The influence of a moderate temperature drift on thermal physiology and perception

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ABSTRACT

 Humans spend approximately 80–90% of their time indoors. In current practice, indoor temperatures in many buildings are controlled very tightly. However, allowing more variation in indoor temperature results in more energy-efficient buildings and could potentially improve human metabolic and cardiovascular health. Therefore, this study aimed to evaluate the effect of a drifting ambient temperature versus a fixed ambient temperature on thermal physiological parameters and subjective perception. A cross-over intervention design was conducted in 16 healthy men (age 26 ± 4 y; BMI 23.0 ± 1.7 kg/m²) between July 2018 and May 2019. All participants underwent two whole-day (8:30–17:00) experimental sessions, during which they were exposed to a drifting (17–25°C with a morning ramp of 2.58°C/h and afternoon ramp of -2.58°C/h) or constant ambient temperature (21°C) in randomized order. The experiments took place in respiratory chambers, which simulated a typical office environment and in which temperature conditions can be controlled accurately. Throughout the experimental sessions core and skin temperature, heart rate, blood pressure, energy expenditure as well as activity levels were measured. Subjective thermal perception, such as thermal comfort and sensation, was assessed by questionnaires every 30 min. Results reveal that energy expenditure was higher in the morning during the drifting session, which was accompanied by an increase in activity levels. Both drifting and fixed sessions were judged as comfortable although during the drift thermal comfort was lower in the morning and afternoon and higher during midday. The results indicate that a drifting ambient temperature can be applied in practice, and as such, can contribute to a healthier and more sustainable built environment. More research is needed to understand the role of a drifting temperature on the long term.

1. Introduction

 Humans spend approximately 80–90% of their time indoors [1,2] and thus a healthy and comfortable environment is very important. Currently, the indoor temperature in many office buildings is generally controlled very stringently with only minor daily variations and limited seasonal adjustments of indoor temperature set-point. The stringent design of thermal indoor environments is mainly the result of strict interpretation and use of standards and guidelines on thermal comfort such as ASHRAE Standard 55 and ISO Standard 7730 [3,4]. These standards are based on Fanger’s Predicted Mean Vote model (PMV) [4,5,6], which was developed in the late 1960s [7]. The model uses a steady state heat balance to predict occupant’s thermal sensation based on six parameters, namely air temperature, mean radiant temperature, humidity, air speed, occupant’s clothing insulation and metabolic rate [5].

The more recent adaptive comfort model, which is for example included in EN16798–1:2019, allows for substantial seasonal variations, but it is developed for so-called Naturally Ventilated buildings in which the occupants usually regulate their thermal comfort by changing clothes or opening and closing of windows.

Importantly, a stringent indoor climate control does not guarantee a healthy working environment. Adding more temperature variability in buildings might stimulate the thermoregulatory system and improve occupants’ health [8]. Temperature variability can be achieved by introducing drifts or ramps [3]. Drifts refer to a passive temperature change and ramps refer to an actively controlled rate of change of temperature [3]. Not only do such temperature variations allow for stimulation of the thermoregulatory system, but they can also improve the energy efficiency of a building. For example, Kramer et al. [9] showed for a case study in a museum that allowing the indoor climate to...
A more variable indoor climate might be beneficial for human health. It has previously been suggested that the stringent way of applying the above-mentioned standards and the resulting little to no variation in indoor climate might make building occupants more vulnerable to temperature fluctuations as their thermoregulatory system is rarely challenged. Indeed, during the winter season, there is a higher mortality rate in the elderly, which has been associated with an impaired thermoregulatory response to cold [10]. Furthermore, previous research has shown that variations in temperature can have positive metabolic health effects. For example, mild cold can increase daily energy expenditure by means of (non-)shivering thermogenesis [11,12,13], which can contribute to maintaining a healthy weight and even improve glucose metabolism. Cold exposure is also known to activate the sympathetic nervous system, which in turn leads to peripheral vasoconstriction and subsequently an increase in systolic and diastolic blood pressure (BP) [14,15]. Such temporary increases in BP are also observed during exercise [16,17] and many of the benefits of exercise can be attributed to this transient activation of the sympathetic nervous system. On the other end of the temperature spectrum, recent studies have shown that heat can also have positive effects on health. Brunt et al. showed that hot water immersion for eight weeks can improve cardiovascular functioning [18]. In another study, participants were exposed to slightly increased constant temperatures (~33 °C) for 6 h/d over seven consecutive days and the authors reported significant decreases in systolic blood pressure after this intervention [19]. Moreover, heat is also shown to improve glucose metabolism [20]. While these studies show health benefits of both mild cold and heat exposure, little is known about what effects drifting temperature can have on human health and subjective acceptance of the thermal environment. During exposure to a drifting environmental temperature the body has to react to a sequence of increasing and decreasing thermal conditions. This variation might challenge the thermoregulatory system beyond what exposure to cold or heat can do alone. Therefore, it is possible that such temperature variations can also induce metabolic benefits, thus potentially providing a novel strategy for improving health that is easily implemented in everyday-life situations, for example in offices.

