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Human thermal comfort under dynamic conditions: An experimental study

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ABSTRACT

Although thermal comfort has been a research topic since the 1960s, some knowledge gaps still affect understanding of the human response to changing thermal environments. To enhance knowledge in this regard, an exploratory study is presented, which aims to understand human response to monotonic thermal variations by describing its relationship with covariates of interest. Thirty-eight participants (29 females, 9 males) worked in an office-like climate chamber and were exposed to dynamic and controlled heating and cooling ramps of the operative temperature with different speeds. Participants' perception, evaluation, preference and acceptability of the indoor thermal environment were recorded by filling in dedicated questionnaires. Additionally, participants could indicate when an uncomfortable event occurred during these temperature ramps by clicking a digital button on a dedicated app. This discomfort event was defined in behavioural terms as the decision to "take action to restore a comfort condition". Survival analysis was used to study participants' reactions to the dynamic thermal stimuli. It showed that two distinct mechanisms caused discomfort events due to overheating and undercooling: warm discomfort is driven by the absolute value of the achieved operative temperature, while the relative change in operative temperature mainly causes cold discomfort. Compared to the current recommendations regarding temperature cycles, drifts and ramps, this result shows that current standard recommendations underestimate the risk of thermal discomfort during a cooling process while overestimating it during a heating one. The new knowledge of human reaction to a dynamic thermal environment can lead to more energy-efficient and satisfactory building control strategies.

1. Introduction

Thermal comfort is a consolidated research subject, first incorporated into standardisation in 1966 [1]. After that, standardisation bodies produced standards dedicated to thermal comfort in moderate and severe thermal environments and indoor environmental quality. Nowadays, all thermal comfort standards include definitions of the requirements for indoor thermal conditions in buildings both for design and operational assessment. However, current standards only indicate the maximum variations in operative temperature for non-steady-state thermal environments. ASHRAE 55-2017 [2] and ISO 7730-2005 [3] classify temperature variations as either temperature drifts and ramps or temperature cycles. Drifts and ramps are defined as "monotonic, non-cyclic changes in operative temperature" [2], and their limits during a period are shown in Table 1. Drifts refer to passive temperature changes in an enclosed space, while ramps denote actively controlled ones. In contrast, cycles refer to "those situations where the operative temperature repeatedly rises and falls, and the period of these variations is not greater than 15 min" [2]. For these changes, ASHRAE 55 allows a maximum peak-to-peak cyclic variation in operative temperature of 1.1 K and recommends treating cyclic variations with a period greater than 15 min as drifts or ramps.

ISO 7730-2005 [3] provides less detailed indications. For temperature cycles, it sets a maximum peak-to-peak variation of 1 K, whereas, for drifts and ramps with a rate of change lower than 2.0 K/h, it prescribes steady-state methods. These standards also include step-changes, which involve changing the environment (i.e., moving to/from another space) rather than a change within the environment. Consequently, they are not described here because out of the scope of this study.

The limiting criteria in Table 1 are probably based on early laboratory studies of thermal comfort under transient exposure [4–6]. During the same period (the 1970s and 1980s), other studies were conducted on both cyclical [7,8] and monotonic temperature variations [9–13]. Hensen [14] reviewed these studies meticulously and found inconsistent

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Table 1
Limits on temperature drifts and ramps by ASHRAE 55-2017 [2].

Time period (h)	Maximum operative temperature to change allowed (K)
0.25	1.1
0.5	1.7
1	2.2
2	2.8
4	3.3

results. He offered several possible explanations for these dissimilarities, including the different voting scales and acceptability criteria and the distinct experimental conditions, among others. Despite these discrepancies, Hensen argued that the experimental results support a 2.2 K/h constraint for cyclical variations in operative temperature. As no evidence had been found to the contrary, he also concluded that this limit could also apply to temperature drifts and ramps. Since this review, only a handful of studies have been conducted on cyclical [15–17] and monotonic variations [18]. Under cyclical variations, these recent studies indicate a positive effect on occupants' thermal comfort. In contrast, for monotonic variations, different rates of temperature change result in inconsistent effects. As mentioned earlier, different acceptability criteria and voting scales could plausibly be a main source of the discrepant findings. Another factor that might be responsible for these differences involves human thermal perception and thermoregulation, described in the following sections.

1.1. *Thermal perception and thermoregulation*

The skin, the largest organ in the human body, is an interface that separates the body from the rest of the world. On a daily basis, its surface processes at least hundreds of physical sensations, among them environmental thermal stimuli. These stimuli are detected by the free nerve endings of the primary sensory neurons in the skin. These neurones, located in the dorsal root ganglia, convert the external stimuli into electrical signals that are then transmitted to second-order neurons (namely dorsal horn neurons), which are located in the spinal cord [19]. At this first relay centre, thermal information is further processed before being sent to the brain.

In neurophysiology, significant progress has been made in identifying primary sensory neurons' thermal response profiles [19–21]. Researchers have ascertained that the principal detectors of the thermal stimuli in the peripheral nervous system are the ion channels of the transient receptor potential (TRP) family [19]. These thermosensitive TRPs are triggered at specific threshold temperatures and function as dedicated transducers of distinct thermal modes. Among them, TRPV1 and TRPM8 are the primary sensors of hot and cold temperatures, respectively. Conversely, the understanding of spinal cord temperature encoding remained limited until recently, when Ran et al. [22] showed that the representation of heat and cold in the dorsal horn is substantially different from the operation of TRPs. They observed that heat-responding neurons are activated gradually with incremental increases in temperature, where higher temperatures activate more neurons. Therefore, higher absolute temperatures induce stronger neuron responses. Furthermore, if a steady heat stimulus persists, these neurons are not able to adapt and thus persistently respond to it. These results combined suggest that heat-responding spinal neurons encode the absolute temperature. Conversely, cold-responding neurons' reaction reaches its highest point during the cooling phase but rapidly adapts to steady cold stimuli. This behaviour allows these neurons to signal changes over a wide range of environmental temperatures. Therefore, they communicate a relative drop in absolute skin temperature rather than absolute skin temperature. As a result, from a neurophysiological point of view [22], the response to heat (i.e., an increase in temperature) in the spinal cord is encoded in absolute terms (i.e., a certain temperature level), whereas the response to cold (i.e., a decrease in temperature) is coded in relative terms (i.e., a certain temperature difference).

1.2. *Thermal alliesthesia*

Skin receptors (thermoreceptors), although ideal for sensing changes in the environmental temperature, do not perform well in detecting increases in core temperature, for example, during exercise. This is because the body's internal temperature would increase to an unbearably high level before the skin thermoreceptors could detect it. Not surprisingly, the body is provided with other temperature-sensitive neurons, located throughout the body core (e.g., in the liver, kidneys, and stomach) and in the brain (i.e., the preoptic hypothalamus), that play a major role in detecting changes in deep-body temperature. Nevertheless, given the body's thermal inertia, these neurons are not suitable for detecting changes in the environment. The lag time of using body core temperature-sensitive neurons would be too large to perform effective regulation. Therefore, if the body's core temperature falls within the thermoneutral zone (TNZ), peripheral inputs play the most significant role in thermoregulation. Inside the TNZ, body temperature regulation is accomplished only through the control of sensible heat loss [23] and therefore involves only autonomic thermoregulatory mechanisms. Anticipating this line of reasoning, Marks and Gonzales [24] predicted "that pleasantness and unpleasantness of thermal stimuli depend on the temperature of the skin before stimulation – which itself reflects environmental conditions – given constant internal body temperatures". Only after 40 years, Parkinson and De Dear [25] formalised this concept as "spatial alliesthesia", where the term alliesthesia, first introduced by Cabanac, is "the property of a given stimulus to arouse pleasure or displeasure according to the internal state of the subject" [26]. In spatial alliesthesia in particular, the perceptual changes are detected by cutaneous thermoreceptors, not the body core, which drive pleasure sensations. This notion becomes more relevant when considering that thermal behaviour is driven by thermal comfort [27] and is regarded as the primary influencing factor in body temperature homeostasis [28]. Also, it is essential to notice that the indoor environment's transient conditions are commonly within the TNZ, where the influence of thermal behaviour is omitted. Kingma et al. [29] analysed the relationship between the TNZ and the thermal comfort zone (TCZ). They concluded that the ambient temperature associated with the thermoneutral zone is greater than that of thermal comfort. This finding implies that thermal behaviour could be initiated even before the thermoneutral zone boundaries are reached. In terms of spatial alliesthesia, negative alliesthesia (i.e., thermal displeasure) can be viewed as thermal discomfort [25], which in turn prompts human beings to counter the thermal environment accordingly.

Following this logic, Vellei and Le Dréau [30] proposed a modified version of Fanger's predicted percentage of dissatisfied (PPD) index that considers both a static and a dynamic component. The former is based on thermal sensation derived from the predicted mean vote (PMV), while the latter includes thermal alliesthesia and thermal habituation/adaptation. Utilising the data from Zhang's experiment on cyclical temperature variations induced by demand response events [16], the authors showed the impact of these psycho-physiological phenomena on dynamic thermal perception.

1.3. *Research aims*

Despite the existence of previous studies on temperature cycles, drifts and ramps, their inconsistent results limit the knowledge of dynamic thermal comfort limits. Regarding the processes driving dynamic thermal perception in temperature cycles, the previously mentioned study by Vellei and Le Dréau is noteworthy. However, the dynamics of temperature cycles differ from the dynamics of temperature drifts and ramps. The latter, being monotonic changes, do not have the same stimulus repeated over time. Furthermore, this study has some potential issues related to the use of different scales to assess satisfaction. In

Zhang's experiment, the percentage of dissatisfied is calculated from actual observed data, measured using a binary acceptability scale. In contrast, Fanger's PPD index is inferred from the 7-point ASHRAE thermal sensation scale (assumed to be ≥ 2 or ≤ -2; see page 130 of [31]). Therefore, there is a problem with the semantic equivalence of these scales. In truth, this is a problem that extends to other psychometric scales (e.g., thermal comfort and thermal preference), and that the thermal comfort research community has yet to address adequately.

The present research is an exploratory study whose goal is to understand human reaction to monotonic thermal variations by describing the relationship between their response and the covariates of interest. Therefore, the emphasis of this work is to derive some insight into the relationships that exist rather than to test hypotheses that certain relationships hold. This is achieved through a laboratory experiment with "office-like subjects", simulating office settings in a ramp-induced thermal environment. In this configuration, the relationship between environmental and demographic factors (with their potential interactions) to participants' thermal discomfort event was analysed. We considered the actual thermal behaviour as the thermal comfort limit, that is, the action prompt from the discomfort event. By doing so, we avoid the issue of semantic equivalence between different psychometric scales. Nevertheless, participants' perception, evaluation, preference and acceptability of the environment were collected.

