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Experimental evaluation of the effect of body mass on thermal comfort perception

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Abstract: Globally 39% of adults are overweight, 13% are obese, and 9% are underweight. Current thermal comfort standards, catering to the normal weight occupant, may hence be ignoring nearly 60% of the population. This could have significant comfort, productivity and energy implications. We performed a climate chamber study of the thermal response of 76 subjects in all the body mass index (BMI) categories, from 17 and 37 kg/m^2. Every participant underwent the same four sessions at average operative temperatures of 19.9, 22.4, 25.3, and 28.2 °C. We obtained subjective feedback from participants on their thermal sensation and preference, humidity sensation and preference, thermal comfort rating, and air quality perception. We also measured skin temperature, blood pressure, pulse rate, blood glucose level, weight, height, waist and hip circumferences and body composition. Overall, we did not find significant impact of BMI on the thermal sensation. However, the overweight and obese participants preferred lower temperature compared to normal weight and underweight participants which may indicate practical implication for control strategies.

Keywords: thermal comfort; thermal preference; body type differences; BMI; obesity

1. Introduction

Standards for the built environment (ANSI/ASHRAE 55, 2017; EN 16798-1, 2019) are based on two conventional approaches for thermal comfort models: the Predicted Mean Vote (PMV) model (Fanger, 1970) and adaptive models (de Dear and Brager, 1998; Nicol and Humphreys, 2002). Both approaches have limitations and have poor accuracy in the estimation of individual comfort parameters because they are aggregate models designed for the average population (Cheung et al., 2019; de Dear et al., 2013; Humphreys and Nicol, 2002; van Hoof, 2008). Several factors such as weight, height, basal metabolic rate, and sex were studied to check their effects on body temperature distribution, thermal sensation and individual preferences (Beshir and Ramsey, 1981; Dougherty et al., 2009; Fanger, 1970; Grivel and Candas, 1991; Lan et al., 2008). Personal factors are not given due consideration in the conventional approaches (Zhang et al., 2001).

So far, there is limited knowledge about the impact of body mass index (BMI), which takes into account weight and height, on thermal comfort. Some laboratory studies have been done with a small sample size, without firm conclusions or they had different research focus (Blaza and Garrow, 1983). Research shows that the skin temperature decreases with increase of body fat percentage (BF) (Chudecka et al., 2014; Salamunes et al., 2017). Thermal sensation is closely related to skin temperature (Benzinger, 1969; Yao et al., 2007), and as skin temperature correlates with BF, it is likely that thermal sensation, in turn, may be related to BMI. Obese people are under higher heat strain than lean people, and are under increased risk of heat-related disorders (e.g., heatstroke, heat cramps, and heat exhaustion) (Bar-Or et al., 1969; Buskirk E. R. et al., 2006; Chung and Pin, 1996). Some surveys have suggested that people with higher BMI tend to prefer lower temperatures (Daly, 2014; Rupp et al., 2018). In the tropics, this would imply higher cooling energy needs for people with higher BMI, we may speculate that this may also affect the issue of building overcooling.

World Health Organization qualifies obesity as a global epidemic (WHO, 2018): 39% of adults were overweight in 2016, and 13% were obese. The percentage is higher in the high-income countries, where overweight and obese people account for over 60% of the population. In Singapore, the percentage of overweight and obese people is 33%, and this fraction has an increasing trend (Epidemiology and Disease Control Division, 2011). Additionally, the percentage of underweight people in Singapore (9%) is nearly triple that of other developed countries. So, traditional thermal comfort requirements do not consider ~43% of Singaporeans. We aim to explore if and how body mass index is related to thermal comfort, sensation, and preference, and physiological parameters for typical thermal conditions found indoors.

2. Methods

2.1. Facilities and measuring equipment

The experiments were conducted in two identical physical chambers (5.6×4.3×2.6 m) located at SinBerBEST in the CREATE Tower, Singapore. Simultaneously, conditions were kept the same in both rooms. The first chamber was arranged with 6 computer workstations for participants, while the other was used for experimenters' workstation, measurements of body composition and changing rooms (Figure 1).

