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Is there short-term adaptation to repeated thermal stress relief and pleasure? First insights from an experimental study

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ABSTRACT

Dynamic thermal conditions have the potential to support human health and energy efficiency of buildings. However, certain reluctance with respect to the acceptance of such conditions can be observed. While relief and pleasure are considered as components of reward, relief gained little attention within built environmental research. Furthermore, the level of personal control is a known influence on thermal assessment, but its association with perceived relief unknown. Therefore, the objective was to gain insights into the effects of sequences of thermal stress and relief with differing levels of control on thermal sensation, perceived pleasure, perceived relief, and physiological reactions.

A laboratory study (N = 60) with 8 sequences of elevated and reduced thermal stress lasting 15 min each, half with reduced, half with increased personal control over thermal environmental conditions was conducted. The data was analysed applying the Bayesian approach to explore effects of these exposures on subjective experience and physiological reactions.

Results suggest that the reduction of thermal stress leads to cooler thermal sensation, increased perceived pleasure, and perceived relief (each changing one unit on the 7- and 5-point assessment scale, 0% in the region of practical equivalence (ROPE)), while changes of hand skin temperature (<0.1 K) and heart rate variability were negligible. Over repeated sequences of thermal stress and relief perceived pleasure and possibly relief slightly increased. Despite limitations, this supports a shift towards more dynamic and wide temperature ranges and a more widespread application of Bayesian framework.

1. Introduction

1.1. Background

Research on, and design of, workplaces and residential areas aim to establish and provide conditions supporting human health, satisfaction, performance and recovery. When considering physical conditions at workplaces, like thermal conditions, a strong focus is placed on the avoidance of stressors through the provision of stable conditions within small exposure ranges. However, such focus on the avoidance of distress has been increasingly criticized, starting with notions of “thermal boredom” [1] and more recently summarized as the "neutrality fallacy" [2].

More and more studies indicate benefits of dynamic, broad-ranged conditions for increasing human health- and comfort-parameters [3–5]. Furthermore, laboratory studies suggest that certain thermal stressors outside classic comfort ranges are beneficial for a variety of health-related parameters, like the metabolic profile [6–8]. Schweiker [9] reviewed potential benefits with respect to human resilience, and highlighted encouragement and enjoyment as two of three requirements for health-supporting indoor environments, beyond relief from high thermal strains. In addition, dynamic conditions were also beneficial with respect to increasing energy efficiency – relevant for combatting climate change [10].

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Hence, a necessity evolves to look beyond the negative consequences of thermal stressors alone and to distinguish between negative (dis-) and positive (eu-)stress as known in occupational medicine, psychology, and beyond for decades [11]. Within the building science context, eustress can be related to thermal delight or pleasure and the concept of alliesthesia, which was coined by Cabanac [12]. Positive thermal alliesthesia is explained as the assessment of an external stimulus as pleasant when it has the potential to remove an existing thermal load outside comfortable ranges [13]. Heschong [1] as well as deKay and Brager [2] argued that elements of the built environment can be designed to create delight through dynamic and variable environmental conditions. Thereby, alliesthesial experiences can occur due to temporal or spatial dynamics [14,15] as well as seasonal variations [16].

Despite this evidence on positive effects of dynamic thermal conditions on health and subjective assessments, questions remain regarding the acceptance of such conditions, the motivation of occupants to get exposed to such conditions and related behavioural actions. The role of pleasure as a determinant of behaviour has been mentioned decades ago in the fields of psychology (e.g., by Young [17]) and physiology (e.g., when introducing the concept of alliesthesia by Cabanac [12]). In pain research, pleasure is the hedonic experience when relief is achieved and considered as a part of the reward that induces the motivation to achieve it [18,19]. Furthermore, the experience and expectation of achieving relief can induce learning and alter future behaviours [20]. Based on these thoughts, alliesthesial experiences could be connected to the relief from thermal exposures not "useful […] to remove [relief from] heat from the body and reduce hyperthermia" [21]. Hence, addressing not only pleasure but extending research on dynamic thermal exposures towards the concept of relief could be meaningful, but the authors are not aware of studies addressing the assessment of relief from thermal stressors.[1]

Dynamic indoor environmental conditions will expose occupants to multiple stress-relief sequences, while Buonocore et al. [23] mentioned the exact effect of repetitions as a research gap related to dynamic airflow patterns and thermal perception. Hence, knowledge on the effect of repeated sequences of stress and relief on subjective and physiological human reactions is needed for practical applications.

Another aspect in relation to subjective thermal assessment of dynamic thermal environments is perceived control. Earlier studies and frameworks indicate that the assessment of thermal conditions differs depending on the degree of perceived control a person has over their thermal environment. Higher perceived control is associated with wider ranges of temperatures being evaluated as acceptable [24–26]. Beyond thermal comfort, perceived control is also related to relief and reward. The existence of control has been associated with reward-related neural systems [27], while perceived pain relief was positively related with having control over the pain stimuli [19]. Still, potential effects of perceived control within dynamic thermal environments remain largely unknown.

Overall, minimal knowledge exists regarding human subjective and physiological reactions to repeated sequences of stress and relief and potential positive influences on thermal assessment and human physiology. Closing such gaps is relevant for design and operation of buildings supporting this new paradigm.

1.2. Objectives

Hence, the overall objective of this study was to gain insights into the effects of sequences of thermal stress and relief on thermal sensation, pleasure, perceived relief and physiological reactions. The term stress is defined here analogue to ISO 10,075–1:2018 as the thermal load through environmental conditions (air temperature, radiant temperature, relative humidity, and air velocity), human activity and clothing level. As such, thermal stress contrasts with thermal strain, which would consider the effect of the thermal stress on an individual and varying due to further human characteristics such as sex, age, psychological or physiological characteristics [see also 9].

The objective is addressed through three primary research questions (see also Fig. 1c).

The first research question (RQ1): to what extent do short-term and sudden reductions in the magnitude of thermal stress elicit changes in the outcome variables perceived thermal intensity (sensation), thermal pleasantness, perceived relief and thermoregulatory (skin temperature) as well as stress related (heart rate variability (HRV)) physiological reactions?

RQ2 focuses on the potential effect of repetition on the subjective and physiological outcome variables. Repetitions could a) directly affect the outcome variables or b) affect their difference between thermal stress and relief exposure (i.e., the changes addressed in RQ1). Therefore, we have RQ2a: to what extent do the outcome variables vary with repetition?, and RQ2b: to what extent do the differences of the outcome variables between stress and relief exposure vary with repetition?

The last research question (RQ3) considers the potential influence of different degrees of control of thermal exposures. Two sub-questions exist again and are RQ3a: to what extent influences control the outcome variables?, and RQ3b: to what extent do the differences of the outcome variables between stress and relief exposure vary with the degree of control?

2. Material and methods

2.1. Study design and procedures

The experiment took place in autumn 2018. Upon arrival at the test facility, the researcher provided the participants with an overview on the procedures and methods. Following explanations of the procedures and clarification of potential questions, written informed consent was obtained. Next, participants were guided into one of the two laboratory rooms and the experimental procedure started (Fig. 1). All testing sessions were performed in the Laboratory for Occupant Behaviour, Thermal comfort, Satisfaction and Environmental Research (LOBSTER; [28]) belonging to the Building Science Group at the Karlsruhe Institute of Technology, Karlsruhe, Germany. The Ethics committee and data protection officer of Karlsruhe Institute of Technology (Karlsruhe, Germany) approved the study on June 28th, 2018.

2.2. Participants

Participants were recruited using announcements placed on a local online job market for students, a free newspaper, and on the institutional homepage. Exclusion criteria were age younger than 18, self-reported use of opioid or psychotropic drugs, presence of past mental disorders, sleep disorders, and any pain present for more than 6 months and more frequently than one day every two weeks. Inclusion and exclusion criteria were assessed in a telephone interview before participation in the study. During this telephone interview, the interviewer also assessed whether the German language level was sufficient for participation. For a completed participation, participants received 45 € in cash.

61 healthy volunteers participated in the study. One participant had to cancel participation before completing all conditions due to health problems unrelated to the study, leading to complete datasets from 60 participants. Participants from two age groups, and both male and female, were invited in order to go beyond common bias towards male-dominating student-aged groups in studies and to consider respective variations in thermoregulation and perception [29]. An even

[1] Arens et al. [22] mentioned the word relieved when "body thermal stress was being relieved by the local cooling/warming", but do not assess it directly. Schweiker [9] included relief in his work on resilience. However, the meaning differs as in his work, relief is considered related to steady-state conditions and not as the result of a reduction in thermal stress that is meant here.