2. Methods

2.1. Participants

Participants were recruited from the university campus with a targeted age between 20 and 67. A summary of the main demographic and anthropometric characteristics of the subjects is listed in Table 2. Participation in the experiment was voluntary, and participants were informed about the possibility of withdrawing their consent at any time, without giving a reason in agreement with the principles and instructions of the European General Data Protection Regulation (GDPR). A printed information letter was distributed, and the participants signed a consent form prior to participation. The letter included information on data protection measures and general information about questionnaires and measurements. However, it did not inform the subjects about specific changes in environmental variables, such as changes in temperature. To comply with the GDPR, the experiment description was submitted to the Norwegian Centre for Research Data (NSD) and approved with reference code 525790.

2.2. Experimental set-up

The experiment was conducted in the ZEB Test Cell Laboratory on the Norwegian University of Science and Technology (NTNU) premises (Trondheim campus) between September 2019 and January 2020 (see Appendix A for a summary of the outdoor climatic conditions). Two identical climatic chambers (2.4 m × 4.2 m x 3.3 m in height, surrounded by two guard rooms kept at 22 °C) (Fig. 1), furnished like a typical single office, were used to recreate a change in the environment induced by thermal ramps. Space heating and cooling were provided from a constant air-volume system that supplied 100% fresh air from outside, distributed by a 2 m long perforated fabric tube installed at the ceiling. The temperature of the supplied air was controlled through a PID controller (implemented in LabVIEW) utilising a Class A Pt100 temperature sensor located in the extraction air duct. Chamber's walls, ceiling, and floor consist of prefabricated sandwich panels with a low thermal mass; therefore, the surface temperatures almost instantly follow the air temperature. The climatic chambers were illuminated with office pendant and task lighting, as well as natural lighting through a south-facing window with a window-to-wall ratio of 0.56. The shading configuration was composed of 13 louvres tilted at 15° mounted on the external side of the window. Further details on the facility's experimental equipment, as well as the properties of the ZEB laboratory, can be found in Goia et al. [32].

During the experiments, the indoor environment was monitored by measuring air temperatures (at 0.10, 0.60 and 1.10 m), surface temperatures (five on the two side walls, three on the floor and the ceiling, four on the window and one above the door), globe temperature (at 1.70 m), relative humidity (at 1.75 m), airspeed (at 0.10, 0.60, 1.10 and 1.70 m), CO_2 concentration (at 1.75 m), horizontal and vertical illuminance (on the work-plane and at eye levels, respectively) every minute throughout every session. In addition, a weather station installed in proximity to the southern façade of the ZEB Test Cell measured ambient air temperature, relative humidity, wind speed and direction, global solar irradiance on the horizontal plane and precipitation in 10-min intervals. The accuracy of the sensors used, both for indoor and outdoor measurements, are shown in Table 3.

2.3. Experimental conditions and procedure

The operative temperature set-point of 22.0 ± 1.0 °C was defined in accordance with the thermal comfort limit for winter according to Category A of ISO 7730-2005 [3]. Both space heating and cooling variations were tested within winter conditions. The rates of temperature changes were derived from the limit in ASHRAE 55-2017 (Table 1) [2]. Given the limit of 3 h for each experimental session (Fig. 2) and compatible with a typical office occupancy schedule, only the following thermal ramps were implemented: (i) ±4.4 K/h, (ii) ±3.4 K/h, (iii) ± 2.2 K/h and (iv) ±1.4 K/h.

The study's design was a randomised crossover trial; a longitudinal study in which participants received a randomised sequence of different exposure (i.e., thermal ramps). The schematic of the experimental session, illustrated in Fig. 2, was composed of seven and a half hours with a half-hour lunch break included (as a typical standard Norwegian workday). To increase participation, the day could be split into half days, meaning one morning session (8:00–11:30) and one afternoon session (12:00–15:30). However, participants were required to attend an even number of morning and afternoon sessions. Subjects could choose to join the experiment for two or four days and were offered compensation, upon completion of the agreed days, of 200 or 600 NOK, respectively. In addition, a lottery was set up: one lucky participant, selected from among those who successfully completed the agreed-upon days, received an Apple iPad.

After arrival, participants were asked to take a seat at the workplace assigned beforehand by the researchers. At this time, they were asked to fill out a first questionnaire consisting of questions related to demographic and anthropometric characteristics, current clothing level and satisfaction with the workplace (q1 in Fig. 2). During the first 30

Table 2
Demographic and anthropometric characteristics of participants.

Gender	Number	Age (year)	Height (cm)	Weight (kg)	BMI (kg/m^2)
		Median (IQR*)	Median (IQR*)	Median (IQR*)	Median (IQR*)
Male	9	28.0 (30.0–25.0)	174.0 (184.0–170.0)	70.0 (85.0–67.0)	24.2 (26.3–22.1)
Female	29	26.0 (31.0–22.0)	170.0 (172.0–165.0)	63.0 (70.0–53.0)	21.6 (23.4–20.7)
Total	38	26.5 (30.8–23.0)	170.5 (173.0–165.0)	65.0 (70.0–58.3)	21.8 (24.2. – 20.8)

*IQR is the interquartile range, that is, the difference between upper and lower quartiles.

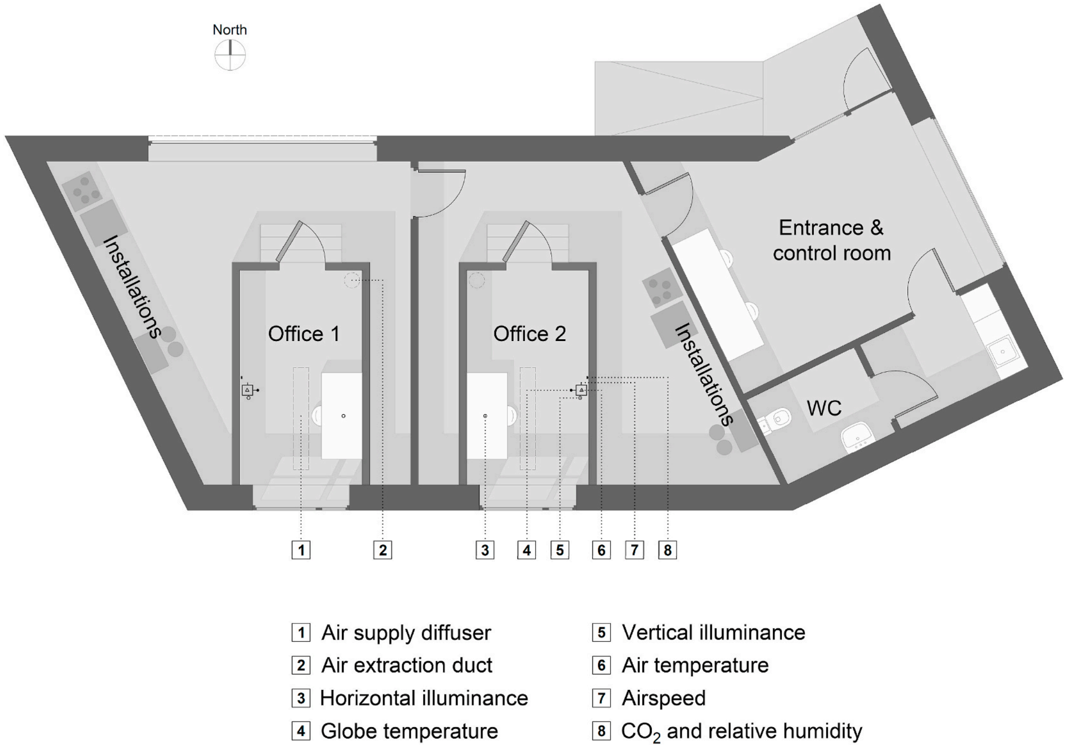

Fig. 1. Floor plan of the facility.

Table 3
Characteristics of the sensors for the measurement of indoor and outdoor conditions.

Physical variable	Type of sensor	Accuracy
Indoor		
Air temperature	Pt100	±0.3 °C
Surface temperature	T-type thermocouple	±0.5 °C
Globe temperature	Pt100	±0.3 °C
Relative humidity	Capacitive	±5%
Airspeed	Hot wire	0 ÷ 0.1 m/s = NA 0.1 ÷ 0.5 m/s = ±0.083 m/s 0.5 ÷ 1 m/s = ±(0.05 + 0.05 va*) m/s >1 m/s = ±(0.1 + 0.05 va*) m/s
CO2 concentration	Non-dispersive infrared	±70 ppm +5 $\%_{measured}$
Horizontal illuminance	Photodiode	±5%
Vertical illuminance	Photodiode	±3%
Outdoor		
Air temperature	Pt100**	±0.1 °C
Relative humidity	Capacitive**	±1.5%
Wind speed	N.32 step optoelectronic disk	0 ÷ 3 m/s = 1.5% >3 m/s = 1%
Wind direction	See above	1%
Global solar irradiance	Thermopile pyranometer	10%
Precipitation	Tipping bucket***	0 ÷ 20 mm/h = ± 0.2 mm 20 ÷ 240 mm/h = 1%

*va is mean airspeed.
**Thermohygrometer with multi-plate natural ventilation radiant screen.
***Rain gauge equipped with heater and siphon.

min, participants acclimatised to the constant set-point temperature and were free to adjust their clothing ensemble. After this period, the experimental session started. At this time, the subjects were instructed to report the final clothing level (i.e., if any change in the initial clothing level occurred during the acclimation period) and to maintain the adopted garment level throughout the experimental session. Furthermore, participants were not allowed to interact with the environment (e.g., open the window/door, regulate the thermostat). However, due to the long sessions, participants were allowed to stand up and move around the climate chamber, leave it for a short period (to visit the restroom), and consume refreshments. No specific tasks or tests were carried out during the experiment, and participants were asked to carry out their typical office activity. This contributed to the simulation of a typical office activity pattern. Nevertheless, subjects had to fill out computer-based questionnaires at different scheduled intervals (q2 in Fig. 2). By means of graphic categorical scales, these questionnaires were used to assess perception, evaluation, preference, and acceptability of the thermal, visual, acoustic and air quality of the environment. These scales, derived from the standard ISO 10551-2019 [33], are shown in Appendix B.