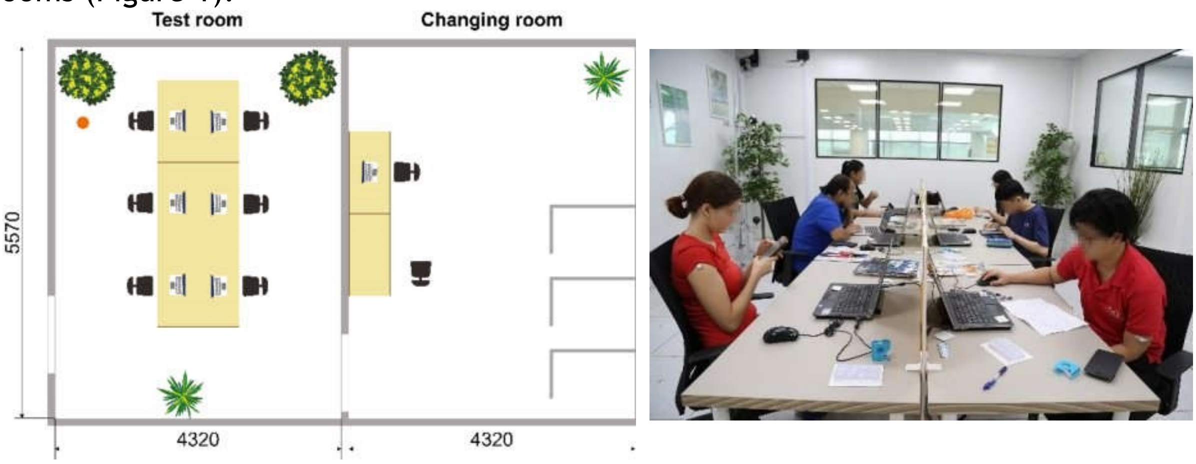

Figure 1. (Left) Plan view of the climatic chambers (orange dot – placement of ThermCondSys). (Right) Photo of the test room during the experiments.

All measurement instruments fulfilled requirements for accuracy according to EN ISO 7726 (2001). Prior to the investigation, all sensors were calibrated. We used ThermCondSys 5500 measuring system (Sensor Electronics, Poland) to monitor the room conditions at the reference point during experimental sessions. The system is equipped with omnidirectional thermal anemometers (accuracy of ±0.02 m/s

±1% of readings), air temperature and black globe temperature sensors (accuracy of ±0.1 °C), and relative humidity probe (accuracy of ±2% in range 10-90% RH). The skin temperature was measured with iButtons (DS1922L, Maxim Int., UK; accuracy of ±0.5 °C). Body composition was estimated based on hand-to-foot measurements with an 8-electrode, dual-frequency, bioelectrical impedance analysis (BIA) scanner (Tanita RD-545, Japan).

2.2. Study conditions

The study included an examination of four conditions with the design temperature set-points of 20 °C, 23 °C, 26 °C and 29 °C. Humidity levels were maintained at 55±5% for all sessions and mean radiant temperature was kept within 0.5 °C of the air temperature. All other indoor environmental parameters were kept unchanged across the sessions. Selected conditions were roughly corresponding to predicted thermal sensation "cool", "slightly cool", "neutral" and "slightly warm" (Hoyt et al., 2019) assuming clothing insula on of 0.57 clo and metabolic activity of 1.0 met (more details in the next paragraph). Table 1 summarizes the studied conditions.