Our research group has previously shown that temperature drifts (17–25 °C, with a ramp UP of 2.58 °C/h and a ramp DOWN of ~2.58 °C/h) do not lead to unacceptable situations and that the studied drifting conditions were not perceived as uncomfortable [21]. However, the study by Schellen et al. [21] mostly focused on thermal comfort and thermal sensation. Therefore, in the present study, we aim to build upon this previous work and investigate, under controlled laboratory settings, the effect of a moderate temperature drift on physiological and health related parameters as well as subjective perception of the thermal environment. In this study, we hypothesize that the temperature drift will increase energy expenditure, while maintaining thermal comfort. In addition, the ramp may affect cardiovascular parameters, by influencing thermal physiology and blood pressure.

### 2. Methods

The study was performed at Maastricht University between July 2018 and May 2019. In total, 16 healthy young men participated on two separate occasions. The two test days differed only in temperature conditions (fixed or drift). There was at least one day in between testing days and a maximum of five days.

This trial was registered at the Netherlands Trial Registry (NTR) as NL7638. The Medical Ethics Committee of Maastricht University approved the study and it was conducted in conformity with the Declaration of Helsinki (Fortaleza, Brazil, 2013).

| Table 1: Participant characteristics. |
|-------------------------------------|
| Mean(±SD)                           |
| N                                   | 16  |
| Age (yr)                            | 26 ± 4  |
| Height (m)                          | 1.78 ± 0.67  |
| Weight (kg)                         | 73.2 ± 7.3  |
| BMI (kg/m²)                         | 23.0 ± 1.7  |
| Fat content (%)                     | 18.5 ± 4.6  |

### 2.1. Participants

Participants were healthy males, aged between 20 years to 40 years and had a BMI between 18.5 kg/m² and 27.5 kg/m² (Table 1). They were recruited by advertisements on local billboards in the university. They were included in the study if they were generally healthy, did not use any medication that could influence their cardiovascular or thermoregulatory responses and had normal chronotype as assessed by the Morningness-Eveningness Questionnaire (MEQ-SA) [22]. Raynaud’s phenomenon is a common clinical disorder consisting of recurrent, long-lasting, and episodic vasospasm of the fingers and toes often associated with exposure to cold [23]. Due to the possible effects on the physiological and subjective responses evaluated in this study, participants with this condition were excluded from participation.

### 2.2. Facilities

The experimental sessions were done in the respiration chambers in the Metabolic Research Unit of Maastricht University (MRUM). In short, the chambers are 18m² in size and they give impression of a normal room. Windows are positioned in the door for contact with researchers and curtains on the windows ensure privacy when needed. For full description of the respiration chamber including technical information, see reference [24].

### 2.3. Protocol

#### 2.3.1. Ambient temperature

During the fixed session, the ambient temperature was set to 21 °C (21 ± 0.5 °C), which emulates a typical office setting. This temperature setting falls within the optimal operative temperature range according to the PMV model [25].

During the drift session, a moderate temperature ramp was applied (Fig. 1). During the morning, the temperature increased with 2.28 °C/h and in the afternoon, it decreased with ~2.28 °C/h. These changes fit within the maximum temperature change allowance [3]. The minimum temperature was set to 17 °C to avoid shivering and the maximum temperature was set to 25 °C.

#### 2.3.2. Procedures

Participants arrived at the laboratory at 8 AM after an overnight fast. They were instructed to refrain from alcohol and heavy physical activity for at least one day before each session. After arrival at the laboratory, participants were asked to ingest a telemetric pill and were fitted with a blood pressure cuff, 16 skin temperature sensors and a heart rate chest belt. Participants were provided with standardized clothing, which included a t-shirt, sweater and sweat pants (~0.8 clo). Participants then entered the respiration chamber, where they stayed for the next 8.5 h. Participants were allowed to bring their own laptops and were instructed to perform normal office-type activities (reading, typing, etc.; ~1.2 METs) during each experimental session. In the chamber, energy expenditure was measured by means of indirect calorimetry. Participants were instructed how to measure their blood pressure and fill in a thermal perception questionnaire every 30 min. Three times during the day, during periods of stable temperature (see Fig. 1) participants were

![](image-url)
instructed to lay down in bed quietly so that basal metabolic rate (BMR; morning in fasted condition) or resting metabolic rate (RMR) could be measured. Two times during the day, a short stepping exercise was performed. Total daily energy requirements were estimated by the Harris-Benedict equation. Breakfast contributed ~25% to total energy intake and lunch ~30%, which is similar to the energy content of a typical Dutch diet [26]. The total macro nutrient distribution provided was: 55% carbohydrate, 30% fat and 15% protein, which is in accordance with the Dutch and American dietary guidelines [27, 28].