During the experimental session, the participants were instructed to press a digital button (available on a dedicated laptop situated on the desk, see Fig. 3) as soon as they felt uncomfortable. Here uncomfortable was defined as the decision to "take action to restore a comfort condition" (e.g., if the environment is too warm, then regulate the thermostat or open the window). It is important to point out that participants could press the button for any source of discomfort related to the indoor environment (e.g., stuffy air, noise from the ventilation system, lack of daylight) and not only for temperature-related discomfort. After pressing the digital button, a computer-based questionnaire appeared on the dedicated laptop (q3 in Fig. 2). This questionnaire was used to assess the environment (in the same manner as q2) and record the source(s) of discomfort through multiple-choice answers (shown in Appendix C). Participants were also requested to rank, from 1 to 3 (with one being the most important), the strategies (among a predefined set of listed options) that they would use to restore comfort. These strategies varied from simple actions (such as adding/removing a clothing layer and opening/closing the window) to more complex ones (such as adjusting the cooling/heating set-point temperature and plugging-in a local/personal cooler/heater).

The thermal ramp was interrupted when one of the two following conditions was met: (i) the session ended (i.e., at 11:30 and 15:30); (ii)

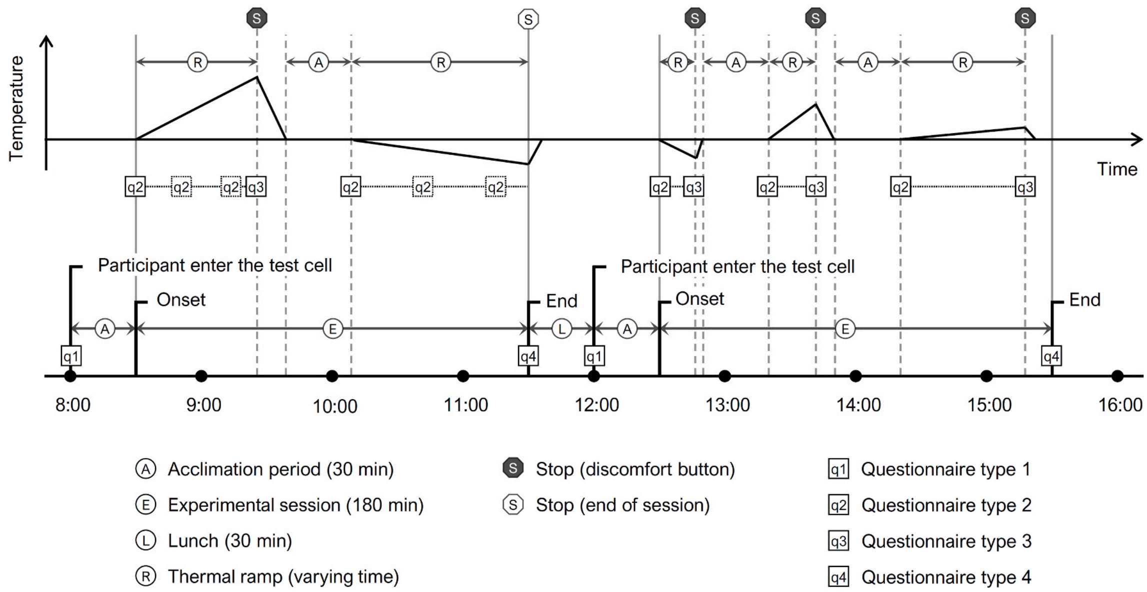

Fig. 2. Schematic of the experimental procedure (bottom) with an example of a possible scenario (top).

Fig. 3. View of the workstation in one of the two single offices.

the participant pressed the digital button. In the latter case, the thermal ramp was stopped only if the discomfort event was related to the temperature level, that is, the participant selected “temperature too high” or “temperature too low”. At the end of every session, subjects were asked to fill out a questionnaire (q4 in Fig. 2) about their satisfaction with the workplace as a whole, expressed on a Likert scale.

3. Statistical analysis

Environmental, demographic and anthropometric data were studied using a survival analysis. Survival analysis comprises a family of methods that examine and model the time it takes for events to occur. However, its goal is not limited to investigating the effects on the time until the event occurs, but also to evaluate the relationship of survival time to covariates. Covariates (often referred to interchangeably as predictors or independent/explanatory variables) assess the impact of certain features on the dependent variable.

The prototype event is death – hence the name “survival analysis” and much of its terminology – but the range of applications of survival analysis is much broader. For example, the same methods are known as “failure-time analysis” in engineering and “event-history analysis” in sociology.

3.1. Survival analysis

In survival analysis, there are two crucial quantities that need to be introduced, namely the survivor function, denoted by $S(t)$, and the hazard function, denoted by $\lambda(t)$. Let T be a non-negative random variable representing the waiting time until the occurrence of an event. The survival function $S(t)$ can be written as the probability that the random variable T is larger than a specified time t, that is

$$S(t) = \Pr(T \geq t) \quad \text{Eq. (1)}$$

More generally, it is the probability that the event of interest has not occurred by duration t.

An alternative characterisation of the distribution of T is given by the hazard function, defined as

$$\lambda(t) = \lim_{dt \to 0} \frac{\Pr(t \leq T < t + dt | T \geq t)}{dt} \quad \text{Eq. (2)}$$

which gives the instantaneous rate of occurrence of the event at time t, given survival up to time t.

The two functions in Eq. (1) and Eq. (2) express, in essence, opposing concepts: while the survivor function focuses on surviving, the hazard function focuses on failing, given survival up to a certain point in time. Moreover, there is a clear relationship between these two quantities. Knowing the form of $S(t)$, the corresponding $\lambda(t)$ can be derived, and vice versa. More generally, this relationship can be expressed equivalently in either of the two formulae:

$$S(t) = \exp\left(- \int_0^t \lambda(u) du \right) \quad \text{Eq. (3)}$$

$$\lambda(t) = - \frac{d}{dt} \log S(t) \quad \text{Eq. (4)}$$

The integral in the round brackets in Eq. (3) is called the cumulative hazard (or cumulative risk) and is denoted as

$$\Lambda(t) = \int_0^t \lambda(u) du \quad \text{Eq. (5)}$$

Furthermore, censoring and its assumptions need to be mentioned as well. Censoring is a form of missing data problem in which the time-to-event is not observed. Therefore, there is only partial information about individual survival time. There are three different types of censoring, as graphically illustrated in Fig. 4:

- Left-censored: the event occurs between t_{start} and t_3, but the exact time is unknown.
- Interval-censored: the event occurs within t_1 and t_4, a specified time interval, but the exact time is unknown.
- Right-censored: the event does not occur before the end of the study, t_{end}.

There are three assumptions about censoring for survival data: independent censoring, random censoring, and non-informative censoring. These assumptions, even though they have similarities, are different and should not be used interchangeably. Among the three, independent censoring is the most relevant since it affects validity.[1] Many of the analytical techniques discussed in the next paragraph rely on this assumption for valid inference in the presence of right-censored data. For mathematical definitions of these three assumptions, the reader is referred to Kalbfleisch and Prentice [34] and Klein and Moeschberger [35], and for more intuitive definitions and examples to Kleinbaum and Klein [36].

As mentioned before, survival analysis is the name for a collection of statistical techniques. These techniques can be summarised into three categories: (i) non-parametric models, (ii) parametric models, and (iii) semi-parametric models. The main difference between the three categories is whether the outcome, namely the survival time, is assumed to follow a specific distribution. Non-parametric methods are used when no theoretical distribution adequately fits the data; therefore, they are distribution free. The Kaplan-Meier method is an example from this category. Conversely, in the parametric model, the underlying distribution of the outcome is specified. Typical examples of parametric models in a regression-type framework are linear regression, logistic regression, and Poisson regression. The outcome is assumed to follow some distribution with these models, such as the normal, binomial, or Poisson distribution. For survival analysis, several parametric distributions can be used to describe time to event data, such as exponential, Weibull and log-normal distribution, each of which is defined by a different hazard function. Semi-parametric models are a combination of the two previously mentioned categories. Even if the regression parameters (the betas) are known in these models, the outcome's distribution remains unknown. The Cox proportional hazards (PH) model belongs to this category.

In this investigation, since the outcome distribution (i.e., the survival time distribution) is unknown, non-parametric and semi-parametric models were utilised, more specifically, the Kaplan-Meier method and Cox regression. The former has been used in this study only to describe and visualise the survival curves at a preliminary stage, while the latter evaluates the relationship of survival time to covariates.

3.1.1. Kaplan-Meier method

The Kaplan-Meier (KM) estimator of a survival function at time t, $\widehat{S}(t)$, is given by [37].

$$\widehat{S}(t) = \prod_{i:\ t_i \leq t} \left(1 - \frac{d_i}{n_i} \right) \quad \text{Eq. (6)}$$

where d_i is the number of events at time t_i and n_i is the number at risk at time t_i. This method is based on individual survival times and assumes independence between censoring and survival, that is, the reason an observation is censored is unrelated to the cause of failure. From Eq. (6), it can be seen that Kaplan-Meier requires a minimal feature set. Kaplan-Meier only needs the time when the event (or censorship) occurred and the duration between the onset and the event. Also, as mentioned before, it is distribution-free. However, it cannot estimate the magnitude of the survival-predictor relationship of interest, nor control for multiple covariates. Therefore, it has been used only to describe and visualise the survival curves at a preliminary stage.

3.1.2. Cox proportional hazards model

The Cox proportional hazards (PH) model is the most used procedure for modelling covariates' relationship to survival or other censored outcomes. It is mainly popular because it does not require any assumptions about the shape of the hazard function (that is, the specific way that risk changes over time); however, it allows for estimating the regression coefficients.

The Cox PH model is usually written in terms of the hazard model formula

$$\lambda(t) = \lambda_0(t) e^{X\beta} \quad \text{Eq. (7)}$$

where $\lambda_0(t)$, is an unspecified non-negative function of time called the baseline hazard, while $e^{X\beta}$, is the time-independent exponential expression that involves the covariates X.

A fundamental assumption of the Cox model is proportional hazards, which implies that the hazard ratio for any two subjects i and j is constant over time.

[1] Validity is meant as lack of bias. The presence of non-independent censoring will result in a biased estimated effect.