Table 1. Experimental conditions (mean ± standard deviation)

Condi on:	20 °C	23 °C	26 °C	29 °C
Predicted thermal sensation based on PMV	cool	slightly cool	neutral	slightly warm
Air temperature (°C)	19.9 ± 0.2	22.5 ± 0.3	25.5 ± 0.3	28.5 ± 0.2
Operative temperature (°C)	19.9 ± 0.2	22.4 ± 0.4	25.3 ± 0.3	28.2 ± 0.2
Relative humidity (%)	53.5 ± 1.0	54.3 ± 1.9	51.3 ± 1.4	51.3 ± 3.0

2.3. Procedure and questionnaires

Participants were asked to arrive 15 min before the start of the experimental session. During this preparation time, they put on 8 iButtons, with medical grade tape, for the skin temperature measurements (forehead, right scapula, le upper chest, right arm in upper location, left arm in lower location, left hand, right anterior thigh, left calf) (ISO 9886, 2004). Afterward, they filled the first questionnaire to record their response at the beginning of acclimatization. During the remaining part of the acclimatization phase, the body composition analyses were performed. Participants filled the remaining two questionnaires at the 35th and 55th minute of the experiment, between which the blood pressure and glucose level were measured. Participants were seated for the most me of the experiment and could use their phone or bring in their books, magazines, paperwork, etc. However, they needed to answer the questionnaires when prompted and to cooperate with the performance of measurements when asked. During experiments, participants wore their own clothes that they chose based on some guidelines from us (no e, short sleeve shirt or T-shirt, long trousers, full shoes—estimated clothing insulation of 0.57 clo). The chairs they sat on had estimated insulation of 0.1 clo. We asked them to keep the same set of clothes for all four sessions.

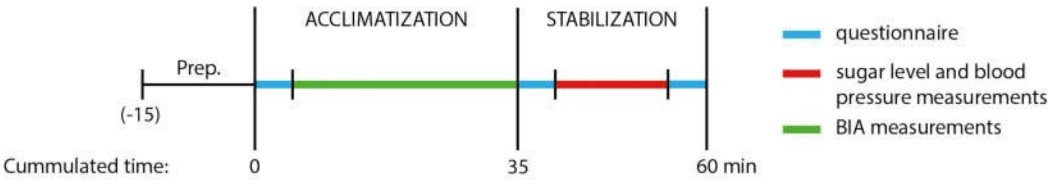

Figure 2. Experimental procedure.

We used a continuous scale with 7-points (the ASHRAE scale: −3 – cold; 0 – neutral; +3 – hot) to examine current thermal sensation (ANSI/ASHRAE 55, 2017). Similarly, 7-point continuous scales were used for air movement sensation (−3 – much too breezy; 0 – neutral; +3 – much too still) and humidity sensation (−3 – very humid; 0 – neutral; +3 – very dry). The acceptability of thermal sensation, air movement, humidity and air quality were examined with a 5-point discrete scale to achieve fine gradation in respondents' perception (Revilla et al., 2014). Likewise, a 5-point Likert scale was used for assessment of thermal comfort, air freshness and self-reported wellbeing. The intensity of odour and mucous irritation (nose, throat, eyes) were evaluated with a 6-point scale (0 – no, 6 – overwhelming). The first questionnaire, answered by participants immediately after the session started, included questions about participants' transportation, last meal and drinks, sleep quality in the previous night, and menstrual cycle phase (for female participants). The questions are shown in Appendix A.

Table 2. Descriptive characteristics of participants (mean ± standard deviation for normally distributed; median (1st quartile, 3rd quartile) for non-normally distributed)

	All (N = 76)	Males (N = 29)	Females (N = 47)
Age (yrs.)	29.0 (24.0, 36.0)	28.0 (23.0, 32.0)	29.0 (24.0, 38.0)
Height (cm)	165.7 ± 8.8	172.8 ± 7.6	161.3 ± 6.2
Weight (kg)	69.4 ± 15.4	73.6 ± 16.7	66.7 ± 14.1
BMI (kg/m^2)	25.1 ± 5.2	24.4 ± 5.1	25.6 ± 5.3
≤ 18.4	13 (17%)	5 (17%)	8 (17%)
18.5–24.9	25 (33%)	12 (41%)	13 (28%)
25.0–29.9	23 (30%)	7 (24%)	16 (34%)
≥ 30.0	15 (20%)	5 (17%)	10 (21%)
Waist circumference (cm)	86.0 (73.5, 93.5)	86.6 ± 12.7	83.5 (72.0, 93.0)
Hip circumference (cm)	101.3 ± 9.8	99.5 ± 9.5	102.4 ± 10.0
Waist-to-hip ratio	0.83 ± 0.09	0.87 ± 0.07	0.81 ± 0.09
Total body fat (%)	31.0 ± 10.1	22.5 ± 7.0	36.3 ± 7.8
Muscle mass (kg)	42.6 (37.6, 49.5)	53.3 ± 9.1	39.1 ± 4.7
Visceral fat (level)	7.6 (4.0, 11.4)	8.9 ± 5.4	7.3 (4.1, 10.3)
Metabolic age (yrs.)	34.0 (26.0, 45.0)	29.0 (23.0, 37.0)	39.1 ± 12.8
In tropics (yrs.)	23.0 (4.0, 30.0)	21.0 (4.0, 28.0)	24.0 (4.5, 35.2)