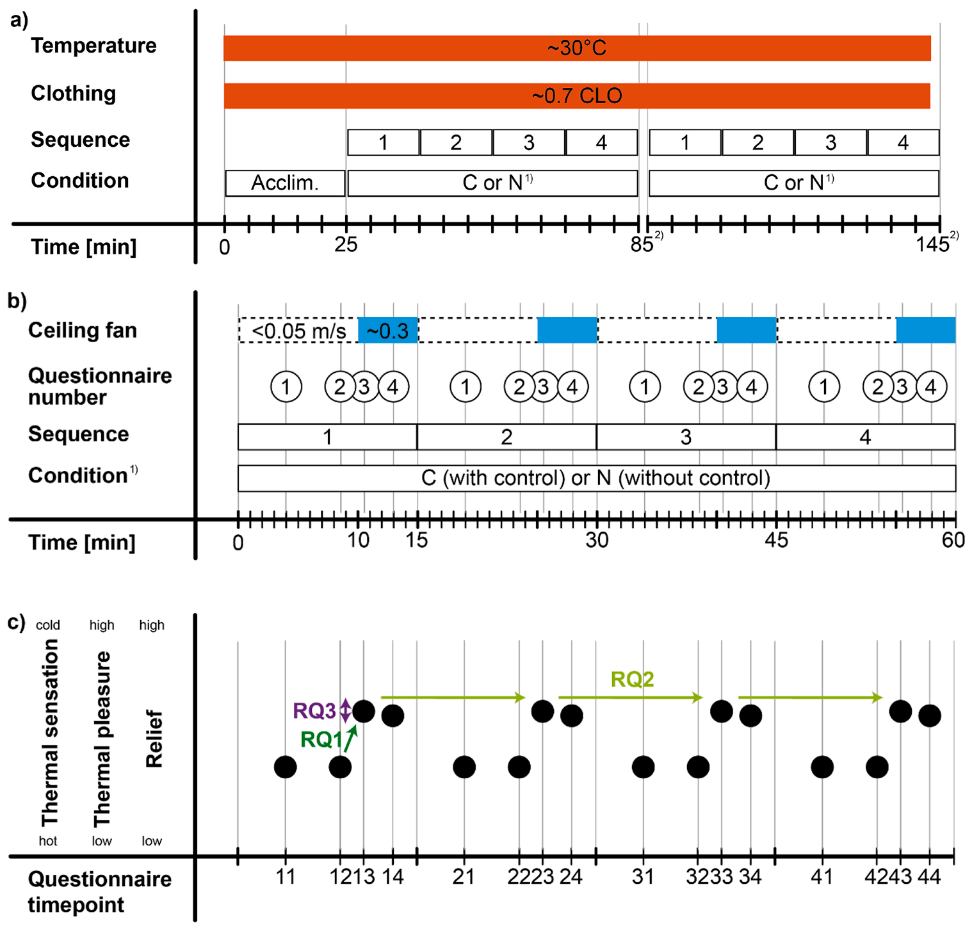


Fig. 1. a) Overview of the experimental protocol. After an acclimatization phase (acclim.), participants performed two times four sequences either with control (C) or without control (N). b) each sequence lasted 15 min of which the ceiling fan was switched off the first 10 min and switched on the remaining 5 min. c) predicted changes in the three subjective outcome variables and visualization of the research questions across questionnaire timepoints (two-digit identifier consisting of sequence and questionnaire number).
1) conditions with control (C) and without control (N) of the start of the ceiling fan were in counterbalanced order; 2) in between the two conditions, settings had to be changed, which took on average 2 min (SD: 1 min, maximum 9 min).

distribution across the age and biological sex categories was aimed for (Table 1).

Table 1
Age and sex distribution of participants.

Sex/ age group	< 32 years of age	> 50 years of age	Total
Female	17 (28.3%)	14 (23.3%)	31 (51.6%)
Male	16 (26.7%)	13 (21.7%)	29 (48.4%)
Total	33 (55%)	27 (45%)	60 (100%)

2.3. Thermal stimulation and environmental conditions

The experimental protocol consisted of three phases lasting a total of three hours (see also Fig. 1a). First, participants were welcomed to the laboratory and underwent the informed consent procedure as described above, which took around 20 min (not shown in Fig. 1). Then, they entered one of the laboratory rooms conditioned to an operative temperature (T_{op}) of 30 °C. Clothing item instructions required participants to wear long thick trousers, a short-sleeved T-shirt and an additional long-sleeved upper part in addition to common underwear, socks and shoes, leading to an estimated value of 0.7 clo. After entering the office, the acclimatisation[2] phase of 25 min started, during which participants received further instructions and filled out a background questionnaire. The third and fourth phase were nearly identical and lasted one hour each. In both phases, periods with a running ceiling fan (0.3 m/s) were

[2] We use the term acclimatization here, which is the standard terminology used in the field of thermal comfort research for the initial phase harmonizing participants thermoregulation and bringing it into comparable steady-state prior to the exposure. We are aware that this usage is in contrast to the field of (thermal) physiology, where the term acclimatization, or phenotypic adaptation, refers to a process of “[p]hysiological or behavioural changes occurring within the lifetime of an organism that reduce the strain caused by stressful changes in the natural climate (e.g., seasonal or geographical)” [30] established over longer time (days or weeks).

followed by periods without the ceiling fan running (<0.05 m/s) (Fig. 1b). It should be noted that the mean of a ceiling fan was chosen for the change between phases of thermal stress and relief because the increase in air velocity nearly instantly changes the heat balance of the human body. In contrast, room-based changes in air temperature have much longer response time, or changes in clothing levels, which have an instant effect, require active participation of participants. The ceiling fan was switched off for 10 min, followed by 5 min being switched on. The duration of this sequence together with the value of 0.3 m/s of air velocity was determined in pilot tests, so that on average, the skin temperature of participants was at the same level at each start of the 15-minute period.

This 15-minute period was repeated four times in each phase. During this period, participants were asked four times about their assessment of thermal sensation, pleasure, preference and additional affect-related items (see next section): 4 and 8.5 min (fan off), 10.5 min (fan just on), and 13 min (fan on for three minutes) after the start of each 15-minute period.

The difference between the two phases was the communicated level of control. In the no-control condition, the ceiling fan switched on according to the pre-set protocol automatically. In the control-condition, participants were shown a button on the screen after 10 min of each exposure and were instructed to press the button in case they wanted to switch on the ceiling fan. As such, during the control condition, participants were given the impression that their behaviour to press the button or not influenced powering on the fan, or not. Unknown to the participants, the ceiling fan was switched on automatically in case participants did not press the button within 10 s. The reason for not giving participants more time to react or choose not to react was that we wanted to keep the length of the sequences the same in order to avoid effects due to variations in the duration of the exposure. Powering off the ceiling fan was not under control of the participants in both conditions. Note that in order to reduce predictability, the automated on-/off-signal was jittered ±10 s around the above-described timing.

The timing of ceiling fan and questionnaires was automated and synced through the building control system, programmed with LabView. The order of conditions was balanced across participants. The ceiling fan used in this experiment was extremely silent, so participants could see the ceiling fan start to run in case they looked up, but there was no perceptual increase in noise level, just the perception of reduced thermal load. The ceiling fan is described in more detail in Rissetto et al. [31].

The design conditions during the periods with the ceiling fan off, including the assumption of 1.1 MET and an average relative humidity of 50% rH were: 1.74 Predicted Mean Vote (PMV), 30.6 °C Standard Effective Temperature (SET), 1.17 Adaptive Thermal Heat Balance (ATHB) model [32], vote on the7-point scale for thermal sensation (ASHRAE) of “warm”; and during the periods with powered ceiling fan: 1,03 PMV (ASHRAE with elevated air speed), 28.8 °C SET, 1.02 ATHB, “slightly warm”).

The laboratory room with windows offering a view outside was naturally lit when possible, and artificial lighting was switched on to guarantee a minimum desk illuminance of 500 lx at all times. Levels of carbon dioxide as indicator of indoor air quality were kept below 800 ppm. Outdoor thermal conditions had an average of 14.9 °C ± 5.1 °C across the entire study period.