2.4. Measurements

2.4.1. Indoor and outdoor environment

In the respiration chamber, air temperature and relative air humidity (RH) were measured at one-minute intervals by means of three iButton dataloggers (DS-1923, temperature sensor accuracy ±0.5°C, RH sensor accuracy ±5% RH, Maxim, USA). The iButtons were placed next to the participant at 0.1 m, 0.3 m and 1.1 m levels, which are representing the ankles, mid-body and neck, respectively, of seated occupants [3]. Detailed measurements of the indoor climate (air temperature, RH and black bulb temperature) were obtained by an indoor climate analyzer (Almemo 2890–9, temperature sensor accuracy ±0.05°C, RH sensor accuracy ±1% RH, UK) during the first four days of two participants. The data was compared between the devices and the two measurements provided similar results for both air temperature and RH (data not shown).

Outdoor temperature was obtained from Royal Netherlands Meteorological Institute (KNMI). In order to account for seasonality effects, a weighted running mean of outdoor temperatures (RMOT) was then calculated based on the previous 7 days prior to each participant’s visit to the laboratory. RMOT was calculated according to EN16798:2019 [29], which is the most recent European standard.

2.4.2. Skin and core body temperature

Core temperature was measured using a telemetric pill (VitalSense® medical grade capsules, EquivitalTM, UK). The pill was ingested in the morning 30 min before each condition commenced. Skin temperatures were measured at 17 body sites by means of iButton dataloggers (DS-1922 L, Maxim, USA). Mean skin temperature was calculated using skin temperatures measured at the 14 ISO-defined skin sites [30]. Two extra iButtons were placed at the underarm and the middle finger to assess the underarm-finger temperature gradient, which we used as a proxy for peripheral vasoconstriction [31]. Furthermore, we used the supraclavicular skin temperature as an indicator of brown adipose tissue activity (Fig. 2) [32]. The sensors were attached to the skin using Fixomull tape (BSN, Hamburg, Germany). Proximal skin temperature was calculated as the average of the ISO-defined sites of scapula, lower back, upper chest and abdomen. For distal skin temperature, the temperatures of the left hand and the right foot were averaged.

2.4.3. Energy expenditure, substrate utilization and physical activity

Oxygen consumption and carbon dioxide production (in mL/min) was measured continuously in the respiration chamber using indirect calorimetry equipment (Omnical, Maastricht Instruments, the Netherlands). Energy expenditure was calculated using Weir’s equation [33]. The rate of lipid and carbohydrate oxidation (in g/min) was calculated using the Péronnet and Massicotte’s formula [34]. Physical...
activity, in counts per minute, was measured using a three-axial accelerometer, which was attached approximately 10 cm above the right patella (MOX, Maastricht Instruments, the Netherlands).

2.4.4. Cardiovascular parameters

Heart rate (HR) was measured using a Polar H10 chest belt (Polar, USA). Data was measured every second and then averaged per minute to decrease the effects of measurement noise. Participants were fitted with an OMRON M6 blood pressure cuff (Omron Healthcare B.V., Hoofddorp, the Netherlands) before entering and once inside the respiration chamber, they were asked to measure their BP every 30 min.

2.4.5. Thermal questionnaire

Every 30 min, participants filled in a questionnaire that was used to evaluate the perception of the thermal environment. Subjective thermal sensation was evaluated using the standard 7-point ASHRAE thermal scale (−3 ‘cold’ to 3 ‘hot’) and another continuous visual analogue scale (VAS) was used to indicate thermal comfort [3]. The thermal comfort scale was divided into two parts to urge participants to indicate whether they perceived the thermal environment as ‘comfortable’ or ‘uncomfortable’. Subjective thermal preference was evaluated with a standard 7-point scale (−3 ‘much cooler’ to 3 ‘much warmer’). Fig. 3 shows the questions and their corresponding response scales.

2.5. Statistical tests

To analyze the differences in both physiological and subjective responses between the two sessions, the MIXED procedure in SPSS was used. The MIXED procedure in SPSS fits models more general than those of the general linear model procedure (GLM), and it encompasses all models in the variance components procedure. The MIXED procedure makes it possible to handle correlated data and unequal variances. For details, see reference [35].

The maximum likelihood estimation and either a first-order autoregressive (AR1) covariance matrix or unstructured covariance matrix was used, whichever was associated with the lowest values on the Akaike’s Information Criterion (AIC) for the final model selection.