2.4. Participants

We recruited the study population from adult volunteers who responded to local announcements at the campus of the National University of Singapore and advertisements published on social media platforms. The inclusion criteria included the BMI as the objective of the study was to recruit 25 subjects within each BMI range: below 18.5 kg/m ^{2} (underweight), from 18.5 to 25 kg/m^2 (normal-weight), 25 to 30 kg/m^2 (overweight) and above 30 kg/m^2 (obesity) (WHO, 2018). The major problem encountered was recruiting underweight and obese participants. Overall, we included 76 participants in the study (29 men and 47 women). For all participants, we measured height, weight, and waist and hip circumferences. Body composition parameters were measured four times and averaged.

Baseline characteristics of studied participants are shown in Table 2. All participants were living in Singapore and were acclimatized to the tropical climate in which the study took place (*Mdn* = 24.0 yrs. in tropics, IQR [4.5, 35.2]). One of the recruitment criteria was a conservative 6 months of constant stay in a tropical climate as De Freitas and Grigorieva (2014) showed 3 months are sufficient for short-term acclimatization. The University of California Berkeley Ethics Committee approved the study protocol (Protocol # 2018-0611181), and all recruited participants gave their written consent.

2.5. Statistical analyses

Analyses were carried out using R version 3.6.2 so ware (R Core Team, 2016). The normal distribution of data and residual was tested with Shapiro-Wilk's W test. Brown–Forsythe test was used to analyse the equality of group variances. As analyses showed non-normal distribution for survey data, Spearman's rank coefficient was used to measure the degree of similarity between variables, and to assess the significance of the relationship between them. Wilcoxon rank-sum test was used to compare results between participant groups. Bonferroni correction was used for multiple comparisons with non-parametric tests to avoid (adjusted critical level of significance $p = .05/4 = .0125$). Graphs were prepared using "GGplot2" (Wickham, 2009). The data distributions are shown with box-and-whisker plots (horizontal line – median, rhombus – mean, and circles – outliers).

3.Results and Discussion

In this paper, we present preliminary results focusing on the thermal comfort perception. To study the impact of body mass index, we plotted the trend of changes in thermal sensation with the increase of BMI (Figure 3). Overall, we did not find any practical effect of BMI on thermal sensation both for the entire dataset (TS~BMI+TO, BMI linear model coefficients
$b = -0.01$ (*SE* .01), $t = -1.14$, $p = .26$) and when separated for the four temperature conditions (TS~BMI+TO, BMI linear model coefficients at 19.9 °C: $b = 0.02$ (*SE* .02), $t = 1.16$,
$p = .25$;
22.4 °C: $b = -0.01$ (*SE* .02), $t = -.67$, $p = .50$.; 25.3 °C: $b = -0.04$ (*SE* .02), $t = -2.48$, $p = .016$;
28.2 °C: $b = -0.01$ (*SE* .02), $t = -.42$, $p = .68$). The Spearman's rank correlation did not indicate the significance of those changes ($p = .65$ and $r_s = -.06$ at 19.9 °C; $p = .56$ and $r_s = -.08$ at 22.4 °C; $p = .32$ and $r_s = -.13$ at 25.4 °C; $p = .21$ and $r_s = -.17$ at 28.2 °C). Analogous trends, not reported here, were obtained for the thermal sensation in the relation to the total body fat percentage. No significant differences ($p < .0125$) in thermal acceptability between BMI categories were noticed.