2.4. Rating scales

At the times of rating, participants were shown two screens in a fixed order (Fig. 2). On the first screen, participants assessed their perceived intensity on the ASHRAE thermal sensation scale from cold to hot, the un-/pleasantness of the thermal stimulation from very pleasant to very unpleasant and their thermal preference from much cooler to much warmer. All of these ratings were done on 7-point rating scales. On the second screen, participants were asked to assess seven adjectives related to their mood and well-being on 5-point rating scales. The adjectives were positive excitement, externally controlled, stimulated, irritated, relieved, tired, and focused. The response options were ‘not at all’, ‘a little’, ‘to some extent’, ‘considerably’, and ‘extremely’.

All items were prepared in German, and participants were familiarized with the rating scales at the beginning of the experiment prior to the first exposure.

2.5. Physical measurements

To characterize the thermal environment, air temperature, globe temperature, air velocity, and relative humidity were measured at 1-minute intervals at 1.1 m height to the left and right of the participant. In addition, CO2-concentration was measured at the same height behind the table. All sensors were calibrated against high-performance laboratory equipment from Ahlborn.

2.6. Physiological measurements

An electrocardiogram (ecg) sensor (movisens ecg3) was used for continuous measurements of the time duration between two heartbeats, the N-N-intervals, which were the basis for assessing HRV. To measure the skin temperature continuously, iButtons were attached to four body sites (neck, shoulder, hand, and shin) [33] and set to measure at 10-second intervals. The iButtons on shoulder and shin were covered by clothing. For the present analysis, only the skin temperature of the hand will be considered, because it is the only one with considerable changes within the short dynamic cycles of this experiment. Skin temperature data from one participant had to be excluded from the analysis due to a sensor failure.

2.7. Statistical analysis

In addition to quality checks, data preparation included processing of heart rate data. The heart rate data from the ecg sensors were processed using software provided by the manufacturer of the sensor (i.e., the Data Analyzer software by movisens). The same software was used to calculate the 10-second interval root mean square of successive differences (RMSSD), a measure of HRV. RMSSD was chosen because it is less affected by respiratory influences and providing a good assessment of the vagal tone [34]. While typically 5-minute intervals are used to assess HRV, short and ultra-short periods are common and reliable [35,36], as well as necessary for our study due to its dynamic protocol.

Data was analysed applying a Bayesian and a frequentist approach. Results from the frequentist approach are presented in the Supplementary materials. The reason for presenting results from the Bayesian approach are (i) the added value of posterior distributions compared to p-values, and (ii) the ability of Bayesian cumulative mixed models to better account for unequal variances often encountered in ordinal outcome variables compared to related frequentist methods.[3] In addition, Bayesian methods tend to provide more intuitive ways to interpret results (e.g., through credibility intervals). In case deviations occurred between outcomes of Bayesian and Frequentist approach, these are mentioned in the discussion.

Table 2 summarizes basic characteristics of the statistical models calculated in relation to the three RQs. Given the repeated measures design, an identifier for each participant was added as varying effect to each model. The statistical analysis was conducted for all 13 dependent variables (i.e., the three thermal assessment votes, the seven mood and well-being related responses, the skin temperature of the hand, mean skin temperature, and the HRV). Cumulative link mixed models with

[3] It should be noted that in the present analysis homoscedastic models were analysed (i.e., a constant latent residual variance was assumed), so that the second advantage does not apply to this work and should be considered as potential for future work.

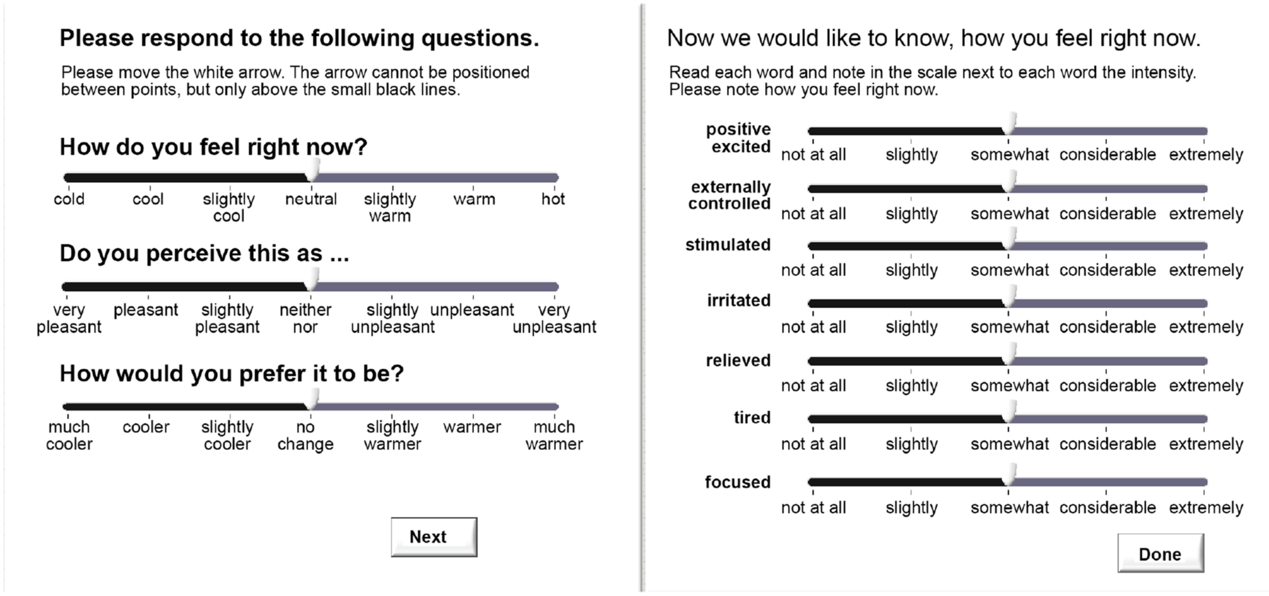


Fig. 2. Translated screenshots of questionnaires shown to participants at each questionnaire timepoint (see also Fig. 1). The original version in German is available in the Supplementary materials.

Table 2
Model formulation and data used related to the three research questions.

RQ	Model formulation (constant effects)	Data used for dependent variables
1	DV ~ Questionnaire number (Q_{num})	2nd and 3rd Q_{num}
2a+3a	DV ~ Sequence*Exposure*Control	2nd and 3rd Q_{num}
2b+3b	dDV ~ Sequence* Control	dDV

DV = dependent variable; dDV = difference in DV between 2nd and 3rd questionnaire number.

logit link and flexible thresholds were applied for all models with ordinal dependent variables (i.e., all models with assessment votes); a Gaussian mixed model was used for models with continuous dependent variables (i.e., all models with physiological parameters). For the continuous dependent variables (skin temperature and HRV), models with their original values and scaled values were estimated.

Rather weakly informative priors were chosen for all RQs, so that they can be overwhelmed even with our moderately sized data if needed [37,38] for the following reasons.

Based on previous literature and thermal sensation models like PMV [39] or ATHB [32], we can hypothesise that a significantly reduced perception of warmth intensity would be expected during relief conditions due to a lower thermal exposure (RQ1). In addition, knowledge on alliesthesia would suggest a so-called overshoot in intensity ratings (e.g., conditions perceived as cooler than expected after the end of a warmth condition) [13]. At the same time, literature is far from providing evidence suitable to inform precise priors in these cases. Furthermore, despite no known study, one would expect also clear tendencies towards higher thermal pleasantness and higher perceived relief with decreased magnitude of exposure. For skin temperature, a trend towards lower skin temperature at cooler conditions can be expected and HRV would be expected to be higher (i.e., less stressed) during phases of relief.

Based on literature in other areas [19], there are at least two possible mechanisms leading to opposing outcomes with respect to the effect of repeated exposures to thermal stress and relief (RQ2). Repeated sequences of exposure and relief could lead to perceptual sensitization to the external stimuli. Such sensitization describes here that the thermal stress is assessed as increasing at each sequence. Similarly, the potential relief increases over time. Hence, participants would react increasingly extreme to these changes. Repetition could also lead to habituation, so that any potential initial pleasure or relief could vanish with repetition. Hence, no clear expectation can be formulated for RQ2 with respect to any of the subjective and physiological parameters.

As perceived control (RQ3) has been shown to increase satisfaction with the thermal conditions and to lead to broader temperature ranges perceived as acceptable [24–26], the expectation is that higher control reduces thermal sensation towards neutrality, increases thermal pleasantness, and increases perceived relief. At the same time, it is known from research on reward processing, that unpredicted rewards elicit stronger release of phasic dopamine as discussed in Becker et al. [19] based on Fiorillo et al. [40], which is linked to pleasure. Hence, uncontrolled and unpredicted relief could also increase thermal pleasure and perceived relief, so that also for RQ3, two pathways are possible. No prior research on the effect of differences in the degree of control over thermal exposures on physiological parameters could be identified, but at least for stress-related parameters like HRV, it can be expected that higher control would reduce stress (i.e. higher HRV values).