Since some variables (body core temperature, skin temperature, HR) were measured every minute, the average of the previous five min per participant prior to filling in the questionnaire was used as a representative value for the time point at which the questionnaire was filled in. Energy expenditure and PA were averaged for the previous 15 min per participant due to the slower response of the respiration chamber.

The temperature session (fixed vs. drift), experimental time (30 min, 60 min, 90 min, etc.) and the interaction of the two were treated as fixed factors in the models. The variable D_Temp was entered as a covariate to account for the differences between the protocol temperature and the observed temperature. In order to account for seasonality effects on
participants’ thermal perception, the RMOT was added to the models that evaluated thermal sensation, comfort and preference. Separate analyses were performed for the morning \((t \leq 240)\) and afternoon \((t > 240)\). All \(P\) values were corrected for multiple testing with the Benjamini-Hochberg procedure (BH procedure) to reduce the False Discovery Rate (FDR) \([36]\). The procedure was applied for all calculated \(P\) values and the adjusted \(P\) values are reported in the results.

Associations between the different physiological parameters and thermal sensation were analyzed using Spearman’s correlation \(r_{\text{Spearman}}\). All data were analyzed using IBM SPSS Statistics 25 for Mac (SPSS, Chicago, IL). Data are reported as mean \(\pm\) SEM, unless stated otherwise, and significant effects are reported for \(P < 0.05\).

3. Results

The series of figures in this section show the estimated marginal means (EMS) per time point with the standard error of the mean (SEM). The trends of the data are described below and the details for the statistical analysis are shown in the Supplementary File.

3.1. Environmental measurements

The average ambient temperature for all participants during the fixed session was 20.10 \(\pm\) 0.33°C. During the morning of the drift session, the average ambient temperature was 20.21 \(\pm\) 2.00°C and during the afternoon 20.01 \(\pm\) 2.17°C (Fig. 4). RH was allowed to vary with

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**Fig. 5.** Body core (a), mean skin (b), proximal skin (c), distal skin (d), underarm-finger gradient (e), during fixed and drift. Data presented as EMS \(\pm\) SEM. \(N = 16\). Note: * \(P < 0.05\); ** \(P < 0.01\); *** \(P < 0.001\) fixed versus drift. The dotted line indicates the boundary between morning \((t \leq 240)\) and afternoon \((t > 240)\), and where the analysis was split.
3.2. Physiological measurements

3.2.1. Body core and skin temperatures

Body core temperature was not significantly different between the two sessions, $P > 0.05$. However, there was a significant effect of time, $P < 0.001$, showing a gradual increase in core temperature during the day (Fig. 5a).

Mean skin temperature followed the ambient temperature profile during drift and remained relatively stable during fixed (Fig. 5b). Participants had similar mean skin temperatures in both fixed and drift sessions during both the morning and the afternoon (EMS_f: $M_{fixed} = 32.53 \pm 0.10 ^\circ C$; $M_{drift} = 32.26 \pm 0.10 ^\circ C$ and EMS_a: $M_{fixed} = 32.53 \pm 0.15 ^\circ C$; $M_{drift} = 32.57 \pm 0.16 ^\circ C$).

Participants had higher mean proximal skin temperature during the fixed session in the morning compared to the drift (EMS: $M_{fixed} = 34.07 \pm 0.14 ^\circ C$; $M_{drift} = 33.75 \pm 0.14 ^\circ C$). No differences in proximal skin temperature were observed in the afternoon (EMS: $M_{fixed} = 34.31 \pm 0.15 ^\circ C$; $M_{drift} = 34.10 \pm 0.16 ^\circ C$). During the drift session, mean proximal skin temperature during drift followed the ambient temperature profile, and remained relatively stable during the fixed condition. The interaction between protocol $\times$ time was significant during both the morning and the afternoon. Pairwise comparisons revealed significant differences at the time points observed in Fig. 5c.

Participants had higher mean distal skin temperature during the fixed compared to the drift session in the morning (EMS: $M_{fixed} = 29.35 \pm 0.28 ^\circ C$; $M_{drift} = 28.58 \pm 0.27 ^\circ C$). In the afternoon, no differences between the two sessions were observed (EMS: $M_{fixed} = 28.86 \pm 0.37 ^\circ C$; $M_{drift} = 28.90 \pm 0.39 ^\circ C$). Distal skin temperature during drift followed the ambient temperature profile and remained relatively stable during the fixed session. The temperature trends are shown in Fig. 5d.

The underarm-finger gradient during both morning and afternoon is shown in Fig. 5e. Higher underarm-finger gradient values were observed during the drift session early in the morning ($t < 150$ min) and in the late afternoon ($t > 390$ min). The gradient was higher during the fixed protocol midday (210 min $< t < 330$ min). Lastly, no significant differences in supraclavicular skin temperature were observed between the two sessions, fixed versus drift (data not shown).