Participants' thermal preference responses are shown in Figure 4. Thermal preference is arguably more important than thermal sensation because it is a direct indication of what people would like to have. Results indicate that overweight and obese participants preferred cooler environments. At the temperature set-point of 19.9 °C, obese participants in 50% of responses indicated a desire for "no change". Conversely, the underweight and normal-weight participants substantially preferred warmer conditions (85% and 77% respectively). The temperature set-point of 22.4 °C was the most preferable for overweight (59%) and obese (84%) responses declared "no change". The favourable condition for underweight and normal-weight participants was the temperature set-point of 25.3 °C (77% and 50% of responses for "no change" respectively).

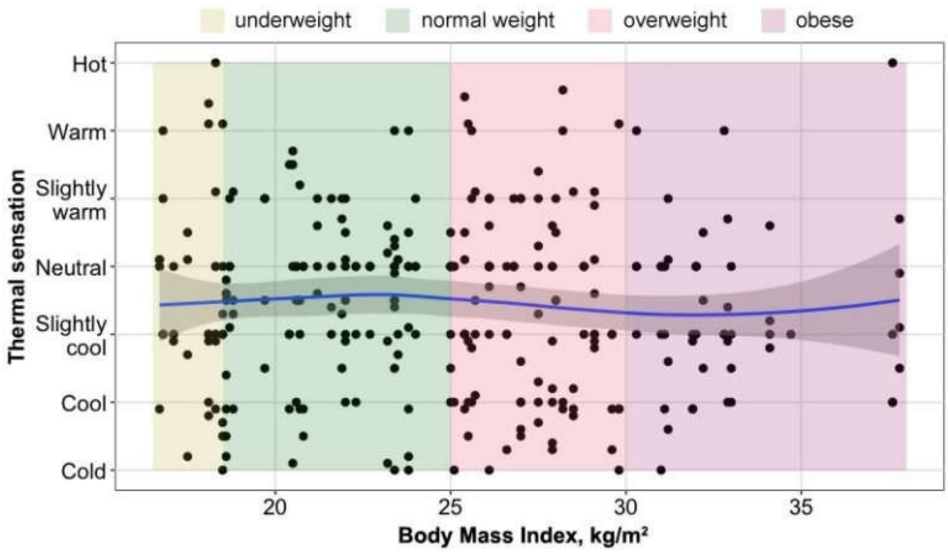

Figure 3. Thermal sensation as a function of the body mass index (BMI) – LOESS regression with 95% confidence intervals.