Each Bayesian model was sampled using 4 chains, each with 3500 iterations (including 1000 warm-up samples), yielding 10,000 posterior samples per model. Model specifications, Bayesian Factors (BF), $\hat{R}$, and effective sample sizes (ESS) for each Bayesian model are provided in Supplementary Materials. Diagnostic criteria across all Bayesian models provided strong indications of model convergence. All statistical analyses were performed using R 4.5.1 [41]. Results of the models with dependent variables related to one of the three RQs (i.e., thermal sensation, thermal pleasantness, perceived relief, skin temperature of the hand, and HRV) will be reported in the main document. Results of the other variables are placed in the Supplementary materials.

For the interpretation of effects, the following characteristics of the posterior distribution are used following the recommendations by Makowski et al. [42] and Pan et al. [43]: estimates for the median and 95% credibility intervals (CI) based on the Highest Density Interval, the Probability of Direction (PD) as a measure of effect probability, and the percentage within the Bayesian Region of Practical Equivalence (ROPE) as a measure of significance. After rescaling (i.e. dividing the coefficients by the latent standard deviation of the logit model ($\sigma = \pi/\sqrt{3} \sim 1.81$), the estimates from our regression analyses can be interpreted as standardized effect sizes, similar to Cohen's d [44] and are representing the change in the outcome variables in standard deviation units per unit change in the predictor. The PD states the proportion of posterior distribution that is either strictly positive or strictly negative and is a measure of the certainty of the existence of an effect [42]. Thus, the PD corresponds to p-values without transformation and permits familiar interpretations for those used to parameters from frequentist statistics. Here, a PD ≥ 97% is considered as evidence for the certainty of an effect's existence [42]. As a further measure, we applied Bayesian ROPE on posterior effect estimates to assess the practical existence of effects. The ROPE's lower and higher bounds were kept as the default range (i.e., x ± 0.181 on the log-odds scale, which relates to the recommended x ± 0.1*SD of the latent scale of the response variable). Converting this range back to the original 5- and 7-point scales, a shift of ±0.181 log-odds changes the expected rating in a range between 0.04 and 0.07 points (i.e., less than a tenth of a category). Following recommendations based on simulation studies data [42], we calculated the percentage within the ROPE based on 100% of the HDI (i.e., reporting the full ROPE percentage). If the percentage within the ROPE was > 97.5% we considered the effect practically equivalent to zero; in case it was < 2.5%, we concluded that the effect was credibly different from zero. Otherwise, no decision could be made, and further research would be needed.

3. Results

The main results related to the primary and secondary objectives are described in the following sections. Additional figures and results can be found in the Supplementary materials.

Overall, 60 participants completed all questionnaires, leading to n = 1920 data points for each subjective outcome variable. The operative temperature remained within close boundaries slightly above the targeted 30 °C (mean 30.6 ± 0.47 SD – see also Figure S2–1a).

In Fig. 3, an overview is presented for each of the three main subjective outcome variables together with the perception of being externally controlled and their values across the 8 sequences (four with and four without control).

Fig. 4 presents an overview of the values for skin temperature at the hand and HRV at each questionnaire timepoint. As intended, skin temperature recovered through each sequence, so that there was no significant difference between the skin temperature at questionnaire timepoint 11 (Q_{tp} 11, i.e. the first questionnaire of the first sequence) compared to the questionnaire timepoint 41 (Q_{tp} 41, i.e. the first questionnaire of the fourth sequence; 41) (Q_{tp} 11: 34.3 ± 1.04; Q_{tp} 41: 34.4 ± 0.87, t(117): −1.66, p = .10).

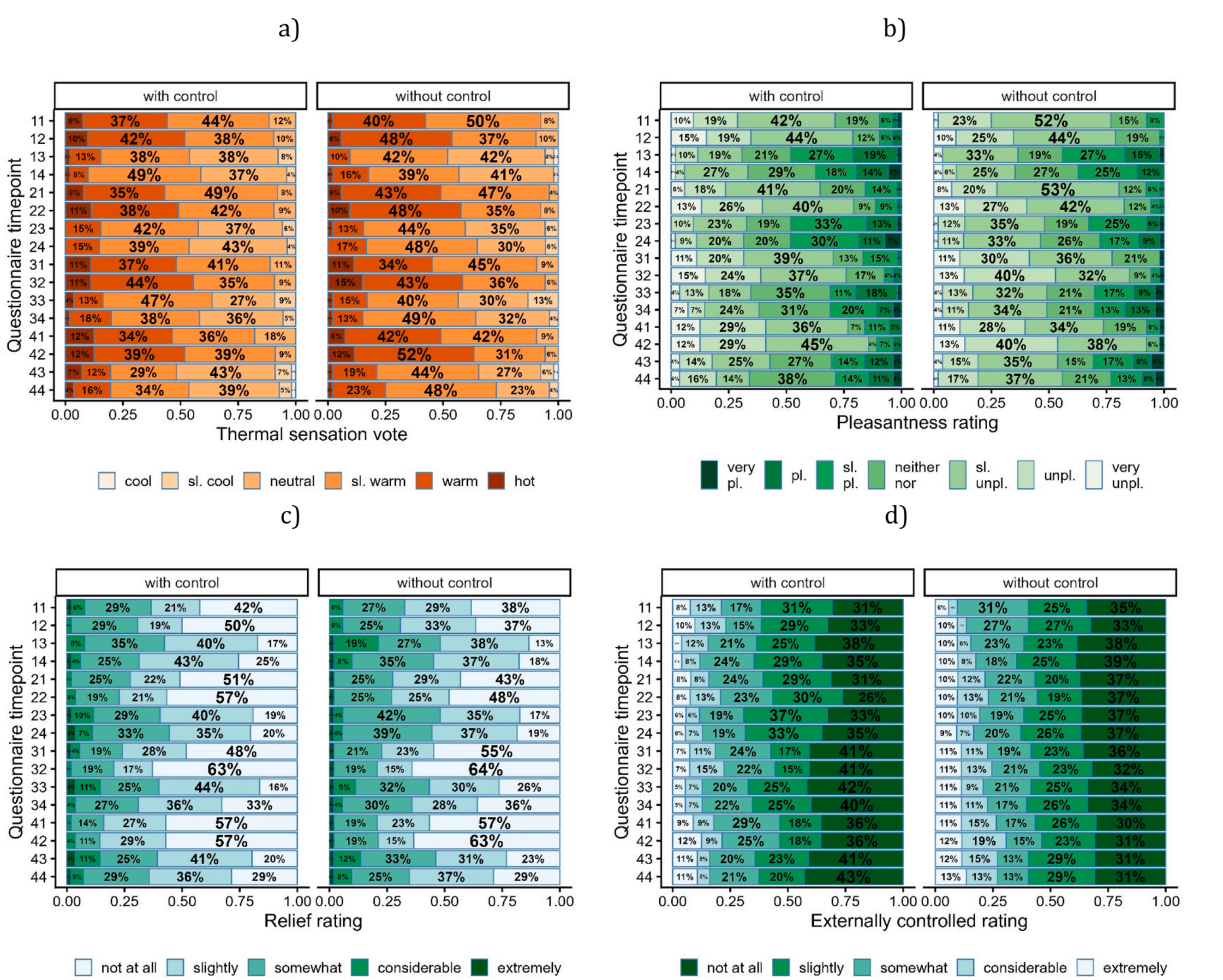
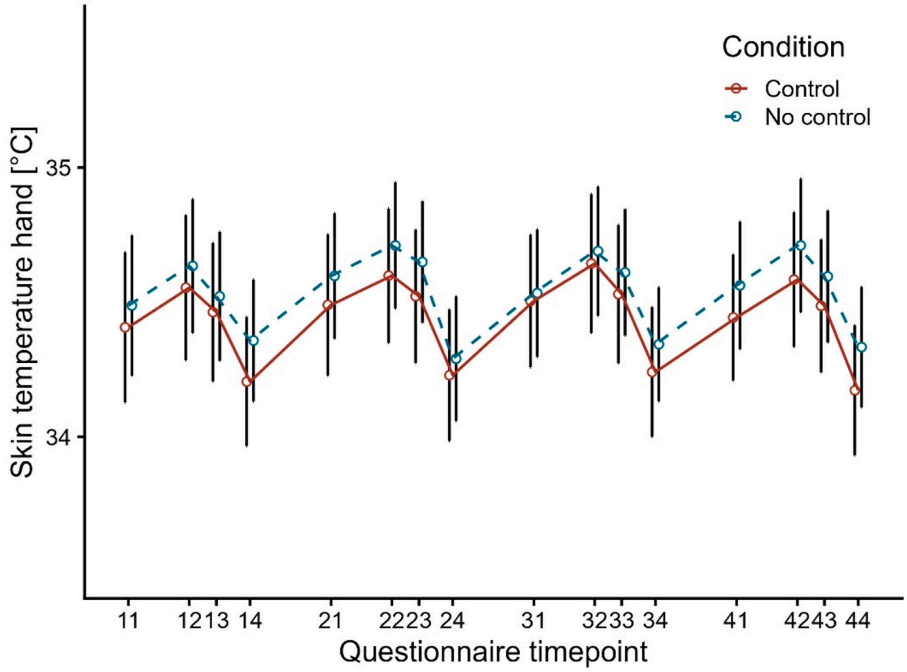


