

It must be admitted that the sensation of dryness could be caused by many factors that include air humidity, temperature and perceived air stuffiness, and that humans do not have a dryness receptor.[35] Studies have generally shown that the "sensation of dryness" has little to do with physical air humidity.[36] Dryness of lips and mouth in the present study could thus be caused by a combined effect of low relative humidity and temperature, probably also caused by the perceived stuffiness. We cannot separate these effects from each other in the present work though we believe that they were all caused by changing the inhaled air temperature. For dryness, it is likely that delivering cool air to the breathing zone when ambient temperatures were high would alleviate the symptoms. But this was not the case for general symptoms such as "difficult to concentrate" as delivering cool air at 30°C did not alleviate these symptoms so it is likely that for these types of symptoms both the ambient air and inhaled air should be low. Previous studies seem to agree with this conclusion.[34,37]

High temperature has been shown previously to increase the arousal level.[35,36] Human thermoregulation is governed by the hypothalamus response, which controls various mechanisms to regulate energy consumption, to maintain the body core temperature.[38] Homeostasis is regulated by the autonomic nervous system consisting of the parasympathetic nervous system (PNS) and the sympathetic nervous system (SNS). The PNS and the SNS have competing effect on the heart rate:[39,40] the PNS branch usually handles inputs from internal organs and causes a decrease in the heart rate while the SNS branch reacts with responses to external stimuli like stress and exercise, and increases the heart rate. In this study, heart rate increased with the room air temperature in the isothermal environment, as shown earlier.[27,41–43] This study also supported a previous finding[44] that time-domain HRV indices also increase when the room air temperature is reduced in an isothermal environment.[43] pRR50 decreased significantly while heart rate and LF/HF increased significantly with increased inhaled air temperature, independently of the ambient temperature. The significant change of pRR50, heart rate, and the LF/HF ratio indicate higher physiological stress caused by the increase in inhaled air temperature, the effect being stronger than that caused by the ambient temperature. This suggests parasympathetic withdrawal due to the stress induced by the high inhaled air temperature. This may suggest that heating of internal body organs (respiratory tract and lung) result in increased SNS activity. Higher inhaled air temperature caused a more active SNS while the PNS becomes more active when subjects inhale air at a low temperature.[45–47] Some of these responses can be used in the future in a control loop to ensure that the environment provides the best conditions for the occupants.

In recent experiments, Lan et al.[27,48,49] inferred that both thermal discomfort and increased temperature induce physiological stress, which then results in reduced cognitive performance. A similar mechanism was proposed by Wargocki and Wyon[50] who additionally suggested that elevated temperatures would induce acute health symptoms. The present results provide support for these findings, especially by disconnecting thermal effects on the whole body from any thermal effects of the inhaled air. As a result, the trade-offs between energy-saving and work performance and overall well-being should be carefully considered when the Adaptive Thermal Comfort (ATC) model is used to justify allowing indoor temperature to drift according to outdoor temperature levels. It would be useful to determine the highest air temperature at which thermal acceptability can be achieved by adjusting clothing and air velocity without activating sufficient physiological stress to cause the negative effect on performance that was demonstrated by Lan et al.[43] to occur within that range.

The present results were obtained with young and healthy college students. We explored only two inhaled air temperatures and two ambient air temperature conditions, which spanned a narrow range that included the highest temperatures recommended in standards for thermal comfort.[16] The clothing insulation and metabolic rate were constant, and we did not explore their effect. We also did not consider the impact of inhaled air speed on the thermal sensation of inhaled air, perceived air quality, or thermal perception, as the air was always delivered at a very low flowrate. Extrapolation of the present results should take account of these limitations and the results require further validation, especially for extended exposures and more moderate temperatures. It would be useful to determine whether the effects observed exhibit linear or non-linear dependence.

5 | CONCLUSIONS

The present study explored the effects of inhaled air temperature on perceived air quality, the intensity of acute health symptoms, and thermal responses at two different ambient temperatures (22 and 30°C). The main findings are as follows:

1. Reducing the inhaled air temperature did not change the overall thermal sensation at either of the ambient temperatures.
2. Changing the inhaled air temperature did not change mean skin temperature.
3. Reducing the inhaled air temperature significantly improved perceived air quality at both ambient temperatures.
4. Reducing the inhaled air temperature significantly decreased lip dryness and throat dryness symptoms at an ambient temperature of 30°C. Difficulty in concentrating and shortness of breath were reduced when both ambient temperature and inhaled temperature were reduced.
5. Reducing the inhaled air temperature significantly increased time-domain heart rate variability indices and decreased heart rate and the LF/HF ratio at an ambient temperature of 30°C, indicating increased activity of the parasympathetic nervous system.