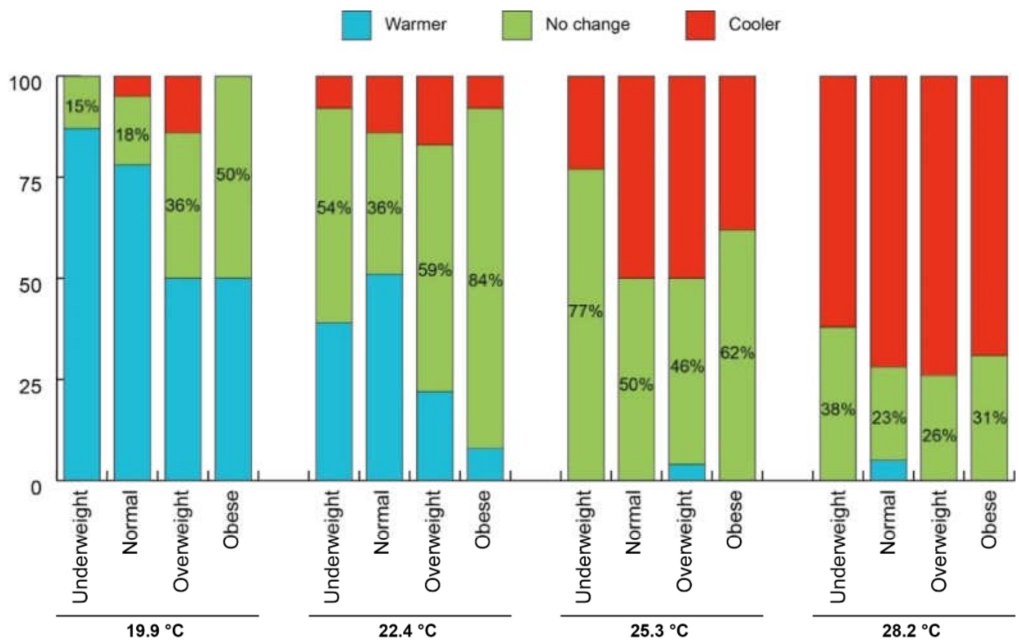

Figure 4. Thermal sensation preferences depending on the BMI category at each experimental condition.

To further study how BMI affected thermal preference over the range of investigated conditions, we used the quadratic discriminant analysis (QDA) algorithm to create a classification model for thermal preference, using BMI and operative temperature as inputs. The model is shown in Figure 5; the actual data is also shown. The predicted thermal preference areas from the application of QDA show that for temperatures under 23 °C, participants with higher BMI (> 26 kg/m^2) have a clear likelihood of desiring no change of their thermal environments. The distinction on the lower BMI side is less prominent, but the prediction is that for BMI under 20 kg/m^2, a participant is likely to be okay with temperatures of 26-27 °C. Counterintuitively though, the model suggests that people with high BMI (> 34 kg/m^2) may accept temperatures warmer than the limits expressed for people with BMI between 20 and 34 kg/m^2 – though not more than people with BMI under 20 kg/m^2. This could be due to the small number of participants at such high BMI values, who might have had specific personal preferences.

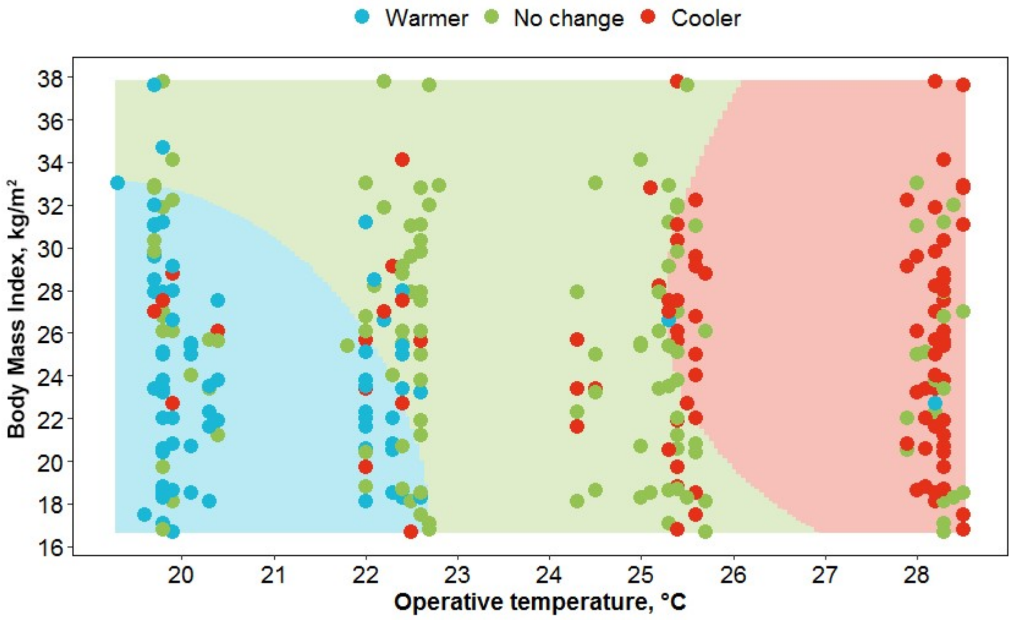

Figure 5. Thermal preference classification (QDA) with body mass index (BMI) and operative temperature as inputs, along with actual participant votes (circles in foreground).