Fig. 3. Distribution of the three main subjective responses: thermal sensation (intensity rating) (a), thermal pleasantness (b), perceived relief (c), together with the perception of being externally controlled (d). Data is visualized separately for each questionnaire timepoint (sequence number + questionnaire number) as well as split for condition with and without control. (sl. = slightly, pl. = pleasant, unpl. = unpleasant).



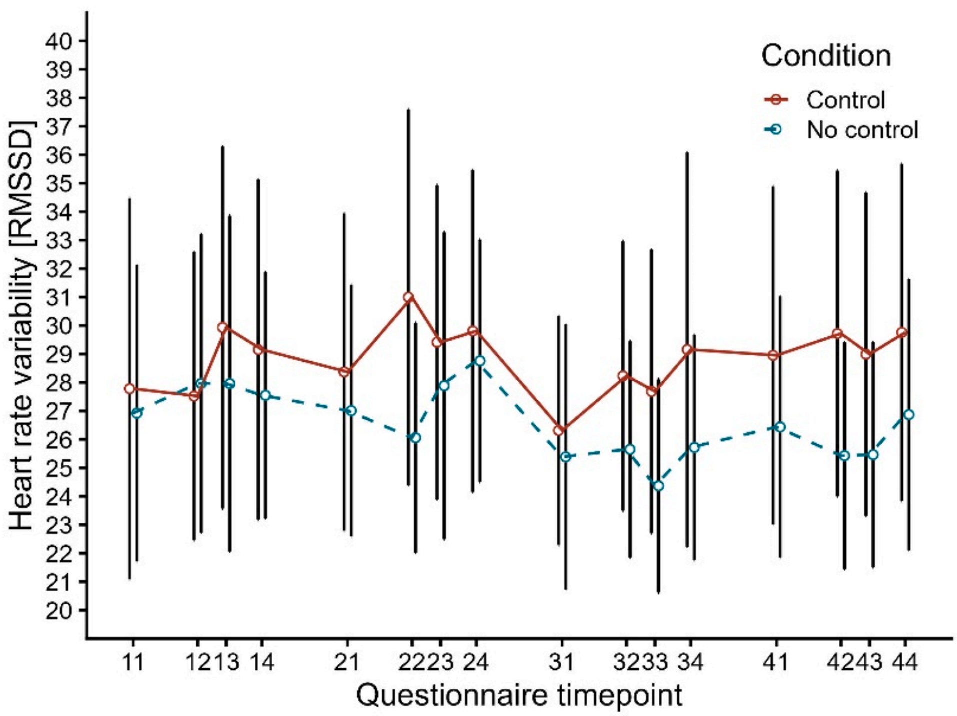


Fig. 4. Overview of means and standard variations of the two physiological parameters: skin temperature at the hand (a) and HRV (RMSSD) (b). Data is visualized separately for each questionnaire timepoint (sequence number + questionnaire number) as well as split for condition with and without control.

3.1. Increased pleasure and perceived relief with reduced thermal stress (RQ1)

As hypothesized, thermal sensation changed from warm towards neutral perception, while thermal pleasure and perception of relief increased between questionnaire number 2 (Q_{num} 2, i.e., before the ceiling fan got switched on) and 3 (Q_{num} 3, i.e., immediately after the ceiling fan got switched on) (Table 3 and Fig. 5). The effect of a reduction in thermal stress has a PD of 100% on all subjective assessments (i.e., of being negative on TSV and TPL and positive on the Relief rating) and can be considered large (median values: TSV: Q_{num} 2: "warm", Q_{num} 3: "slightly warm", TPL: Q_{num} 2: "slightly unpleasant", Q_{num} 3: "neither nor", Relief rating Q_{num} 2: "slightly", Q_{num} 3: "somewhat") and significant (0% *in ROPE*). Converting the coefficients to the original scale the estimated changes correspond to a change of −0.5 points for TSV and for TPL and +0.7 units for the relief rating. With respect to the skin temperature of the hand, the effect does have a PD of 100% as well, suggesting negative changes with negligible effects (std.

Table 3
Characteristics of the posterior distribution of the models related to RQ1 (i.e., the effect of differences in thermal stress level).

Dependent variable	Median/mean [± 95% CI]	PD [%]	% in ROPE
TSV	**−3.09 [−3.43, −2.76]**	**100**	**0**
TPL	**−2.60 [−2.89, −2.32]**	**100**	**0**
Relief rating	**1.73 [1.46, 2.00]**	**100**	**0**
TSK_{Hand}	**−0.09 [−0.12, −0.05]**	**100**	60.4
TSK_{Hand} (scaled)	**−0.08 [−0.11, −0.05]**	**100**	60.6
HRV	0.19 [−0.80, 1.16]	65.1	**100**
HRV (scaled)	0.01 [−0.05, 0.07]	67.4	**99.78**

Note. CI = credibility interval, PD = probability of direction, ROPE = Bayesian region of practical equivalence, TSV = thermal sensation votes, TPL = thermal pleasure vote, TSK = skin temperature, HRV = heart rate variability.

median = −0.08, mean±sd Q_{num} 2: 34.54±0.93, Q_{num} 3: 34.45±0.91), while there is not sufficient data to make a decision on significance (% in ROPE >2.5 and <97.5). Based on the data, there is no clear direction of the effect on HRV (PD < 97%) and the % in ROPE >97.5% suggests that there is no effect (mean±sd Q_{num} 2: 28.1 ± 19.7, Q_{num} 3: 28.6 ± 20.4).

3.2. Variations in subjective assessment and physiological parameters across repetitions (RQ2)

Overall, the results indicate that intensity related changes due to the relief are stable, while the potential to evoke pleasantness and direct relief perception may differ with repeated sequences.

The effect of repetition on TPL has a probability of 99.7% of being positive, with a medium and significant (<2.5% in ROPE) effect (median sequence 1–4: “slightly unpleasant”), suggesting TPL to increase linearly over time (see also Table 4 and Fig. 6a). Based on the data, there is no clear direction of the effect of repetition on TSK_{Hand} (PD < 97%) and the % in ROPE >97.5% suggests supporting that there is no effect. The evidence regarding the effect of repetition on TSV, the relief assessment, and HRV is inconclusive.

As presented in Table 5 and Fig. 6b, the effect of repetition on the change in relief rating has a PD of 99.1%, suggesting positive changes (i.e., increasing difference between relief ratings between stress and relief exposure over repetitions) with moderate effects (std.median = 0.32, median difference sequence 1–3: 0, sequence 4: 1 unit on the 5-point scale), while there is not sufficient data to make a decision on significance (% in ROPE >2.5 and <97.5). Based on the data, the evidence regarding the effect of repetition on TSV, TPL, TSK_{Hand}, and HRV is inconclusive.

3.3. Variations due to control opportunities (RQ3)

Even though Figs. 3 and 4 suggest some influence of the control opportunity on subjective ratings, the variable of control condition and its interactions have no statistical influence on any of the main outcome variables (Tables 6 and 7). The evidence regarding the effect of an increased control opportunity is inconclusive for TSV, TPL, and the Relief rating.

With respect to physiological reactions, based on the data, there is no clear direction of the effect of repetition on TSK_{Hand} (PD < 97%) and the % in ROPE (>97.5%) suggests supporting that there is no effect. With respect to HRV, the effect does have a PD of 99.5%, suggesting negative changes with negligible effects (std.median = −0.055), while there is not sufficient data to make a decision on significance (% in ROPE >2.5 and <97.5).