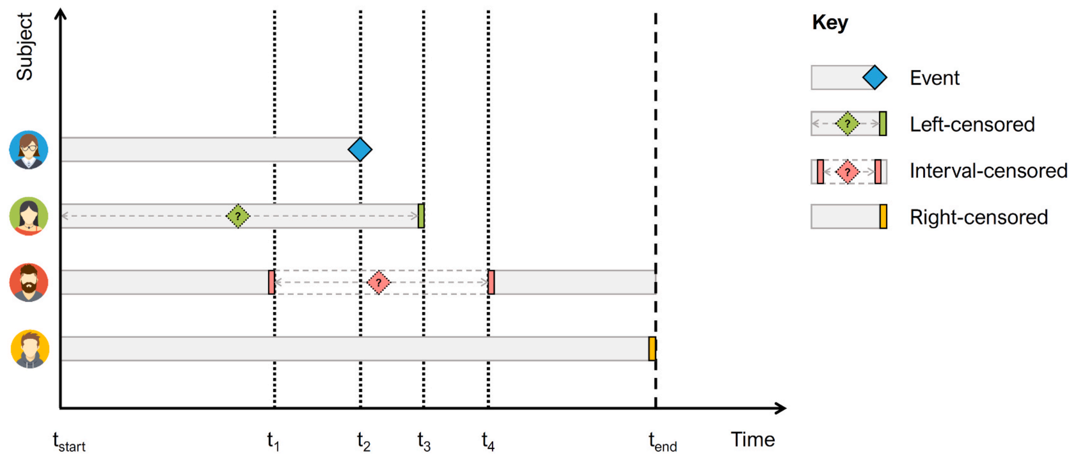

Fig. 4. Different type of censoring.

$$\frac{\lambda_0(t)e^{X_i\beta}}{\lambda_0(t)e^{X_j\beta}}=\frac{e^{X_i\beta}}{e^{X_j\beta}} \quad \text{Eq. (8)}$$

If this assumption holds, each covariate's effect can be summarised with a single number. Since in practice this assumption is never 100% confirmed (for example, this is the case for any Cox model that include time-dependent variables), there are various strategies to deal with this. Models that rely upon this strategy are called "extended Cox models" and can be generally written as

$$\lambda(t)=\lambda_0(t)e^{X(t)\beta} \quad \text{Eq. (9)}$$

$$\lambda(t)=\lambda_0(t)e^{X\beta(t)} \quad \text{Eq. (10)}$$

where Eq. (9) is a time-dependent covariate, and Eq. (10) has a time-dependent coefficient. Note that the PH assumption presumes that the coefficient does not change over time: $\beta(t) = c$.

In the literature, there is another approach called the "stratified Cox procedure", in which the variable that does not meet the PH assumption is stratified. Stratification is suitable only for categorical variables and implies different baselines for each level of the variable being stratified. It can be written as

$$\lambda_g(t)=\lambda_{0g}(t)e^{X\beta} \quad \text{Eq. (11)}$$

where g denotes the levels of the variable. Note, however, that the stratified variable is not included in the model, and it is not possible to obtain a hazard ratio value for the stratified variable adjusted for the other variables. Nevertheless, the same coefficients (the βs) are assumed for each level of the stratified variable.

The Cox model relies upon other assumptions that need to be verified, which derive from the fact that this model is a regression-type model. These assumptions state that the relationship between the covariate and the response (the logarithm of the hazard in this case) is additive and linear. The former means that the effect of changes in a covariate X_k on $\log \lambda(t)$ is independent of the values of the other covariates, while the latter states that the change in the $\log \lambda(t)$ due to a one-unit change in X_k is constant, regardless of the value of X_k. For further detail, the reader is referred to Refs. [36,38].

3.1.3. Data preparation and analysis

Data gathered during the acclimation[2] period were excluded from the data analysis. The mean radiant temperature (MRT) was calculated according to ISO 7726-1998 [39] based on the surrounding surfaces' measured temperature and the angular factor computed for a seated person in the specific climate chamber. Following the aforementioned standard, the calculated MRT was used, combined with the measured air temperature and air velocity, to calculate the operative temperature. Due to a technical problem with the air conditioning during space cooling processes, data from two female participants were excluded from the analysis. This led to a difference in the female sample size between space heating and cooling processes, from 29 to 27, respectively.

All statistical analyses were performed using R [40] with the RStudio integrated development environment (RStudio Inc., Boston, MA, USA). Survival analyses, using both the Kaplan-Meier method and Cox regression, were performed with the *survival* package [41] and the respective graphs were created with the *ggplot2* package [42] and the *survminer* package [43]. The significance level for all analyses was set at 0.05.

4. Results

The results are grouped according to (i) general results and observations, (ii) descriptive analysis from the KM method, and (iii) modelling step and results obtained from the extended Cox model.

4.1. General observations

A total of 314 thermal ramps were performed, which led to 223 thermal discomfort events. Specifically, 104 thermal discomfort events occurred during heating processes (with 155 thermal ramps), while 119 thermal discomfort events occurred during cooling processes (with 159 thermal ramps). Table 4 summarises the results for the different thermal ramps.

Fig. 5 presents a time course of the discomfort events during exposure to the different thermal ramps for both the space heating and cooling processes. In this figure, the right-censored observations are also represented (dots without the black outline). Right-censored

[2] Acclimation and acclimatisation, although etymologically indistinguishable, define two distinct processes. The former describes "adaptive changes that occur within an organism in response to experimentally induced changes in particular climatic factors" (e.g., the ambient temperature in a controlled environment). The latter denotes "adaptive changes that occur within an organism in response to changes in the natural climate" [23].

Table 4
Number of thermal discomfort events for each ramp and each process.

Ramp description	Total number of thermal ramps	Thermal ramps with a thermal discomfort event
Heating		
3.4 K/h < ramp ≤4.4 K/h	41	25
2.2 K/h < ramp ≤3.4 K/h	36	28
1.4 K/h < ramp ≤2.2 K/h	35	26
0.0 K/h < ramp ≤1.4 K/h	43	25
Cooling		
0.0 K/h > ramp ≥ −1.4 K/h	46	36
−1.4 K/h > ramp ≥ −2.2 K/h	40	34
−2.2 K/h > ramp ≥ −3.4 K/h	33	24
−3.4 K/h > ramp ≥ −4.4 K/h	40	25
Total	314	223

observations were observed when the experimental session was interrupted because the time available for the session was over – condition (i) in section 2.3. For ease of interpretation, the ASHRAE 55-2017 [2] comfort limit (dark grey X-shaped cross) and a fitted line between this limit (grey dashed line) are also plotted in Fig. 5. It can be clearly seen that the thermal discomfort events are not symmetrical. Participants were more sensitive to a cold variation than a warm one. In fact, 83% of the discomfort events for cold are within the ASHRAE comfort limit, while on the warm side, only 30% are within the comfort limit.

An overview of participants' assessment of perception, evaluation, preference, and acceptability of the thermal environment during the discomfort event is presented in Fig. 6. In this figure, participants' votes on the four previously mentioned psychometric scales are divided between heating and cooling mode. Particularly:

a) Thermal sensation: Discomfort events are not symmetric. During space heating, thermal behaviours were undertaken mostly when the environment was sensed as "warm" (+2) with ΔT up to 5 K. On the other hand, during space cooling, actions were undertaken when the environment was perceived as "slightly cool" (−1) and "cool" (−2). Here the same range of operative temperature change (−3 K) was perceived differently.
b) Thermal comfort: The distribution of discomfort events for space heating and cooling is remarkably similar. Most of the thermal behaviours were undertaken when the environment was judged to be "slightly uncomfortable" (+1) or "uncomfortable" (+2) for both space heating and cooling processes. This suggests that, indeed, thermal comfort is the driver for thermal behaviour.
c) Thermal preference: Most of the actions were undertaken with a thermal preference vote different from "without change" (0). Reasonably, a participant would initiate a thermal behaviour out of a desire for a higher or lower temperature.
d) Thermal acceptability: For both space heating and cooling processes, discomfort events follow a skewed distribution, specifically a negative skew (or left-skewed) for acceptable environments and a positive skew (or right-skewed) for unacceptable ones. Consequently, most of the actions were undertaken at the boundary between an acceptable and unacceptable environment.

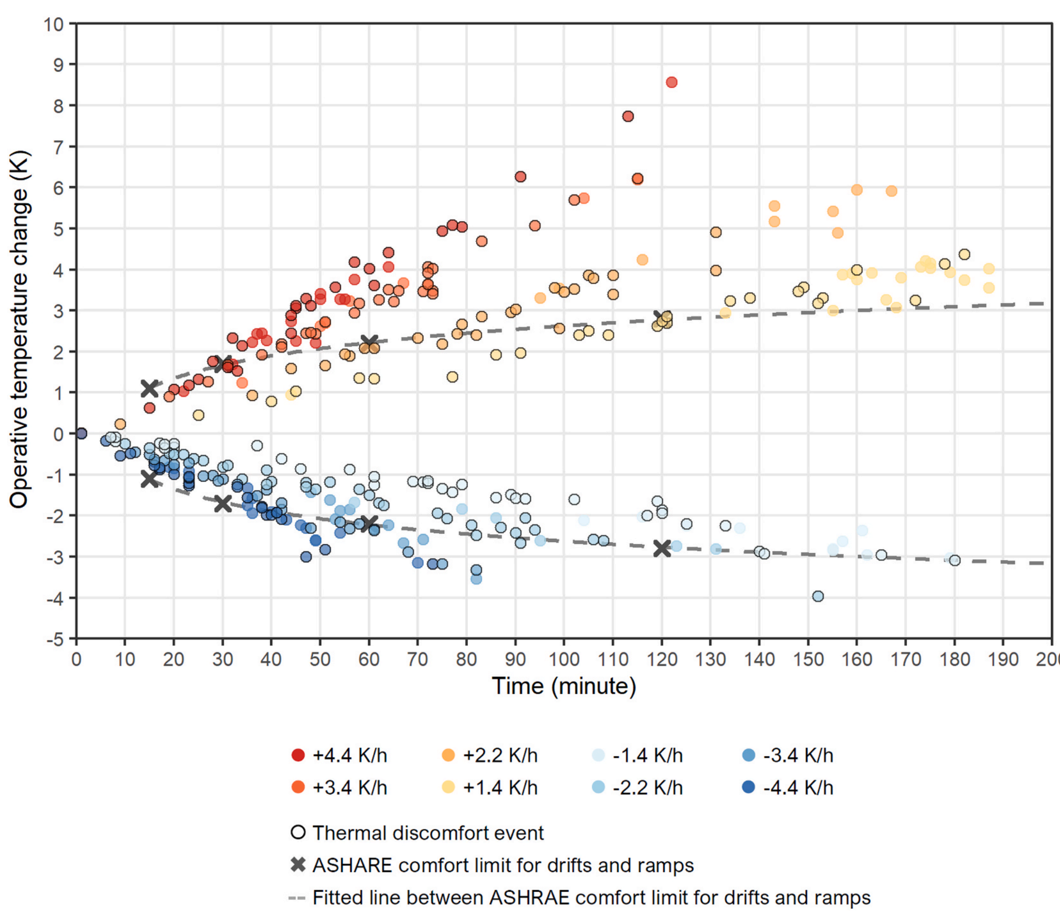

Fig. 5. Thermal ramps endpoint.