AUTHOR CONTRIBUTIONS

Zhibin Wu: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, review & editing. **Nianping Li**: Review & editing, Supervision, Resources. **Li Lan**: Writing – review & editing. **Pawel Wargocki**: Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

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CONFLICT OF INTEREST

The authors declare that they have no competing financial interests or personal relationships that might have influenced the work reported in this paper.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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REFERENCES

1. American Society of Heating R, Engineers A-C. *ASHRAE Guideline 10-2011, Interactions Affecting the Achievement of Acceptable Indoor Environments*. ASHRAE; 2011.
2. Gwosdow A, Nielsen R, Berglund L, DuBois A, Tremml P. Effect of thermal conditions on the acceptability of respiratory protective devices on humans at rest. *Am Ind Hyg Assoc J*. 1989;50(4):188-195.
3. Fang L, Clausen G, Fanger PO. Impact of temperature and humidity on the perception of indoor air quality. *Indoor Air*. 1998;8(2):80-90.
4. Toftum J, Jørgensen AS, Fanger PO. Upper limits of air humidity for preventing warm respiratory discomfort. *Energ Buildings*. 1998;28(1):15-23.
5. Fang L, Wyon DP, Clausen G, Fanger PO. Impact of indoor air temperature and humidity in an office on perceived air quality, SBS symptoms and performance. *Indoor Air*. 2004;14:74-81.
6. Kaczmarczyk J, Melikov A, Bolashikov Z, Nikolaev L, Fanger PO. Human response to five designs of personalized ventilation. *Hvac&R Res*. 2006;12(2):367-384.
7. Kaczmarczyk J, Melikov A, Sliva D. Effect of warm air supplied facially on occupants' comfort. *Build Environ*. 2010;45(4):848-855.
8. Melikov AK, Skwarczynski M, Kaczmarczyk J, Zabecky J. Use of personalized ventilation for improving health, comfort, and performance at high room temperature and humidity. *Indoor Air*. 2013;23(3):250-263.
9. Maula H, Hongisto V, Koskela H, Haapakangas A. The effect of cooling jet on work performance and comfort in warm office environment. *Build Environ*. 2016;104:13-20.
10. Pallubinsky H, Schellen L, Rieswijk T, Breukel C, Kingma B, van Marken Lichtenbelt W. Local cooling in a warm environment. *Energ Buildings*. 2016;113:15-22.
11. Zhang Y, Zhao R. Effect of local exposure on human responses. *Build Environ*. 2007;42(7):2737-2745.
12. Zhang H. *Human Thermal Sensation and Comfort in Transient and Non-Uniform Thermal Environments*. University of California, Berkeley; 2003.
13. Berglund L, Cain W. Perceived air quality and the thermal environment. Paper presented at: Proceedings of IAQ 1989.
14. Albrechtsen O. Twin climatic chambers to study sick and healthy buildings. Paper presented at: Proceedings of Healthy Buildings 1988.
15. Bekö G, Wargocki P, Wang N, et al. The indoor chemical human emissions and reactivity (ICHEAR) project: overview of experimental methodology and preliminary results. *Indoor Air*. 2020;30:1213-1228.
16. ASHRAE. ASHRAE Standard 55. *Thermal Environmental Conditions for Human Occupancy*. ASHRAE; 2013.
17. ISO 9886. *Evaluation of thermal strain by physiological measurements (2nd ed.)*. International Standards Organisation (ISO); 2004.
18. Shaffer F, Ginsberg JP. An overview of heart rate variability metrics and norms. *Front Public Health*. 2017;5.
19. Riganello F, Garbarino S, Sannita WG. Heart rate variability, homeostasis, and brain function. *J Psychophysiol*. 2012;26:178-203.
20. Malliani A, Pagani M, Lombardi F, Cerutti S. Cardiovascular neural regulation explored in the frequency domain. *Circulation*. 1991;84(2):482-492.
21. Electrophysiology TFotESoCtNASoP. Heart rate variability: standards of measurement, physiological interpretation, and clinical use. *Circulation*. 1996;93(5):1043-1065.
22. Wu Z, Li N, Wargocki P, Peng J, Li J, Cui H. Adaptive thermal comfort in naturally ventilated dormitory buildings in Changsha, China. *Energy Build*. 2019;186:56-70.
23. Wu Z, Li N, Wargocki P, Peng J, Li J, Cui H. Field study on thermal comfort and energy saving potential in 11 split air-conditioned office buildings in Changsha, China. *Energy*. 2019;182:471-482.
24. Standardization ECf. *EN 16798-1—Energy Performance of Buildings—Ventilation for Buildings—Part 1: Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics—Module M1-6*. European Committee for Standardization Brussels; 2019.
25. West JB. A strategy for in-flight measurements of physiology of pilots of high-performance fighter aircraft. *J Appl Physiol*. 2013;115(1):145-149.