4. Discussion

An experimental laboratory study with human participants was conducted to investigate the effect of repeated relief from warm thermal exposures on thermal sensation, thermal pleasantness, perceived relief, skin temperature and HRV. Fig. 7 summarizes the main results of the statistical analysis applying the Bayesian framework with respect to the three research questions: RQ1: to what extent relief from warm thermal exposures affected subjective and physiological reactions, RQ2: whether there is an effect of repeated sequences on the outcome variables or the change in outcome variables between thermal stress and relief, and RQ3: whether having control over the end of the warm exposures has an effect on these aspects. The results will be discussed alongside existing limitations and broader implications in the following paragraphs. Noteworthy, interpretation of the results presented here based on the Bayesian approach led to similar conclusions as those based on the frequentist approach presented in the Supplementary materials.

4.1. Changes due to reduction in thermal stress (RQ1)

For all subjective responses, there was a clear direction for large significant effects following the relief from thermal stress. On the one hand, this result was largely expected based on the vast body of literature related to thermal sensation. For example, Buonocore et al. [23] consolidated repeated evidence of stronger cooling effect observed for dynamically modulating air speeds in warm and hot environments compared to constant airflows of comparable mean air speed. On the other hand, this is the first time, such effects are shown for direct measures of perceived thermal pleasure and perceived relief. Given the inverse relationship of their trends, one may wonder whether thermal pleasure and perceived relief are merely opposite aspects of the same assessment. In this study, we observed moderate to strong correlations (Kendall’s Tau = 0.35) between these votes throughout the experiment. Similar strong correlations (Pearsons’ r = 0.56) have been observed by Leknes et al. [45] with respect to perceived pain relief and perceived pleasantness ratings. However, our study design was not intended to and cannot add further evidence to answer this question. Based on Leknes et al. [45] and our own observations, we could hypothesize that perceived relief is a more discriminative interpretation of the perception of a change (i.e., an analogy to thermal sensation for the perception of intensity), while perceived pleasure is the corresponding hedonic component (i.e., analogues to thermal comfort in previous example). Further studies, that are specifically designed to disentangle these to constructs, will be needed to challenge this hypothesis.

In contrast to the clear findings related to subjective responses, there is a probably negative, but negligible effect of the changed exposure on the skin temperature at the hand. Given the warm thermal exposure and the small difference between skin temperature at the hand (mean 34.5 °C ± 0.9 SD) compared to the mean skin temperature (mean 34.7 °C ± 0.5 SD), thermal strain is probably at the higher end of thermoneutral zone. At the same time, this heat strain is most likely still compensable with only minor changes in core temperature due to the relatively short length of the exposure and frequent relief periods [46]. At these conditions, the driver for thermal perception (and thermoregulatory behaviour) is commonly considered the skin temperature [47].

The contrast between subjective thermal sensation and the physiological signal is noteworthy and might have several reasons: (i) the potential small change in skin temperature was sufficient as a signal for a changed thermal sensation. Such observation would be in contrast to earlier associations between skin temperature and thermal sensation [48]. In Song et al. [48] one unit change of thermal sensation was associated with more than 1 K difference in skin temperature of the hand, we observed a 0.1 K difference in skin temperature related to an observed change of thermal sensation of two units. (ii) The perception of air velocity on the skin led to anticipated lowered thermal sensation despite the small change of actual skin temperature, or (iii) the thermal inertia of the iButtons did not capture the true change in skin temperature as an earlier benchmark study demonstrated a delayed response of iButtons compared to thermocouples [49]. Future studies will need to disentangle these potential reasons given that there is an increasing interest in predicting a persons’ thermal state through physiological

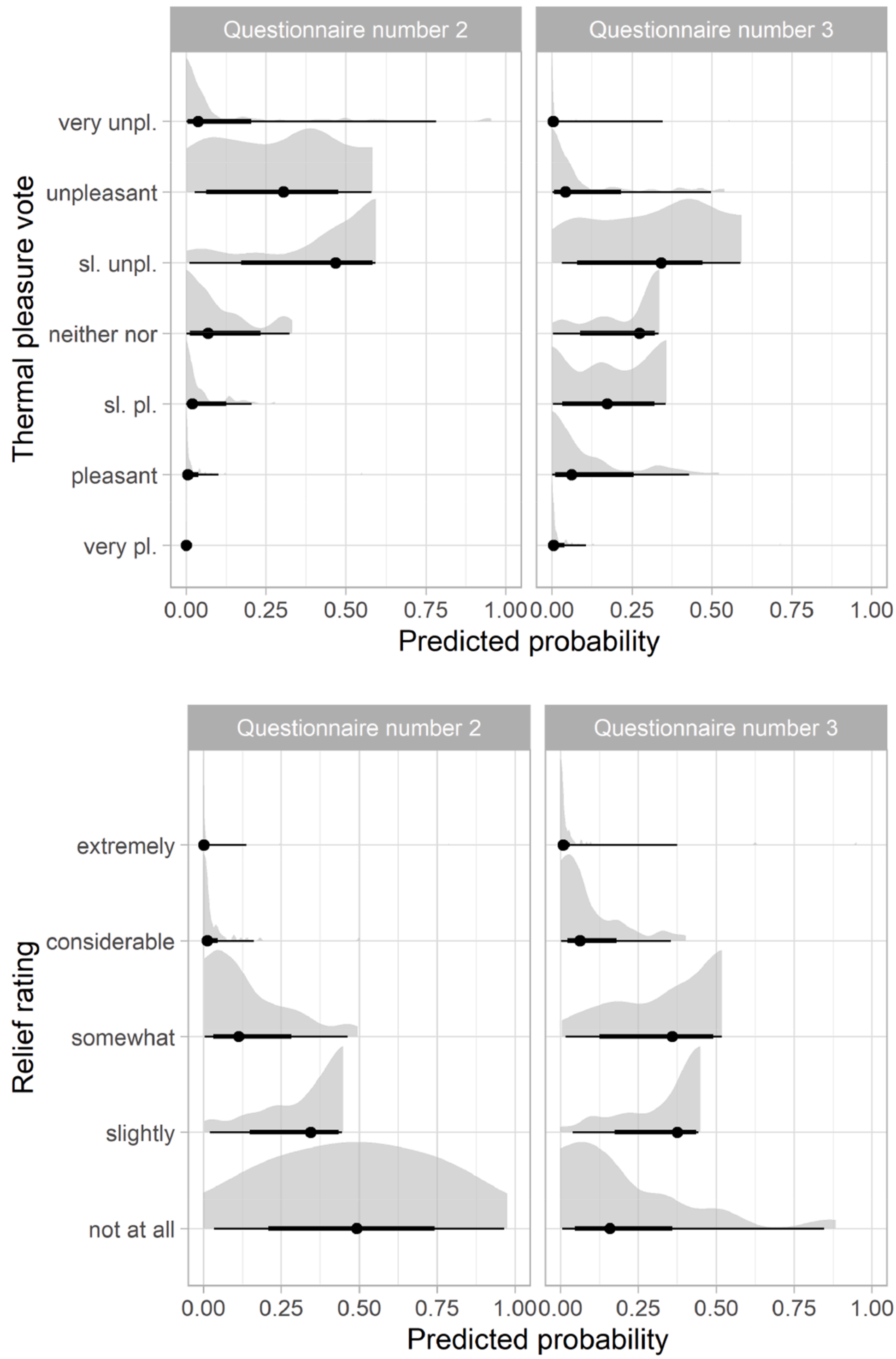


Fig. 5. Predicted probabilities for thermal pleasure vote (TPL) and relief rating at questionnaire number 2 (elevated thermal stress) compared to questionnaire number 3 (just after reduction of thermal stress by means of switched on ceiling fan.

signals alone.

4.2. The effect of repetitions (RQ2)

The effect of repetitions is less clear compared to those of the exposure. For most variables, no decision regarding significance could be made (e.g., TSV, Tskin, HRV) or the data suggested no effect (e.g., Tskin, HRV). These results suggest that the effect of exposure is sustained over the four repetitions (sequences) and neither perceptual sensitization nor habituation occurred for thermal sensation. At the same time, the absolute values of pleasure (Table 4) increased with repetitions (median 0.62) as well as the difference in relief ratings between thermal stress and relief (median 0.58), though the data was not strong enough to make a decision on significance for the latter. The absolute increase in pleasantness across time could be due to participants learning to appreciate the dynamics during the experiment, or simply due to them knowing that the end of experiment is coming closer with each repetition. Hence, the current design cannot distinguish

Table 4
Characteristics of the posterior distribution of the models related to RQ2a (i.e., the effect of repetitions of phases with elevated and reduced thermal stress levels on absolute values of the dependent variables).