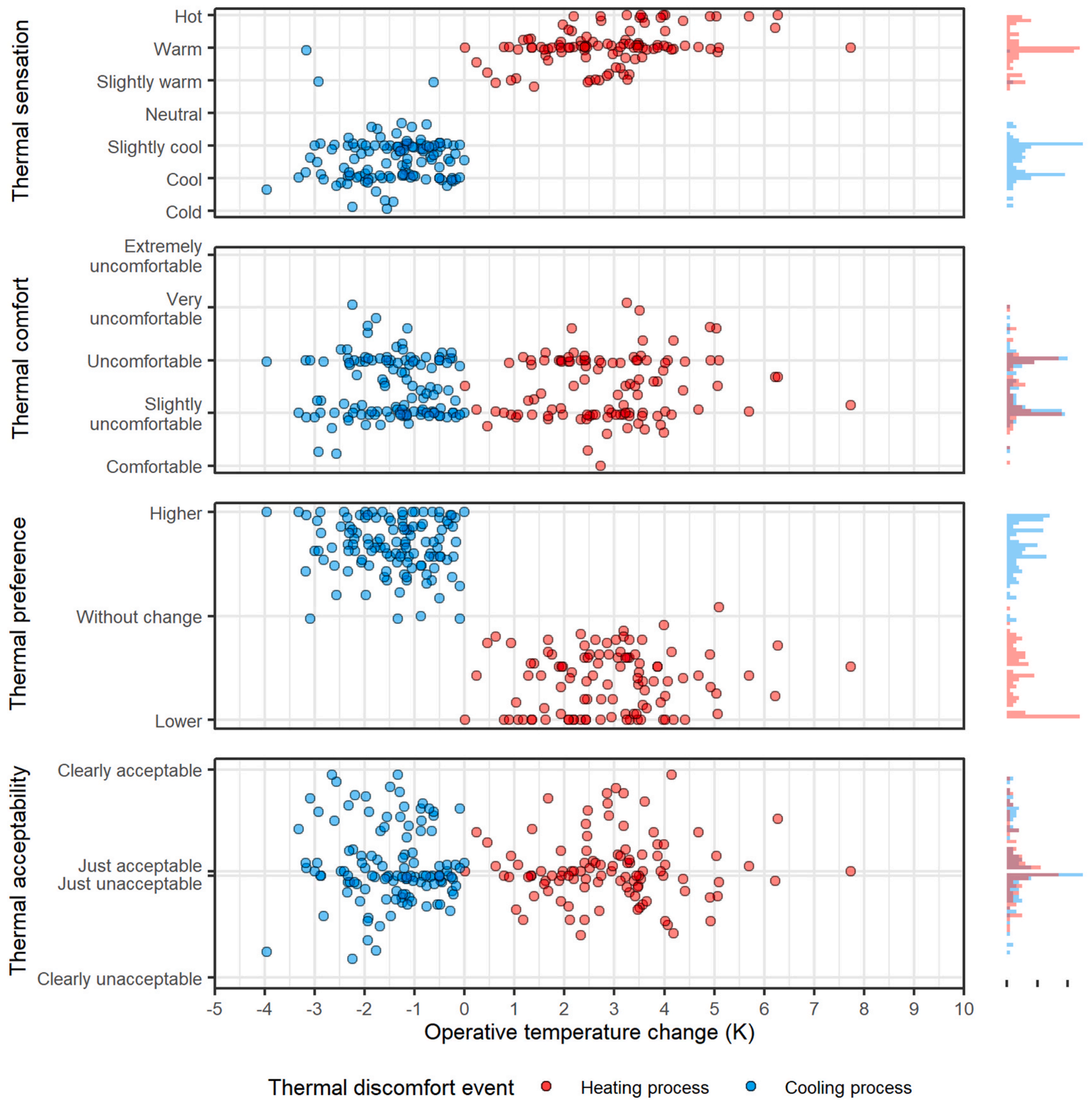

Fig. 6. Psychometric scales for thermal discomfort events. Please note that the data shown here represent the right-here right-now votes on the questionnaire at the moment of the thermal discomfort event (i.e., when the digital button was pressed).

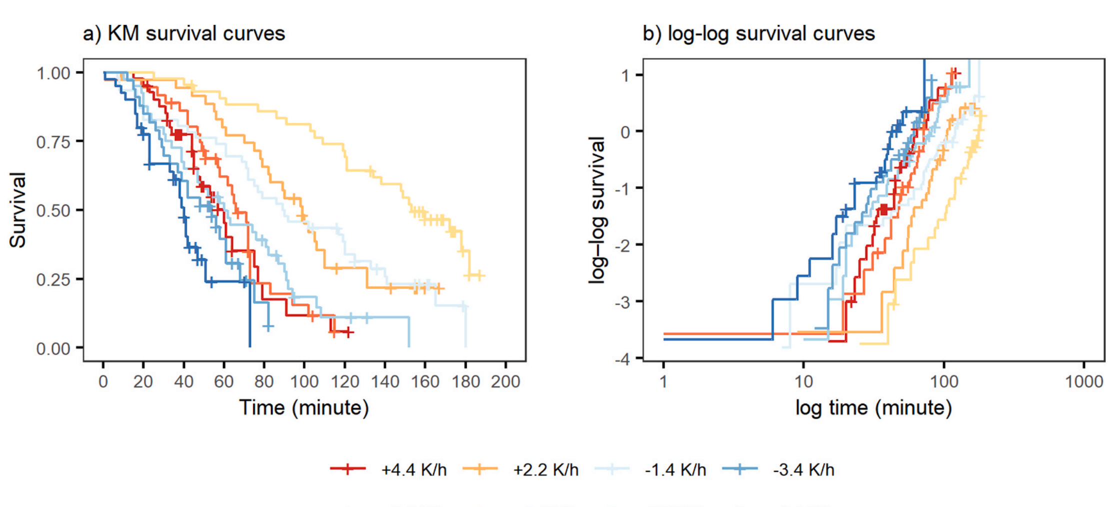

Fig. 7. KM (a) and log-log (b) survival curves for different rates of temperature change.

4.2. KM survival curves

As mentioned in section 3.1.1, the KM method has the advantage of being distribution-free, but, at the same time, it cannot estimate the magnitude of the survival predictor relationship of interest nor control for multiple covariates. Therefore, this method has been used only to describe and visualise the survival curves at a preliminary stage. Fig. 7.a shows the KM curves for the various thermal ramps, where the plus symbol represents the right censoring. In this figure, it is noticeable that the survivability for warm variations was higher than for cold ones. Also, for both space heating and cooling processes, slower variations led to longer survival than faster variations.

In Fig. 7.b, the eight thermal ramps are plotted on a log-log survival scale against time on the log scale. This plot, usually referred to as a log-log plot, is a graphical approach to evaluating the PH assumptions. If the hazards cross or are not parallel in some other way, the PH assumptions for the predictor of interest are not met. In this specific case, since the rates of temperature change for heating and cooling processes intersect, the PH assumptions for this predictor are not satisfied. On the other hand, when considering space heating and cooling separately (plot not shown), the curves for the different rates of change are roughly parallel. However, this is a necessary condition but not a sufficient condition. In fact, even if the hazards do not cross, it is still possible that the PH assumption is not met. Thus, checking for crossing hazards is not sufficient, and other approaches to evaluate the reasonableness of the PH assumption must be used.

In Fig. 8, the log-log plot has been drawn with each slope (in absolute value) plotted separately to increase readability. From this plot, it can be noticed that there is some indication of non-parallelism after 70 min for slope 3.4 K/h (Fig. 8c) and before 15 min for slope 2.2 K/h (Fig. 8b). Also, the initial distance between the curves for space heating and cooling processes is greater for a ramp slope of 1.4 K/h than a ramp slope of 4.4 K/h, indicating an effect between the temperature change and the direction of the change (i.e., increase or decrease of the temperature). Moreover, on the whole, all the curves show a divergent-convergent shape:, that is the curves initially separate but eventually join up.

In the context of monotonic temperature variations (thermal ramps), warm changes induce thermal discomfort with some delay compared to cold ones, but this delay progressively wears off. The underlying process, that is, the discomfort from thermal ramps, is delayed on the warm side, or stated analogously, the survival is prolonged temporarily. However, it is important to point out that the number of participants still at risk decreased towards the curve's end. Therefore, caution is generally required not to over-interpret the right side of this part of the plot.