3.2.2. Energy expenditure, substrate metabolism and physical activity

In the morning mean energy expenditure was significantly higher during the drift than fixed session (EMS: $M_{drift} = 7.19 \pm 0.15$ kJ/min; $M_{fixed} = 6.94 \pm 0.15$ kJ/min; $P = 0.02$) (Fig. 6a). At $t = 150$, energy expenditure was higher during drift than fixed (EMS: $M_{drift} = 8.42 \pm 0.23$ kJ/min; $M_{fixed} = 7.57 \pm 0.23$ kJ/min, $P < 0.05$). No significant differences in energy expenditure between the two sessions, fixed and drift, were observed during the afternoon. In both morning and afternoon, time had a significant effect on energy expenditure ($P < 0.001$) indicating that energy expenditure varied during the day, following the pattern shown in Fig. 6a. Fig. 6b shows that approximately 70% of the participants had higher energy expenditure in the morning during the drift compared to the fixed session. The reverse was true for the afternoon: approximately 70% of participants had lower energy expenditure during drift compared to the fixed protocol (data not shown). There were no significant differences in BMR or RMR between the two sessions (data not shown).

Lipid oxidation was significantly higher during the morning of the drift compared to the fixed session (EMS: $M_{drift} = 0.086 \pm 0.01$ g/min; $M_{fixed} = 0.097 \pm 0.01$ g/min; $P = 0.02$). Time had a significant effect on lipid oxidation in both sessions, fixed and drift, with $P < 0.001$ in both morning and afternoon (Fig. 6c). No significant differences in lipid changes in temperature, resulting in an average RH of 49.04 $\pm$ 5.46% during the fixed session, 49.36 $\pm$ 10.28% during the morning of the drift and 46.40 $\pm$ 8.77% during the afternoon of the drift session.
oxidation between the two protocols, fixed and drift, were observed during the afternoon.

No significant differences in CHO oxidation between the two sessions, fixed and drift, were observed in the morning and the afternoon (Fig. 6d)). During both periods observed (morning and afternoon), a significant effect of time was found ($P < 0.001$).

In the morning, physical activity (in counts/min) was significantly higher during drift than fixed at $t = 150$ min. No significant differences between the two protocols, fixed and drift, were observed during the afternoon. In both morning and afternoon, time had a significant effect on intensity ($P < 0.001$) indicating that activity varied during the day (see Fig. 6e)). Approximately 70% of the participants had higher activity...
3.2.3. Cardiovascular parameters

In the morning and in the afternoon no statistical differences in systolic blood pressure and HR were observed between fixed and drift (Fig. 7a and c). Diastolic blood pressure was higher in the morning during drift compared to the fixed session (EMS: $M_{\text{drift}} = 73 \pm 1.45$ mmHg; $M_{\text{fixed}} = 71 \pm 1.46$ mmHg, Fig. 7b)). In the afternoon, no significant differences in DBP between the two sessions, fixed and drift, were observed.

3.3. Subjective responses

With respect to thermal comfort, overall, participants felt comfortable in the morning in both sessions, fixed and drift (EMS: $M_{\text{fixed}} = 0.71 \pm 0.11$; $M_{\text{drift}} = 0.45 \pm 0.11$). Similar results were observed during the afternoon ($M_{\text{drift}} = 0.37 \pm 0.13$; $M_{\text{fixed}} = 0.52 \pm 0.11$). Significant differences between the two sessions are observed at the time points noted in Fig. 8b. Comfort decreased significantly during the fixed session midday at $t = 270$, right after the RMR measurement. Fig. 8c shows the individual sensation votes that were perceived as comfortable during both sessions, fixed and drift. The figure shows that approximately 75% of participants had wider range of sensation votes that were rated as comfortable during the drift session.

Participants would have preferred a slightly warmer environment under both sessions, fixed and drift, in both the morning (EMS: $M_{\text{fixed}} = 0.28 \pm 0.14$; $M_{\text{drift}} = 0.40 \pm 0.13$) and afternoon (EMS: $M_{\text{fixed}} = 0.62 \pm 0.13$; $M_{\text{drift}} = 0.62 \pm 0.15$). Participants would have also preferred a slightly warmer thermal environment in the morning during the drift session compared to the fixed but in the afternoon the overall mean votes were similar and no differences between the two sessions were observed. The largest differences between the two sessions were observed mid-day at $t = 210$ and $t = 270$, where participants indicated preference for a slightly warmer thermal environment during the fixed compared to drift session (Fig. 8d). Outdoor temperature had no significant effect on thermal sensation, comfort or preference ($P > 0.05$).