Dependent variable	Median/mean [± 95% CI]	PD [%]	% in ROPE
TSV	L. 0.08 [−0.37, 0.54]	63.8	56.35
	Q. −0.29 [−0.74, 0.16]	89.5	30.67
	C. 0.00224 [−0.45, 0.47]	50.4	59.78
TPL	**L. 0.62 [0.19, 1.06]**	**99.7**	**0**
	Q. 0.03 [−0.40, 0.46]	56.5	62.15
	C. −0.19 [−0.61, 0.23]	80.5	46.12
Relief rating	L. −0.05 [−0.48, 0.37]	59.1	60.29
	Q. 0.09 [−0.34, 0.51]	66.6	58.56
	C. −0.05 [−0.48, 0.39]	58.4	60.44
TSK_{Hand}	L. 0.00396 [−0.07, 0.07]	55.0	**98.96**
	Q. −0.04 [−0.10, 0.03]	86.1	94.47
	C. 0.02 [−0.05, 0.09]	69.3	**98.08**
TSK_{Hand} (scaled)	L. 0.00370 [−0.06, 0.07]	54.9	**100**
	Q. −0.03 [−0.10, 0.03]	84.8	96.99
	C. 0.02 [−0.05, 0.08]	70.2	**100**
HRV	L. 0.51 [−0.72, 1.72]	79.3	**99.2**
	Q. −0.68 [−1.92, 0.52]	86.5	**98.3**
	C. 0.40 [−0.86, 1.56]	74.1	**99.6**
HRV (scaled)	L. 0.05 [−0.06, 0.16]	82.0	80.55
	Q. −0.05 [−0.16, 0.06]	81.7	80.29
	C. −0.00125 [−0.12, 0.11]	50.8	96.55

Note. CI = credibility interval, PD = probability of direction, ROPE = Bayesian region of practical equivalence, TSV = thermal sensation votes, TPL = thermal pleasure vote, TSK = skin temperature, HRV = heart rate variability. L = linear component, Q = quadratic component, C = cubic component.

between potential explanations related to short term adaptation, learning, changed expectations or others. The observed increase in relief is in line with the results of the experiment with repeated pain stimuli conducted under similar circumstances [19], where relief increased with repetition, but levelled off after 2 to 4 repetitions.

4.3. The effect of control (RQ3)

The results from this study suggest no effect of perceived control on any of the outcome parameters, although most decisions regarding significance were inconclusive. This result is in contrast to earlier literature suggesting an effect of control on thermal assessment [24–26], while in line with literature that conclude that there is no effect of control on thermal sensation [50,51], These findings also contrast those of the experiment inducing pain, where perceived pain relief was larger in conditions without perceived control compared to those with control [19]. At least two explanations are possible for this finding: (i) the manipulation of control (i.e., applying a quasi-placebo control) was most likely not effective and participants may have realized that their actual level of control was very limited. No data exists whether and if when participants reacted to the prompt, so that no direct analysis can be made. In addition, the onset of relief after pressing the button took a few seconds due to the fan just starting to run silently (i.e., no prior acoustic cue), which may have diluted the direct connection between ones' action and the effect. While the 'externally controlled' ratings showed a moderate effect with high probably direction and significance (Tables S3–2 and S3–3 in Supplementary materials), suggesting that the control manipulation was effective, the absolute magnitude was marginal (i.e., the median value was 1 ("slightly") throughout all timepoints and conditions). (ii) The difference in perceived control was not strong enough to elicit effects on other variables. While the literature mentions effects of control on subjective assessments, there is a lack of quantification regarding the degree of change in actual or perceived control eliciting such effects. In summary, based on the experimental procedure and available data, causal claims related to the effect of control on the outcome variables are not possible and any related conclusions reflected with great caution.

4.4. Reflection on the use of Bayesian analysis methods

Since the application of Bayesian analysis is still rare within the field of thermal assessment, it is meaningful to reflect its usage. The analysis approach offers further and more intuitive decision criteria, which permit interpretations regarding the probability of the direction of an effect, its size, and a decision to what extent the data is supporting an alternative hypothesis, the null hypothesis, or neither of them. Especially the last point (i.e., to identify the probability of null effects) is meaningful within the field of indoor environmental quality-related research given the sometimes large number of potential effects [43]. While we have used standard parameters related to the choice for the ROPE range, future studies could select and transparently communicate values based on accepted decision criteria within the field of research. For example, the selection of the ROPE range could be based on certain thresholds of the scale itself such as accepting a difference within 0.1 units on the 7-point scale as equivalent and a difference outside 0.5 units as a practically meaningful one. Such thresholds would also permit cost-benefit analysis (e.g., related to the question how much it costs when a wrong decision was made) [52].

Following the suggestions by Favero et al. [53], the chosen cumulative link mixed models with logit link permit not only to analyse ordinal data in a statistical correct way, but also to use flexible (i.e., non-equidistant) thresholds. The effect can be observed when looking at the estimates for the intercepts given in the Supplementary materials section S6. For example, the estimates for the model of TSV clearly shows non-equidistant spaces between the individual votes. Together with further evidence that the votes are not equidistant [54,55], such flexibility for a model should be applied in future research on the association between environmental parameters and subjective assessments.

Finally, the estimates observed in this study and presented in the Supplementary materials can be used for future studies applying Bayesian analyses as priors and therefore adding to cumulated science approaches.

4.5. Limitations

Being a laboratory experiment, external validity is a common and major limitation of this study. Data was collected in a controlled environment and despite its natural appearance, which is simulating the appearance of a typical office workplace, participants were not in their natural work environment and exposed for a limited period. Hence, generalizability is limited and further replications including other settings, climatic contexts, and study populations are needed.

Due to the short-term and limited number of repetitions, long-term adaptations cannot be inferred and longer studies are needed. In addition, only a single value for the air velocity of 0.3 m/s was chosen. Higher air velocities could have increased the observed effects of relief, which would deserve replication studies applying variations of the air velocity. It should be noted that the air velocity was measured only around the head level of 1.1 m, which is higher than the value obtained at 0.6 m in conditions with a ceiling fan, and that no measurements of illuminance or the spectral distribution of the lighting nor the prevailing sound pressure level were done. Hence the values for air velocity presented above are not representative for a sedentary occupant according to ASHRAE Standard 55, and we cannot assess whether variations of the visual and acoustic environment affected the subjective or physiological outcome.

The concept of alliesthesia suggests an overshoot in thermal sensation after being relieved from thermal stress [14]. Despite collecting thermal sensation votes frequently, we could not quantify such a potential overshoot. The reason differs depending on the definition of overshoot. In case we define the overshoot as the difference between a predicted and observed thermal sensation, a quantification of the overshoot would require an exact prediction of an expected thermal