4.3. Cox-regression

The descriptive analysis carried out in the previous section showed

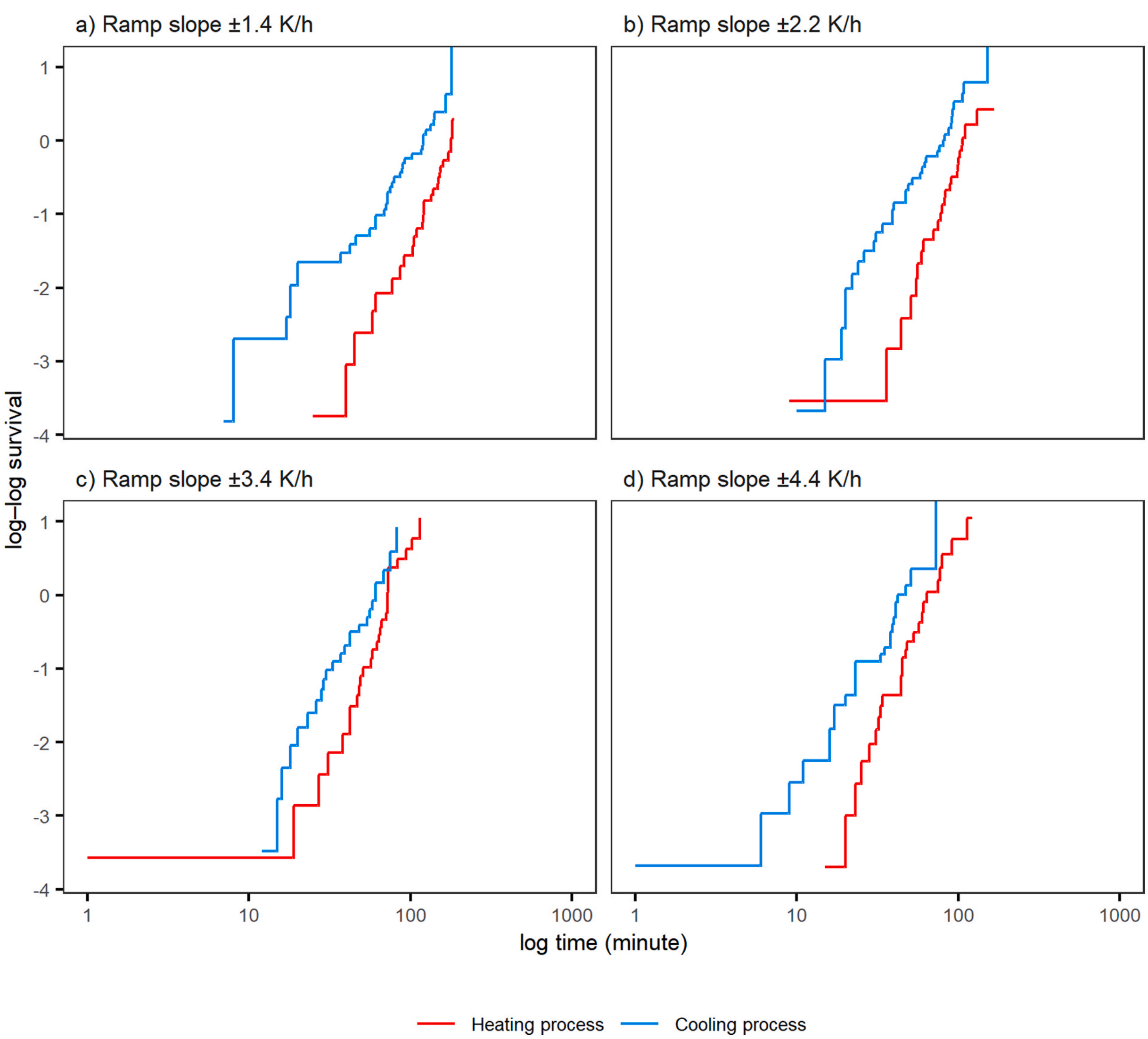

Fig. 8. Log-log survival chart for heating and cooling based on the rate of temperature changes.

Table 5
List of covariates used in the model for both space heating and cooling processes.

Variable	Code	Type	Unit
Thermal resistance of clothing	*Clothing*	Continuous, time-independent	clo
Gender	*Gender*	Categorical, time-independent	Female (reference)/Male
Age	*Age*	Continuous, time-independent	Years
Body Mass Index	*BMI*	Continuous, time-independent	kg/m^2
Time lived in Norway	*Time. Norway*	Categorical, time-independent	Less than or equal to 3 years (reference)/More than 3 years
Air velocity	*Air.vel*	Continuous, time-dependent	m/s
Time of day	*Time.day*	Categorical, time-independent	Morning (reference)/ Afternoon
Vapour pressure	*Vap.pre*	Continuous, time-dependent	N/m^2
Operative temperature change	*Top.delta*	Continuous, time-dependent	K
Initial operative temperature	*Top.start*	Continuous, time-independent	°C
Participant ID-code	*ID.subj*	Categorical, time-independent	–

that if heating and cooling are considered in the same model, the PH assumption is not met. Even though there are methods to deal with this (as mentioned in section 3.1.2), it was decided to develop separate models for the space heating and cooling processes. This choice also had the advantage of assessing the selected covariates' significant predictors separately for the two models. Table 5 lists all the covariates used in the inference of the heating and cooling models.

The rate of temperature change (i.e., ±4.4, ±3.4, ±2.2 and ± 1.4 K/h) was only considered in the descriptive analysis (Figs. 7 and 8) and not incorporated directly into the Cox-regression model. In this model, the rate of temperature change (K/h) is indirectly implied in the operative temperature change (K), a time-dependent covariate.

The variation of the operative temperature (*Top.delta*) and the initial operative temperature (*Top.start*) are the decomposition of the operative temperature. *Top.start* is defined as the operative temperature at time $t = 0$. In contrast, *Top.delta* is the difference between the operative temperature at $t > 0$ and $t = 0$. This division aims to verify whether the operative temperature level affects dynamic thermal discomfort.

The covariate *ID.subj* was used to account for correlated observations since the same subject appears in overlapping intervals. This variable was used in the analysis to create a robust variance, allowing the computation of an infinitesimal jackknife variance estimate [38].

The following modelling steps were undertaken:

1. *Purposeful selection of covariates*: After performing a first fit of the initial multivariable model, the *p* values of the individual coefficient were used to ascertain covariates that might be deleted from the model. This procedure is commonly known as backwards eliminations. The reduced model was evaluated to check if the elimination of a covariate produced a "relevant" change in the parameter estimates of the model's remaining variables. A change of about 20% was used as an indicator of the relevant change. If an important confounder was removed, it was incorporated back into the model.
2. *Define the correct functional form* (i.e., test the linearity assumption): With the previous model, the scale of the continuous variable was analysed to determine whether or not the effect of the covariates was linear in the log hazard (and therefore check if the data support this initial hypothesis). In this analysis, smoothing splines[3] were utilised for this purpose.
3. *Check for interaction terms (i.e., test the additivity assumptions)*: In this step, it was determined whether interactions between predictors needed to be added to the model. Each individual interaction was introduced separately and assessed by comparing the model with the interaction term to the main effect model. This assessment was carried out by examining any changes in the main effect's coefficients and checking the partial likelihood ratio test. All significant interactions were added jointly to the main effects model.
4. *Check the PH assumption*: In this step, the model was carefully evaluated by performing model diagnostics. Also, to avoid overfitting, the number of variables that can be included in the model should be confined. It is not trivial to make a general statement about this, but an approximate criterion is to have one covariate per ten events [44].

4.3.1. Initial models

In this section, both the initial multivariable models for heating and cooling are presented. In this step, the backwards elimination has not been yet applied.

At this point in the analysis, four main significant predictors had been detected for space heating while only two had been detected for space cooling (Table 6). Between the two models, the only common significant predictor is the operative temperature variation. As expected, its coefficient is positive for heating processes and negative for cooling processes. The cooling coefficient is greater than that for heating in absolute value, suggesting that cooling variations are more threatening to thermal comfort. It is important to remember that this coefficient represents the overall effect of the corresponding time-dependent variable, considering all times at which this variable has been measured in the study. Also, at this point, the linearity assumption between the risk and the covariate had yet to be verified.

In the following two sections, only the main results of applying the modelling steps mentioned above are illustrated.

4.3.2. Space heating process

Table 7 summarises the results of the multivariable model for heating after applying backwards elimination. Four significant predictors were identified – BMI, time lived in Norway, operative temperature variation and initial operative temperature – all positively associated with increased risk of "warm discomfort". Among them, three are continuous variables (and will be discussed later), while *Time.Norway* is categorical. This variable has been used as a proxy for inferring a long-term adaptation[4] to the Norwegian environment. In a recent study, Luo et al. [45] investigated the long-term thermal adaptation of building occupants by conducting two comparative field studies on thermal comfort in China. They observed for some years two groups of people, one that moved

[3] Splines are mathematical constructs made up of polynomial functions joined together to form a smooth curve, where the joining points are called "knots". An effective way to find a smoothing spline in survival analysis is with "penalised partial likelihood". When this quantity is maximized, it balances the goodness of fit against complexity [38].

[4] According to the glossary of terms for thermal physiology [23], adaptation is defined as "changes that reduce the physiological strain produced by stressful components of the total environment". It includes both genotypic (genetic selection) and phenotypic adaptation (changes that may occur within the lifetime of an organism, such as changes in the thermoregulatory system).

Building and Environment 204 (2021) 108144

Table 6

Regression coefficients for the predictors in the initial multivariable model (before applying backwards elimination).

Predictor		Heating process				Cooling process			
		coeff	se (coeff)	z	*p*-value	coeff	se (coeff)	z	*p*-value
Clothing		0.693	0.677	1.023	.306	−1.538	1.443	−1.066	.287
Gender	female	Reference				Reference			
	male	−0.507	0.459	−1.103	.270	−0.642	0.439	−1.462	.144
Age		−0.006	0.026	−0.242	.809	0.016	0.019	0.834	.404
BMI		0.174	0.067	2.600	.009*	0.009	0.068	0.128	.898
Time.Norway	≤3 years	Reference				Reference			
	>3 years	1.142	0.325	3.511	<.001*	0.502	0.337	1.491	.136
Air.vel		3.098	4.934	0.628	.530	−4.470	6.048	−0.739	.460
Time.day	morning	Reference				Reference			
	afternoon	0.004	0.233	0.018	.986	−0.668	0.260	−2.572	.010*
Vap.pre		−0.001	0.001	−0.626	.531	0.000	0.001	−0.537	.591
Top.delta		0.784	0.110	7.146	<.001*	−0.894	0.203	−4.400	<.001*
Top.start		0.906	0.333	2.721	.007*	0.340	0.294	1.157	.247
		Likelihood ratio test = 98.35 on 10 df, $p \leq$ 2.2E-16				Likelihood ratio test = 56.92 on 10 df, $p =$ 1.378E-08			

* indicates a significant term.

Table 7

Regression coefficients for predictors in the multivariable heating model (after applying backwards elimination).

Predictor		Heating process			
		coeff	se (coeff)	z	*p*-value
Gender	female	Reference			
	male	−0.564	0.470	−1.200	.230
BMI		0.168	0.068	2.476	.013*
Time.Norway	≤3 years	Reference			
	>3 years	1.067	0.316	3.373	<.001*
Top.delta		0.756	0.101	7.476	<.001*
Top.start		0.871	0.259	3.359	<.001*
Likelihood ratio test = 96.78 on 5 df, $p \leq$ 2.2E-16					

*indicates a significant term.

from southern China (Shanghai) to northern China (Beijing) and one that moved in the opposite direction. The authors concluded that thermal adaptation exhibits asymmetric trajectories: the southern origin groups accepted neutral and warm indoor temperatures in less than one year, while the northern origin groups took three years to adjust to colder indoor temperatures. Based on this result, it was assumed that participants who had lived in Norway for more than three years had adapted to different indoor temperatures and heating/cooling strategies. The estimated hazard ratio (HR) is $\exp(1.067) = 2.907$ for participants living in Norway for more than 3 years (95% CI [1.564, 5.403], $p <$ .001). Therefore, individuals who had lived in Norway for more than three years were, at any given time during this study, 2.907 times as likely to experience "warm discomfort" as those who had lived in Norway for less than three years. In other words, they had an increased risk of 190%.

It can be noticed that the covariate *Gender*, even though not statistically significant, still remains in the model. This because its elimination caused a relevant change in the BMI variable. Therefore, in this study, gender is a confounder for BMI. This can be explained by looking at the participants' anthropometric characteristics in Table 2. Female participants were, generally, shorter and lighter than their male counterparts.