3.4. Morphological and physiological parameters

In order to investigate the relationship between body composition and energy expenditure, regression analyses were conducted between fat free mass (FFM) and BMR, and FFM and RMR. No significant associations between FFM and BMR at either 17°C or 21°C were found. FFM was also not significantly associated with RMR at either 17°C or 21°C (data presented in the Supplementary File). Similar results were observed with regression analysis at 21°C and 25°C.

3.5. Correlations between subjective and physiological responses

Next, we looked at the associations between body core temperature, skin temperatures, thermal sensation and thermal comfort. We analyzed the relationships only during drift due to the larger variation in sensation and comfort votes present in the data.

From the all body temperature sites tested, underarm-finger gradient was the only site negatively associated with thermal sensation (Fig. 9a), meaning the warmer the sensation the lower the underarm-finger gradient. Lower underarm-finger gradient values indicate warm fingers and higher underarm-finger gradient values indicate cold fingers. Similarly, the underarm-finger gradient was also negatively associated with thermal comfort ($r_{\text{Spearman}} = 0.34$, shown in Fig. 9b), indicating that higher comfort votes were associated with lower underarm-finger
gradient values. The highest association with thermal sensation was observed with the shoulder ($r_{\text{Spearman}} = 0.54$) and the lowest with the calf ($r_{\text{Spearman}} = 0.16$). With regards to thermal comfort, the elbow showed the highest association ($r_{\text{Spearman}} = 0.46$) and the ventral side of the upper leg the lowest ($r_{\text{Spearman}} = 0.16$).

4. Discussion and conclusions

The present study evaluated the effects of a drifting ambient temperature on thermal comfort, sensation, and on physiological and health parameters, and compared them with the effects of a fixed ambient temperature profile, currently implemented in many buildings. We show that a moderate temperature drift (morning ramp of $2.28^\circ\text{C/h}$ and afternoon ramp of $2.28^\circ\text{C/h}$) does not lead to thermal discomfort, but significantly increases energy expenditure in the morning, which is also accompanied by an increase in physical activity.

To the best of our knowledge, this is the first study to evaluate the effects of a drifting ambient temperature on the physiological variables presented in this study. No other study in the literature has evaluated the effects of a drifting ambient temperature on energy expenditure and substrate utilization. For this reason, we compared our results to studies in the literature involving mild cold and/or mild heat exposure as the drifting temperature profile exposed our participants to both colder and warmer environments than the static conditions currently accepted in office buildings.

4.1. Health-related and physiological variables

We did not observe any effects of the imposed temperature ramp on body core temperature. This is in accordance with previous studies.
reporting that body core temperature can be maintained in response to mild cold [12,37]. However, a gradual increase in core body temperature was observed during the day, which is indicative of normal circadian rhythmicity [38]. Skin temperature at most body sites changed in line with the protocols, with the exception of the supraclavicular skin temperature, which remained stable during both sessions. Proximal temperature changed less than distal skin temperature.

During cold exposure, the sympathetic nervous system is activated, which leads to a cascade of reactions eventually leading to the activation of different receptors and complexes, which in turn leads to peripheral vasoconstriction and elevation of BP [39,40,41,42]. We did not observe any differences in either systolic or diastolic BP between the two sessions at any of the time points studied including the morning when the temperature conditions (22°C vs 27°C) did see changes in BMR [12,44]. In the present study, the difference in ambient temperature between the BMR measurements was relatively small, 4°C only measured between 17°C and 21°C in the morning at t = 30 when the BMR measurement was performed. This small difference between temperature conditions could explain the difference in findings between the studies. Furthermore, other studies that have looked into smaller differences between temperature conditions (22°C vs 27°C) have also found significant results indicating that energy expenditure is higher at 22°C than 27°C [45]. Here we did not observe any differences in either BMR or RMR between the two sessions. Studies done in somewhat similar conditions (comparing ambient temperature of 16°C vs 22°C) did see changes in BMR [12,44]. In the present study, the difference in ambient temperature between the two sessions was observed in the morning when the temperature during drift was significantly lower than in the fixed session. Heart rate, which is often used as an indicator of sympathetic stimulation, was also not statistically different between the two sessions.