After adjusting the criteria for significance level due to multiplicity, no statistically significant differences were observed in thermal sensation due to the BMI. However, assuming neutral thermal sensation as preferred temperature could be misleading. Results of our study, in laboratory conditions, confirmed conclusions of field surveys that occupants with higher BMI values tend to prefer lower temperature set-points (Daly, 2014; Rupp et al., 2018). Taking into account the increasing prevalence of overweight and obesity in the population, it could limit energy-saving strategies for tropical climates (Duarte et al., 2017; Lipczynska et al., 2018), while in temperate and cold climates support energy-efficient controls.

The limitation of the study was that the obese and underweight participation groups were underrepresented compared to others. Nonetheless, conducted study has the biggest sampling size compared to previous works on similar topics.

4. Conclusions

Data analysis revealed preferences of people with higher BMI for lower temperatures of around 22 °C. For people with BMI indicating normal weight, the preferred temperature lays between 22.5 and 27 °C. Conversely, underweight participants substantially preferred warmer conditions of around 25 °C.

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Appendix A

Enter your ID ____________________

Rate your current thermal sensation

cold	cool	slightly cool	neutral	slightly warm	warm	hot
-3	-2	-1	0	+1	+2	+3

Rate your current sensation of air movement

much too breezy	too breezy	slightly breezy	neutral	slightly still	too still	much too still
-3	-2	-1	0	+1	+2	+3

Rate your current sensation of air humidity

very humid	humid	slightly humid	neutral	slightly dry	dry	very dry
-3	-2	-1	0	+1	+2	+3

At the moment, how acceptable for you is ...?

	Very unacceptable	Somewhat unacceptable	Neither acceptable nor unacceptable	Somewhat acceptable	Very acceptable
thermal sensation:	○	○	○	○	○
air movement:	○	○	○	○	○
air humidity:	○	○	○	○	○
air quality:	○	○	○	○	○

Right now, are you thermally...?

uncomfortable ○ ○ ○ ○ ○ comfortable

Would you prefer to feel...?

thermal sensation:	○ Cooler	○ No change	○ Warmer
air movement:	○ Less air movement	○ No change	○ More air movement
air humidity:	○ Less humid	○ No change	○ More humid

The air is...

stuffy ○ ○ ○ ○ ○ fresh

Right now, do you feel...?

	No	Light	Moderate	Strong	Very Strong	Overwhelming
Odor	○	○	○	○	○	○

Right now, do you have...?

	No	Light	Moderate	Strong	Very Strong	Overwhelming
Eyes irritation	○	○	○	○	○	○
Nose irritation	○	○	○	○	○	○
Throat irritation	○	○	○	○	○	○

Right now, how do you feel?

I am sleepy	○	○	○	○	○	I am alert
It is di cult for me to concentrate	○	○	○	○	○	It is easy for me to concentrate
I do not feel productive	○	○	○	○	○	I feel very productive

(Following questions were included only in the first questionnaire during acclimatization)

How did you arrive here?

O By car O By bus

O Other. Please specify: ____________________________

O On foot O By bike

For how long and how well did you sleep tonight?

I went to bed by: ____________________________

I woke up at: ____________________________

My sleep was disrupted: (No/Yes, please specify how:)

____

Overall, how would you rate your sleep quality last

night? O Very good O Fairly good

O Fairly bad O Very bad

What did you eat for your last meal and when?

I ate my last meal at: ___________________________

I ate: ___________________________

How many liquids have you drunk so far today?

I drank last me at: ___________________________

I have drunk so far (ml): ___________________________

Have you taken any medication today? If yes, please specify what and when.

O Yes. Please specify: ___________________________

O No

Currently, what is your menstrual cycle phase?

O Not applies (men) O Menstrua on. Typically: Days 1-5. Day 1 is the rst

day of bleeding.

O Follicular. Typically: Days 1-13 O Ovulation. Typically: Day 14 O

Luteal. Typically: Days 15-28