26. Lee W, Jung D, Park S, Kim H, You H. Development of a virtual fit analysis method for an ergonomic Design of Pilot Oxygen Mask. *Appl Sci*. 2021;11(12):5332.
27. Lan L, Wargocki P, Wyon DP, Lian Z. Effects of thermal discomfort in an office on perceived air quality, SBS symptoms, physiological responses, and human performance. *Indoor Air*. 2011;21(5):376-390.
28. Proctor DF, Andersen IHP. *The Nose, Upper Airway Physiology and the Atmospheric Environment*. Elsevier Biomedical Press; 1982.
29. McFadden E Jr. Respiratory heat and water exchange: physiological and clinical implications. *J Appl Physiol*. 1983;54(2):331-336.
30. Zhang Y, Zhao R. Physiological and psychological model of local thermal sensation under local cooling. *Measurements*. 2007;28(32):35.
31. Zhang YF, Wyon DP, Fang L, Melikov AK. The influence of heated or cooled seats on the acceptable ambient temperature range. *Ergonomics*. 2007;50(4):586-600.
32. Zhang H, Arens E, Huizenga C, Han T. Thermal sensation and comfort models for non-uniform and transient environments: part I: local sensation of individual body parts. *Build Environ*. 2010;45(2):380-388.
33. Zhang H, Arens E, Huizenga C, Han T. Thermal sensation and comfort models for non-uniform and transient environments, part III: whole-body sensation and comfort. *Build Environ*. 2010;45(2):399-410.
34. Krogstad A, Swanbeck G, Barregård L, et al. *A Prospective Study of Indoor Climate Problems at Different Temperatures in Offices*. Volvo Truck Corporation; 1991.
35. Wolkoff P. The mystery of dry indoor air–an overview. *Environ Int*. 2018;121:1058-1065.
36. Sundell J, Lindvall T. Indoor air humidity and sensation of dryness as risk indicators of SBS. *Indoor Air*. 1993;3(4):382-390.
37. Mendell MJ, Cozen M, Lei-Gomez Q, et al. Indicators of moisture and ventilation system contamination in US office buildings as risk factors for respiratory and mucous membrane symptoms: analyses of the EPA BASE data. *J Occup Environ Hyg*. 2006;3(5):225-233.
38. Hammel HT, Pierce J. Regulation of internal body temperature. *Annu Rev Physiol*. 1968;30(1):641-710.
39. Robinson BF, Epstein SE, Beiser GD, Braunwald E. Control of heart rate by the autonomic nervous system: studies in man on the interrelation between baroreceptor mechanisms and exercise. *Circ Res*. 1966;19(2):400-411.
40. Glick G, Braunwald E, Lewis RM. Relative roles of the sympathetic and parasympathetic nervous systems in the reflex control of heart rate. *Circ Res*. 1965;16(4):363-375.
41. Choi J-H, Loftness V, Lee D-W. Investigation of the possibility of the use of heart rate as a human factor for thermal sensation models. *Build Environ*. 2012;50:165-175.
42. Liu W, Lian Z, Liu Y. Heart rate variability at different thermal comfort levels. *Eur J Appl Physiol*. 2008;103(3):361-366.
43. LeBlanc J, Blais B, Barabe B, Cote J. Effects of temperature and wind on facial temperature, heart rate, and sensation. *J Appl Physiol*. 1976;40(2):127-131.
44. Xiong J, Lian Z, Zhou X, You J, Lin Y. Potential indicators for the effect of temperature steps on human health and thermal comfort. *Energ Buildings*. 2016;113:87-98.
45. Kishino T, Matsuda M. Effects of short time water immersion at the Tempeature of 27. DEG. C., 34. DEG. C., and 38. DEG. C. on cardiac autonomic nerve activity. A study considering the effect of respiration. *J Jpn Soc Balneology, Climatology Phys Med*. 1998;61(3):148-156.

46. Edelhäuser F, Goebel S, Scheffer C, Cysarz D. P02. 181. Heart rate variability and peripheral temperature during whole body immersion at different water temperatures. *BMC Complement Altern Med*. 2012;12(1):1.
47. Xiong J, Lian Z, Zhang H. Physiological response to typical temperature step-changes in winter of China. *Energ Buildings*. 2017;138:687-694.
48. Lan L, Tang J, Wargocki P, Wyon DP, Lian Z. Cognitive performance was reduced by higher air temperature even when thermal comfort was maintained over the 24–28°C range. *Indoor Air*. 2022;32(1):e12916.
49. Lan L, Xia L, Hejjo R, Wyon DP, Wargocki P. Perceived air quality and cognitive performance decrease at moderately raised indoor temperatures even when clothed for comfort. *Indoor Air*. 2020;30(5):841-859.
50. Wargocki P, Wyon DP. Ten questions concerning thermal and indoor air quality effects on the performance of office work and schoolwork. *Build Environ*. 2017;112:359-366.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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