Interestingly, we observed a significant main effect of session on diastolic BP, but only during the morning (EMS: M_{drift} = 73 ± 1 mmHg; M_{fixed} = 71 ± 1 mmHg) and not in the afternoon (EMS: M_{drift} = 72 ± 1 mmHg; M_{fixed} = 72 ± 1 mmHg, P > 0.05). Although no significant differences between the two protocols were observed at any of the time points studied, the largest differences in diastolic BP between the two protocols were observed in the morning (t < 90 min). This coincides with the largest differences in ambient temperature profile between the two protocols. At those time points (t < 90 min), peripheral vasoconstriction as indicated by the underarm-finger gradient, was also higher during drift compared to fixed, which may explain our findings as the effects of cold on peripheral vasoconstriction and BP have been extensively reported in the literature previously [37,39,40,41,42]. Diastolic BP was higher during drift during the morning in the observed study. The increase in BP, typically associated with cold exposure, has been shown to decrease after cold acclimation [43]. Increases in BP are also observed during exercise [16,17] and thus, these transient increases in BP during cold exposure should not be necessarily viewed as a negative effect. Instead, daily changes in skin temperatures and subsequently BP can contribute to an increased resilience to temperature variations. In this way if drifting ambient temperatures are implemented in buildings they can contribute to a healthier working environment.

The average energy expenditure in the morning was 6.95 kJ/min compared to 7.2 kJ/min during the drift session (P = 0.02). This was accompanied by an increase in physical activity in the morning during the drift session compared to the fixed. Although the difference in EE is small, on the long term this can lead to considerable metabolic effects. Future studies are needed to observe such long-term effects. In this study we did not observe any differences in either BMR or RMR between the two sessions. Studies done in somewhat similar conditions (comparing ambient temperature of 16°C vs 22°C) did see changes in BMR [12,44].

\[ \text{Average responses to the question `How do you feel at the moment?' (a), average responses to the question `How do you perceive the thermal environment?' (b), individual thermal sensation votes for the comfortable scale only (thermal comfort votes > 0.001) (c), average responses to the question `What would you prefer at this moment?' (d). Note: *, **, *** indicate } P < 0.05, P < 0.01 and P < 0.001, respectively, fixed vs drift. Data presented as EMS ± SEM. N = 16. The break in the x-axis represents where the analysis was split.
have a strong positive association [12]. We did not observe any associations between FFM and energy expenditure. Of note, our sample size was reasonably homogeneous as we only included participants with a BMI between 19.5 and 25.8 kg/m².

Lipid oxidation was higher in the morning during drift compared to fixed. No differences in either lipid or carbohydrate oxidation during the afternoon between the two sessions were observed. This is in line with previous studies, which have shown that mild cold increase fat oxidation [46], whereas carbohydrate oxidation either stays the same [47] or decreases [32, 48]. The higher lipid oxidation accompanied by the higher BP values observed in the morning compared to the afternoon of the present study indicate that likely the ramp up in the morning induced typical cold exposure responses.

4.2. Subjective and mixed responses

Many existing studies focussed on thermal sensation and comfort in response to step changes [49,50,51]. Only a few studies have previously looked into thermal sensation and comfort in a drifting setting [21,52]. During the moderate temperature drift, thermal sensation followed the ambient temperature profile. Our results indicate that during the day, participants felt on average just slightly cool during the fixed session. This is contrary to what has been previously reported in neutral fixed environments where participants wore similar clothing to the ones in the present study [21,53]. However, these previous studies have used higher neutral temperatures ($T_{\text{fixed}} = 21.5$ and 25.8–27.1°C) than the temperature used here ($T_{\text{fixed-measured}} = 20.10 \pm 0.33$°C). Interestingly, there was a decrease in both thermal sensation and comfort mid-day.

Fig. 8. (continued).
during the fixed session and at the same time participants also indicated they preferred a slightly warmer thermal environment. It is unclear what caused that decline, but one probable explanation is a pre-lunch dip, as participants filled in the questionnaire just before receiving their lunch. As mentioned previously, overall, participants felt comfortable during both fixed and drift sessions (EMS: $M_{\text{fixed-morning}} = 0.71 \pm 0.11$; $M_{\text{drift-morning}} = 0.45 \pm 0.11$; $M_{\text{fixed-afternoon}} = 0.37 \pm 0.13$; $M_{\text{drift-afternoon}} = 0.52 \pm 0.11$). Although there were some time-dependent differences in

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**Fig. 9.** Associations of skin temperature sites with whole-body thermal sensation (a), thermal comfort (b), votes. Spearman’s correlation is denoted with $r_{\text{Spearman}}$. Negative associations are shown with a solid fill. Note: *, **, *** indicate $P < 0.05$, $P < 0.01$ and $P < 0.001$, respectively. $N = 16$. 

thermal sensation between the two protocols as indicated in Fig. 8b, these differences are relatively small and the votes generally remained on the ‘comfortable’ side of the comfort scale. Interestingly, during some periods of the day the drifting session was perceived as more comfortable than the fixed (for example at t = 270 and t = 300). Furthermore, though there was a large interindividual variation in both thermal sensation and comfort votes, during the drift session, the majority of participants felt comfortable over a wider range of sensation votes as indicated in Fig. 6c. Although the individual responses vary, on a group level this implies that relaxing the thermal environment in buildings will not necessarily lead to thermal discomfort as commonly believed. Finally, it is important to note that the present study cannot discriminate between differences in thermal comfort attributed to the temperature level and the ones due to the constant change in temperature. The latter is referred to as ‘thermal alliesthesia’. This phenomenon explains why a cold stimulus can be perceived as pleasant by someone who feels warm, and why a warm stimulus can be perceived as pleasant by someone who feels cold [54].