The next step is to verify whether the linearity assumption for continuous variables in the model has been met. Initially, for each continuous variable, a smoothing spline with four degrees of freedom was fitted, and the resulting plot was checked for significant non-linearity. If non-linearity was detected, the correct functional form was derived by refitting a smoothing spline but with an "optimal" degree of freedom based on the Akaike information criterion (AIC). Otherwise, a linear relationship was assumed. It is important to mention that this flexibility comes at a price. The interpretation of the estimated coefficients resulting from splines is, in fact, meaningless. However, the linear combinations of these coefficients can be used to obtain predicted values that can be plotted and interpreted. Fig. 9 shows this analysis for BMI, operative temperature change, and initial operative temperature.

BMI, formerly called the Quetelet index, is a measure for indicating nutritional status in adults. For adults over 20 years old, the World Health Organization has divided the BMI into: (i) "Underweight" if BMI < 18.5 kg/m^2; (ii) "Normal weight" if 18.5 kg/m^2 $\leq$ BMI $\leq$ 24.9 kg/m^2; (iii) "Pre-obesity" if 25.0 kg/m^2 $\leq$ BMI $\leq$ 29.9 kg/m^2; (iv) "Obesity class I" if 30.0 kg/m^2 $\leq$ BMI $\leq$ 34.9 kg/m^2; (iv) "Obesity class II" if 35.0 kg/m^2 $\leq$ BMI $\leq$ 39.9 kg/m^2; and (vi) "Obesity class III" if BMI $\geq$ 40 kg/m^2 [46]. Fig. 9.a shows that the hazard increases from low BMI to around "normal weight" BMI levels, where it flattens out and then rises slightly in the pre-obesity category, but not significantly. This indicates that participants with lower BMI values have a lower hazard of experiencing "warm discomfort" than participants with normal and pre-obesity BMI values. However, there is no significant difference between the normal and pre-obesity category. This result is not completely in line with the literature. While it is true that the underweight population (BMI $<$ 18.5 kg/m^2) is associated with a higher comfortable temperature, the overweight population (i.e., BMI $>$ 25.0 kg/m^2) is associated with a lower comfort temperature. For instance, Indraganti et al. [47]'s field investigation in India found this difference to be 0.7 K. However, BMI does not actually measure body fat nor the proportion of muscle-to-fat. Therefore, it is possible that some of the participants were incorrectly classified in the pre-obesity category. A smoothing spline with three degrees of freedom has been selected for the functional form (the purple line in Fig. 9a).

Concerning the initial operative temperature, Fig. 9.b shows that a linear fit is within the confidence interval; therefore, a linear relationship between the log(hazard) and the initial operative temperature is assumed (purple line). Interestingly, the hazard increases with a higher value of initial operative temperature even if these values are within 22.0 ± 1.0 °C, which are the comfort limits for Category A from ISO 7730-2005 [3]. This is in agreement with Ran's neuroscience experiment [22], discussed in section 1.1. Since heat-responding spinal neurons encode absolute temperature, higher initial operative temperature values lead to higher absolute operative temperature values for the same increment in temperature.

Fig. 9.c shows that the hazard increases linearly with the increment in operative temperature until about +4 K, where it flattens out. A smoothing spline with two degrees of freedom was selected for the functional form (the purple line in Fig. 9c). Nevertheless, conceptually, it is hard to believe that the hazard of thermal discomfort associated with a monotonous rise in operative temperature levels off as higher delta temperatures are reached. A more logical fit would be a continuation of the linear relationship before the +4 K increment (the green line

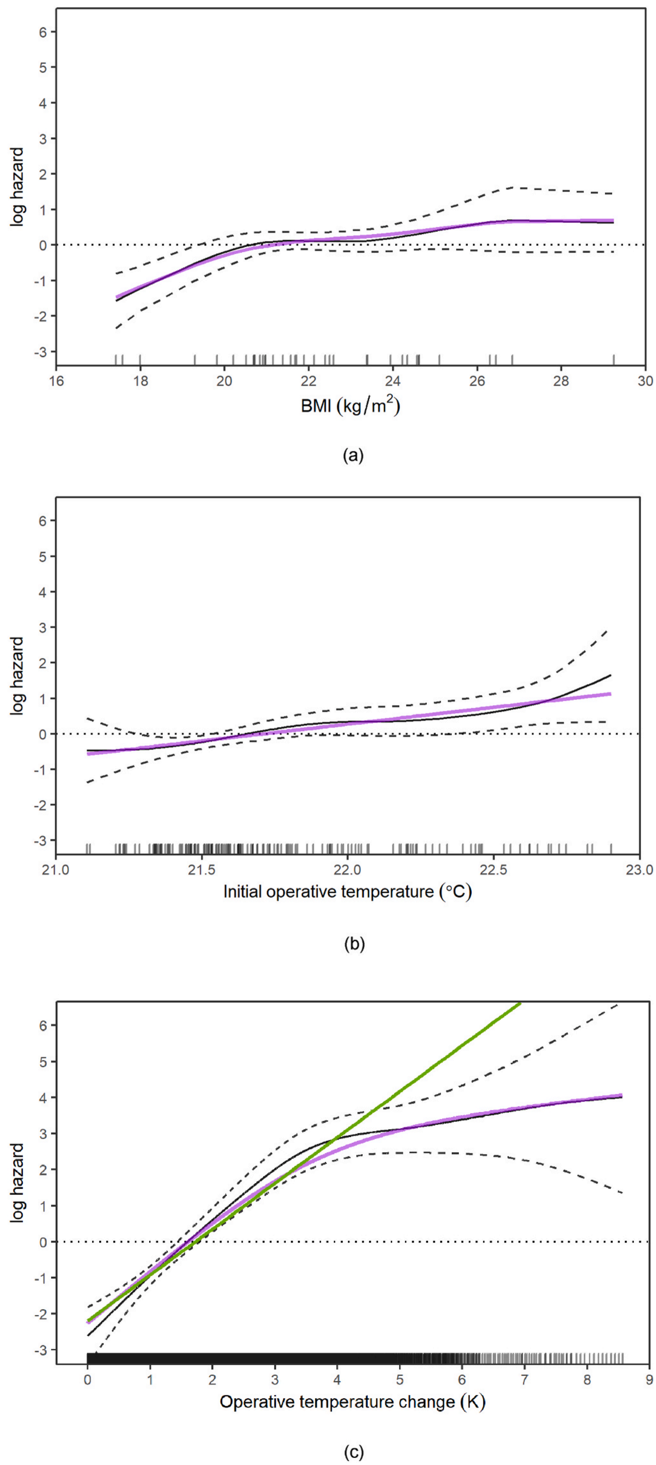

Fig. 9. Penalised spline fit of (a) BMI, (b) initial operative temperature and (c) operative temperature change for heating.

in Fig. 9c). A possible explanation for the hazard's flattening upon reaching higher delta temperatures is that different individuals have different frailty levels. More frail individuals are more likely to experience the discomfort event early. Consequently, over time, the "risk set" has an increasing proportion of less frail individuals, and the hazard flattens out. In addition, looking at Fig. 5, it can be noticed that around a +4 K increment, some participants do not experience the "warm discomfort event" before being censored.

No significant interactions have been found, and the PH assumption for the time-independent variables has been met. It is important to remember that, implicitly, time-dependent predictors do not satisfy it. For these variables, the hazard ratio is a function of time. Consequently, the coefficient of the time-dependent variable represents the overall effect of that predictor, considering all times at which this predictor has been measured in the study (for more details, the reader is referred to section 3.1.2 of this article).

4.3.3. *Space cooling process*

Table 8 summarises the results of the multivariable model for space cooling processes after applying backwards elimination. Three significant predictors were identified – time lived in Norway, time of day and operative temperature variation – one more compared with the initial model (see Table 6). *Time.day* and *Top.delta* are negatively associated with an increased risk of "cold discomfort", while *Time.Norway* is positively associated with the same outcome. As with the heating model, *Time.Norway* is positively associated with an increased risk of discomfort, but this time the relationship is weaker (HR = 1.854, 95% CI [1.060, 3.241], $p = .030$). The *Time.day* predictor is a categorical variable used to distinguish between the morning (8:00–11:30) and afternoon (12:00–15:30) sessions' thermal ramps. It was used to account for the circadian rhythm's influence on the risk of discomfort induced by variation in operative temperature. A circadian rhythm is a natural, internal process that regulates the sleep-wake cycle. This system also modulates other physiological functions, such as the body's core temperature, with a periodic variability over the 24 h (with maximal values in the late afternoon and minimal in the early morning). During periods of decreasing core temperatures, the average skin temperature rises to promote heat loss, and the reverse occurs during periods of rising core temperatures [48]. A circadian rhythm of heat loss from the distal limbs has been observed in humans: skin temperature and blood flow rhythms in these regions show peaks in the late evening and minima in the morning [49,50]. Consequently, an individual is in a "heat gain" mode in the morning (a rise in core temperature) and in a "heat loss" mode in the evening (a decrease in core temperature). Previous studies by Fanger et al. [51,52] found that, although the mean skin and rectal temperatures were slightly higher in the evening than in the morning, subjects did not prefer a different ambient temperature. They concluded that the same thermal comfort conditions can be used independently of the time of day or night. In this study, the hazard ratio for the time until "cold discomfort" for morning versus afternoon was 0.597 (95% CI [0.417, 0.853], $p = .005$), showing a difference between the two parts of the day. However, this result does not necessarily disagree with Fanger's previous findings. A lower risk of "cold discomfort" during the afternoon than in the morning does not inevitably imply a preferred lower temperature. It only suggests that, at any time during this study, participants during the afternoon were 0.597 times as likely to have a "cold discomfort" as during morning (that is, they experienced a reduction in risk of 40%).

It can be noticed that the covariates *Clothing* and *Gender*, even though not statistically significant, are still maintained in the model. In this

Table 8
Regression coefficients for predictors in the multivariable cooling model (after applying backwards elimination).

Predictor		Cooling process			
		coeff	se (coeff)	z	*p* value
Clothing		−1.535	1.422	−1.079	.280
Gender	female	Reference			
	male	−0.666	0.361	−1.844	.065
Time.Norway	≤3 years	Reference			
	>3 years	0.617	0.285	2.164	.030*
Time.day	morning	Reference			
	afternoon	−0.517	0.183	−2.828	.005*
Top.delta		−0.956	0.182	−5.241	<.001*
Likelihood ratio test = 54.17 on 5 df, p = 1.933E-10					

*indicates a significant term.

case, however, they remain not because they are confounders but because their presence improves the model's overall fit compared to the model without them ($\chi^2(2) = 8.438$, $p = .01471$).