In the present study, a negative association was found between underarm-finger gradient and both thermal sensation and comfort. This meant that warmer fingers were associated with feeling warm and comfortable. Although exploring cooler environmental conditions in the present study, our findings are in accordance with previous research [52,53], Schellen et al. [21], who studied environmental conditions similar to the ones presented in this paper (T_{fixed} in our study was ~21°C vs 21.5°C in Schellen et al. [21]), also observed similar results for thermal comfort, but not for thermal sensation. The differences in study population between the two studies could potentially explain the observed findings. Mean as well as proximal skin temperature were significantly associated with both thermal sensation and comfort, as has previously been shown [21,52]. In summary, underarm-finger gradient, finger, mean and proximal skin temperatures can potentially be used as factors relating to both thermal sensation and comfort.

From all the temperature sites studied, the shoulder was the most strongly associated with thermal sensation, followed by mean skin and finger temperature. In Jacquot et al. [52], the shoulder was also strongly associated with thermal sensation. Generally, in the present study the proximal regions (chest, supraclavicular, shoulder) were more strongly associated with thermal comfort compared to distant regions (foot, calf). Similar responses have been recorded previously in the literature [55]. It is important to point out that the purpose of this analysis is not to predict thermal sensation, as there already exist a number of models, ranging from simple to complex, aimed at predicting thermoregulatory responses. Rather, the analyses were aimed at determining potential skin sites that can contribute to thermal sensation and comfort. Such information can be used by building scientists and engineers who are especially interested in ways of improving whole-body thermal comfort by selectively heating or cooling individual body parts, e.g. by personal comfort systems.

4.3. Study limitations

The study outlined here was conducted in a well-controlled laboratory setting. The advantage is that we were able to monitor the effects of the drifting temperature accurately. However, due to technical difficulties, we were not able to measure airflow in the respiration chamber or to control RH, and thus RH was allowed to vary with changes in ambient temperature. Thus, the change in RH could have influenced our findings. However, by using the Standard Effective Temperature (SET) tool of Berkley (https://comfort.cbe.berkeley.edu/) we were able to estimate the SET changes in response to the changing RH in the respiration chamber. The SET changes with ~0.1°C when changing the RH from 50% to 60% or from 50% to 40%, which covers the range of measured RH in this study. Thus, the experienced temperature was not substantially influenced by the RH variation reported in the present paper.

4.4. Conclusions and future perspective

In this study, the influence of a moderate temperature drift on thermal physiology and subjective responses was studied. The following main points can be concluded from the study: (1) the imposed mild temperature drift influences thermoregulatory and cardiovascular capacities as indicated by changes in skin temperature and BP; (2) energy expenditure was significantly higher during drift in the morning compared to the fixed session; this was accompanied by an increased physical activity; (3) participants felt comfortable in both fixed and drift sessions, which is in line with previous studies; during drift, at some occasions during the day, participants also had higher thermal comfort votes compared to the fixed session; (4) ~80% of participants felt thermally comfortable over a wider range of sensation votes during drifting compared to fixed temperature; (5) significant associations were found between thermal sensation and multiple skin sites. A positive association was found between the finger temperature and thermal sensation and a negative association was found between the underarm-finger gradient and thermal sensation. This is in line with previous research.

The present study evaluated the effects of an acute exposure to a mild temperature drift and it is likely that the long-term effects might be different than the ones presented in this paper. Thermal comfort has not yet been studied over the course of multiple days, and thus, a study evaluating the effects of drifting temperature profile on subjective responses over the course of a few days would provide an insight on how thermal comfort and sensation change in response to a dynamic environment in the long term. In this study, we observed differences in energy expenditure between the two sessions in the morning only, and although those differences can be attributed to higher physical activity, in the long run, this can lead to a substantial amount of energy expanded. Finally, it is important to note that while we studied a standardized temperature ramp between 17°C and 25°C, the observed changes in thermal physiology as indicated by the changes in skin temperatures will most likely hold even with a milder temperature ramp. Thus, allowing for more variation in the indoor environment can improve thermoregulatory responses and human health without compromising thermal comfort of office occupants. More long-term studies with possibly larger temperature ranges would be needed to further evaluate the metabolic effects of the dynamic thermal environment presented here. Additionally, field studies are needed to verify the results under less stringent indoor conditions.

Declaration of Competing Interest

None.

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Supplementary materials

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