The next step is to verify whether the linearity assumption for the continuous variables in the model is met. The same procedure as described previously was applied here, but only the statically significant continuous variable (i.e., operative temperature variation) is shown (Fig. 10). Here, the hazard decreases fairly linearly with the decrement in the operative temperature. Therefore, a linear relationship between the log(hazard) and the operative temperature variations was assumed (purple line).

No significant interactions were found, and the PH assumption for the time-independent variables has been met.

5. Discussion

In this study, the results obtained from the observed thermal discomfort events were precautionary for both space heating and cooling processes. The possibility of undertaking voluntary adaptation mechanisms or actions was precluded, including such simple actions as clothing adjustment. This approach agrees with the one used in the ASHARE standard 55 for temperature variation with time. The objective of ASHARE limits on temperature cycles, drifts and ramps (Table 1) is mainly to prevent occupants from experiencing discomfort due to temperature variations. Its applicability is limited to temperature fluctuations that are not under the individual occupant's direct control. Moreover, an occupant's clothing adaptation is implicitly considered only for occupant-controlled naturally conditioned spaces that meet specific criteria (see section 5.4.1 of [2]). Nevertheless, these limits seemed both loose and conservative compared with the results of this study. Cold temperature variations were perceived to be uncomfortable earlier than the standard prescribed. On the other hand, the limits for warm temperature variations were found to be excessively restrictive. This asymmetric behaviour is supported by neurophysiological findings.

As mention in section 1.1, in the spinal cord, cold-responding neurones react to temperature changes, while heat-responding ones react to the absolute temperature. Consequently, humans are more sensitive to cooling than heating, meaning that they react more quickly or more than usual to cooling than to heating. This neurophysiological interpretation can also be directly observed from this study's results, from both a descriptive and analytical perspective. The KM method gave a descriptive point of view. Fig. 7 showed that the survival probability is higher for heating processes compared with cooling ones, even for the same rate of temperature change (thermal ramp). Concerning cooling variations, it can be observed that different temperature change rates initially affected survivability similarly. The contrast between the different cooling ramps is more marked at a later time. This can also be explained using the findings of Ran's neuroscience experiment [22]. In their study, the authors observed that a larger delta temperature produced greater responses than smaller delta temperature values. Nevertheless, they noted no observable cooling rate effects on either the percentage of cold-responding neurons or their response amplitudes. Of course, faster temperature variation results in a greater delta temperature, assuming the same amount of time. However, when the amount of time is small, the temperature difference with distinct temperature change rates is smaller. Therefore, some (perhaps more sensitive) participants experienced a thermal discomfort event regardless of the rate of temperature change for cooling. In turn, this explains why, at an early phase, the survivability for a different rate of temperature change was similar. An analytical point of view was given by the Cox-regression. The model for cooling showed no statistically significant effect on the starting operative temperature. Conversely, in the heating model, the risk of experiencing a warm discomfort event increased with higher starting operative temperatures.

Furthermore, if considering elevated air movement, it is reasonable to assume that the observed thermal discomfort events for warm temperature variation could be postponed. Elevated air movement is a recognised factor that increases the acceptable range of operative temperatures [2]. In this study, the air was kept practically still to avoid local discomfort (a draft) during cooling. This resulted in air movement being an insignificant predictor.

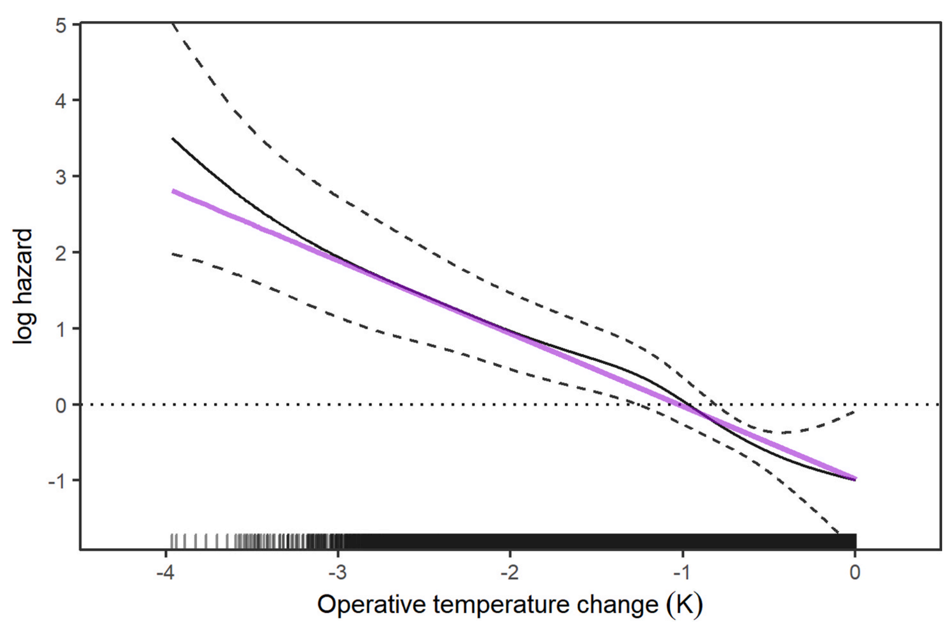

Fig. 10. Penalised spline fit of operative temperature change for cooling.

5.1. Limitations

This study's limitations arise from the relative homogeneity of age and the unbalanced number of male and female participants. Since most of the participants were between 23 and 31 years old, the results are not completely representative of the office worker population. The gender imbalance among participants might be the main cause of nonstatistically significant differences between males and females in terms of thermal discomfort. To reduce the effect of the generally heterogeneous initial metabolic rate, participants spent the first half-hour before starting the session in a constant temperature environment. However, previous studies on thermal comfort in climatic chambers have shown that subjects' average thermal sensation decreases during the first 2 h, even during exposure to constant temperatures [13]. On the other hand, time and organisational constraints did not allow for such an extension of this study's acclimation period. Therefore, it is possible that the potential carry-over effects influenced the participants' thermal sensation even after the 30-min acclimation phase.

Even with some constraints (e.g., clothing adjustment), this study aimed to reproduce a typical office environment and, consequently, simulate a typical office activity pattern. Nevertheless, participants were prone to the Hawthorne effect.[5] Typically, the Hawthorne effect is described as a change in research participants' behaviour in experimental or observational studies. In this study, to avoid potential bias, participants were blinded to the environmental changes; that is, they were not informed about the change in the temperature. However, if the participants changed their behaviour during the experiment – for example, by increasing their awareness and, therefore, sensitivity to change in the indoor environmental condition – the Hawthorne effect would have occurred. Also, the use of the digital button could have introduced a behavioural change. Schweiker et al. [53], in their review of multi-domain approaches to indoor environmental perception and behaviour, pointed out that there is a difference in the intention to perform an action and the action itself. It is undeniable that performing an actual action, for example, adjusting the thermostat, would have required more effort than pressing the digital button. On the other hand, the opposite is also true. A specific human-building interface affects the level of interaction that a person has with it, and therefore its usability, which could lead to a different behavioural choice [54]. For example, even in a more familiar context, such as a residential setting, a common usability barrier for a thermostat is its complexity or the buttons' reduced size and comprehensibility [55]. Furthermore, it would be unfeasible to provide all the real means of possible interaction with the indoor environment (e.g., for the thermal environment alone, these include open/close window, thermostat adjustment, beverage intake, personalised/local cooler/heater, and ceiling/desk fans). Therefore, even with the aforementioned limitations, the discomfort button was adopted.

5.2. Conclusion and future perspectives

An experimental study has been conducted to explore the effects of ramp-induced temperature variations in an office setting. The purpose was to understand human reaction to monotonic thermal variations by describing the relationship between human response and covariates of interest. The study's design was a randomised crossover trial, a longitudinal study in which participants received a randomised sequence of different exposure (i.e., thermal ramps). Based on the analysis carried out, the following conclusions can be drawn:

- The distributions of participants' thermal comfort ratings during warm and cold discomfort events were remarkably similar, despite different temperature changes. This suggests that, indeed, thermal comfort is the driver for thermal behaviour. Thermal sensation votes were found to be asymmetric during discomfort events, while most of the thermal acceptability votes were at the boundary between an acceptable and unacceptable environment. This could indicate that thermal acceptability has a broader meaning, which, in a general sense, might be interpreted as tolerance.
- A distinct discomfort mechanism for space heating and cooling processes was observed in this experiment. For warm discomfort, the operative temperature level is a significant predictor, while for cold discomfort, the relative change in operative temperature is the trigger. This result agrees with the recent research evidence from neuroscience experiments [22].
- During heating variations, in addition to operative temperature (that is, the operative temperature variation plus the initial operative temperature), BMI and time lived in Norway significantly predicted participants' warm discomfort. For cooling processes, besides operative temperature variation, time lived in Norway and time of day were significant predictors of cold discomfort. For both space heating and cooling processes, gender and age did not significantly affect discomfort. Furthermore, no significant interaction has been identified.
- The current experimental results imply that the limits for drifts and ramps are not symmetric in winter conditions. The limits on temperature cycles, drifts and ramps defined in ASHRAE 55-2017 [2] are loose for cold temperature variations and conservative for warm ones.

In addition, this paper overcomes some important methodological issues concerning the semantic equivalence of different psychometric scales, highlighting, at the same time, the practical implications. For instance, a classic hypothesis (rule-of-thumb) is to consider an environment "satisfactory" when the thermal sensation vote is between "slightly cold" (−1) and "slightly warm" (+1). In this study, this conversion is well suited for warmer variations. Still, it is utterly misleading for colder ones. Fig. 6 shows that the majority of the discomfort events were experienced when the environment was perceived as "slightly cold".

In the context of multi-domain comfort, the methodology applied in this study could be used to analyse the relation between perception and action. It would also be possible to evaluate which contextual and personal factors affecting behaviour influence perception and vice versa.

Furthermore, the new knowledge of human reaction to a dynamic thermal environment can be used to design more energy-efficient and satisfying control strategies to enable buildings' thermal flexibility. Indeed, controlling the indoor temperature of buildings within a comfort range is a way to provide energy flexibility to the grid [56], exploiting the slow thermal inertia of a building's envelope in combination with the users' comfort band. However, the comfort band is usually assumed symmetric for space heating and cooling purposes and defined solely by absolute values of the indoor operative temperature, such as in the ASHRAE 55-2017 standard [57]. The findings presented in this paper have the potential to improve the performance of such controllers by providing a more accurate description of the human thermal response under dynamic conditions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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[5] The Hawthorne effect got its name from a study of psychological aspects and physical and environmental influences in the workplace at the Western Electric Company's Hawthorne facility in Cicero, Illinois, during the 1920s. There, the workers increased their productivity when under observation but decreased it at the end of the study.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2021.108144.

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