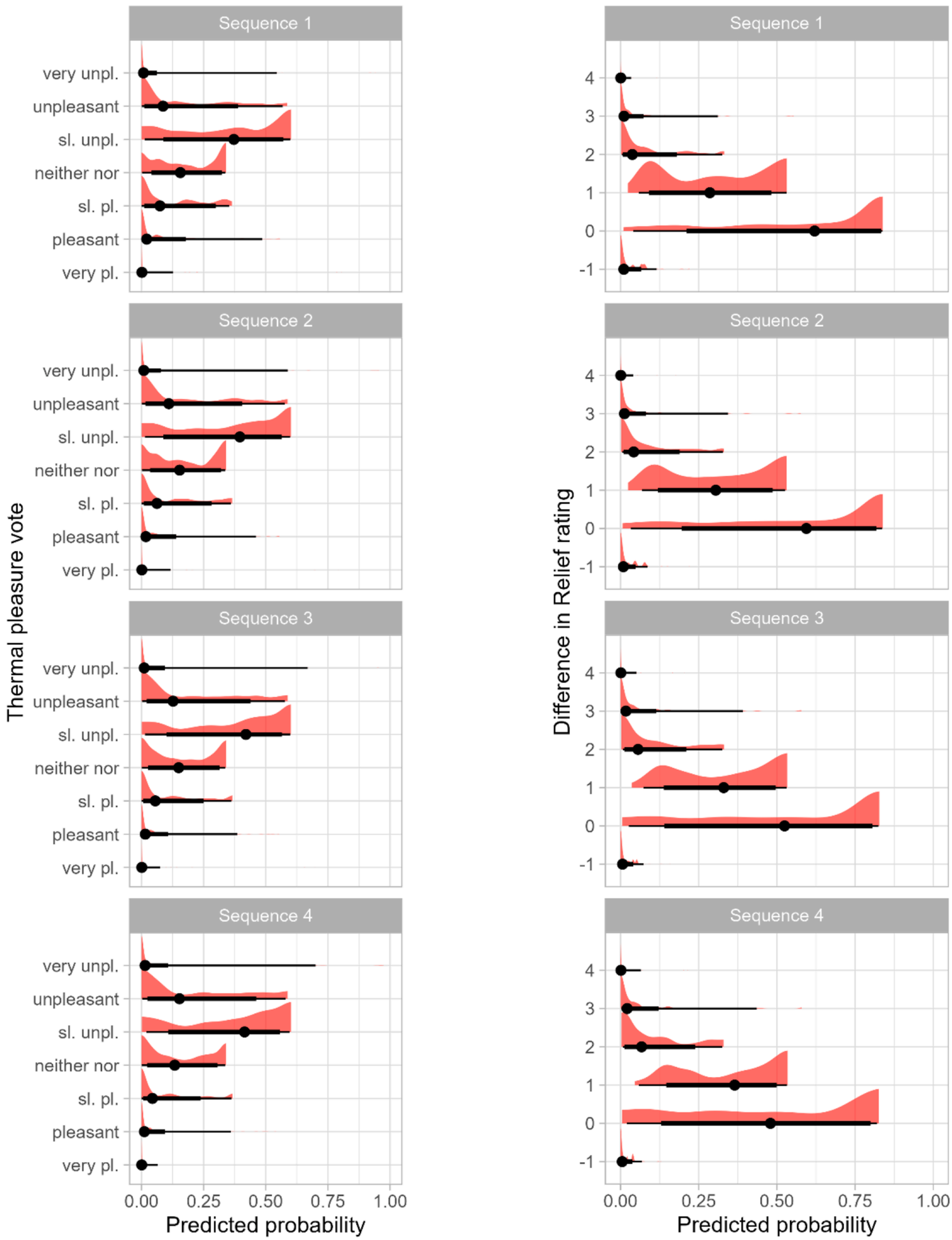


Fig. 6. Predicted probabilities a) for the absolute values of the thermal pleasure vote (TPL) across repetitions, and b) for the difference in relief ratings between conditions with just reduced and elevated thermal stress across repetitions. A positive difference related to an increase in perceived relief after the ceiling fan was switched on.

Table 5
Characteristics of the posterior distribution of the models related to RQ2b (i.e., the effect of repetitions on the difference of the dependent variables between phases with elevated and reduced thermal stress levels).

Dependent variable	Median/mean [± 95% CI]	PD [%]	% in ROPE
dTSV	L. 0.00522 [−0.49, 0.50]	50.9	56.71
	Q. −0.20 [−0.69, 0.28]	79.3	42.71
	C. −0.06 [−0.53, 0.42]	59.9	55.72
dTPL	L. 0.46 [−0.01, 0.92]	97.2	10.38
	Q. −0.002.84 [−0.46, 0.45]	50.4	59.31
	C. −0.30 [−0.75, 0.14]	90.7	28.48
dRelief rating	**L. 0.58 [0.10, 1.08]**	**99.1**	3.23
	Q. −0.23 [−0.73, 0.27]	80.7	38.95
	C. 0.05 [−0.45, 0.54]	57.2	54.09
$dTSK_{Hand}$	L. −0.00759 [−0.05, 0.03]	63.9	55.78
	Q. 0.03 [−0.02, 0.07]	88.2	32.02
	C. −0.00103 [−0.04, 0.04]	52.0	57.55
$dTSK_{Hand}$ (scaled)	L. −0.04 [−0.27, 0.20]	64.2	59.50
	Q. 0.14 [−0.09, 0.39]	88.2	35.20
	C. −0.00307 [−0.24, 0.23]	50.9	62.15
dHRV	L. −1.00 [−2.32, 0.30]	93.3	40.05
	Q. 0.36 [−0.90, 1.78]	70.1	71.33
	C. 0.24 [−1.09, 1.51]	63.8	75.42
dHRV (scaled)	L. −0.22 [−0.47, 0.06]	94.6	17.88
	Q. 0.13 [−0.13, 0.40]	83.2	38.93
	C. −0.08 [−0.34, 0.19]	71.1	49.37

Note. CI = credibility interval, PD = probability of direction, ROPE = Bayesian region of practical equivalence, dTSV = difference in thermal sensation votes, dTPL = difference in thermal pleasure vote, dTSK = difference in skin temperature, dHRV = difference in heart rate variability. L = linear component, Q = quadratic component, C = cubic component.

Table 6
Characteristics of the posterior distribution of the models related to RQ3a (i.e., the effect of different levels of control on absolute values of the dependent variables).

Dependent variable	Median/mean [± 95% CI]	PD [%]	% in ROPE
TSV	−0.23 [−0.59, 0.12]	90.5	38.74
TPL	0.28 [−0.04, 0.60]	95.2	27.55
Relief rating	0.13 [−0.20, 0.47]	77.6	61.78
TSK_{Hand}	−0.00947 [−0.06, 0.04]	64.7	**100**
TSK_{Hand} (scaled)	−0.00867 [−0.06, 0.03]	64.4	**100**
HRV	**−1.23 [−2.39, −0.17]**	**98.6**	91.20
HRV (scaled)	**−0.10 [−0.19, −0.03]**	**99.5**	46.48

Note. CI = credibility interval, PD = probability of direction, ROPE = Bayesian region of practical equivalence, TSV = thermal sensation votes, TPL = thermal pleasure vote, TSK = skin temperature, HRV = heart rate variability. L = linear component, Q = quadratic component, C = cubic component.

Table 7
Characteristics of the posterior distribution of the models related to RQ3a (i.e., the effect of different levels of control on the difference of the dependent variables between phases with elevated and reduced thermal stress levels).

Dependent variable	Median/mean [± 95% CI]	PD [%]	% in ROPE
dTSV	−0.36 [−0.71, 0.00]	97.5	15.06
dTPL	0.08 [−0.26, 0.42]	67.8	69.52
dRelief rating	−0.18 [−0.55, 0.19]	82.5	50.55
$dTSK_{Hand}$	0.00466 [−0.02, 0.03]	62.9	72.69
$dTSK_{Hand}$ (scaled)	0.03 [−0.14, 0.20]	62.2	77.61
dHRV	−0.34 [−1.58, 0.84]	70.3	75.96
dHRV (scaled)	−0.07 [−0.25, 0.14]	74.6	61.68

Note. CI = credibility interval, PD = probability of direction, ROPE = Bayesian region of practical equivalence, dTSV = difference in thermal sensation votes, dTPL = difference in thermal pleasure vote, dTSK = difference in skin temperature, dHRV = difference in heart rate variability. L = linear component, Q = quadratic component, C = cubic component.

sensation or control conditions. However, given the lack of accuracy for predicting individual votes of established models [56], there is currently no available thermal sensation model that would be able to predict such value for an individual person under specific conditions. Future studies may add steady-state reference conditions for both temperature levels or multiple baseline temperatures together with the assessment of expectations before fan onset so that each person can be compared under steady-state and dynamic conditions. Alternatively, one could compare participants initial sensation response after the relief with their later response (i.e., the thermal sensation votes between Q_{num} 3 and Q_{num} 4). This comparison shows that median values do not differ (median TSV Q_{num} 3 and Q_{num} 4: "neutral). However, such result is no sign of missing overshoot as the literature does not permit specifying a specific length for the overshoot. Earlier studies by Parkinson and de Dear [14] or Arens et al. [22] suggest a degrading overshoot within the first 4–5 min. Given the short distance of Q_{num} 4 to the point of relief (3 min after switching on the fan), could explain the result in a way, that there is either no overshoot or the overshoot still exists at Q_{num} 4. Further research is needed to quantify the length and degree of the overshoot.

There were no measurements of core body temperature, hence it cannot be assessed whether the thermal strain increased over time. The lack of change in skin temperature of the hand over repetitions suggests no to minor increased thermoregulatory deviations. At the same time, descriptive analysis of mean skin temperature data (see Supplementary Materials sections S2 and S4) showed a negligible positive effect over repetitions below 0.1 K between the first and last repetition with high probability of direction and significance.

As discussed in Section 4.3, the manipulation of control was very likely not successful so that any conclusions regarding the effect of control on the observed outcome variables should be drawn with great cautiousness.

5. Conclusions

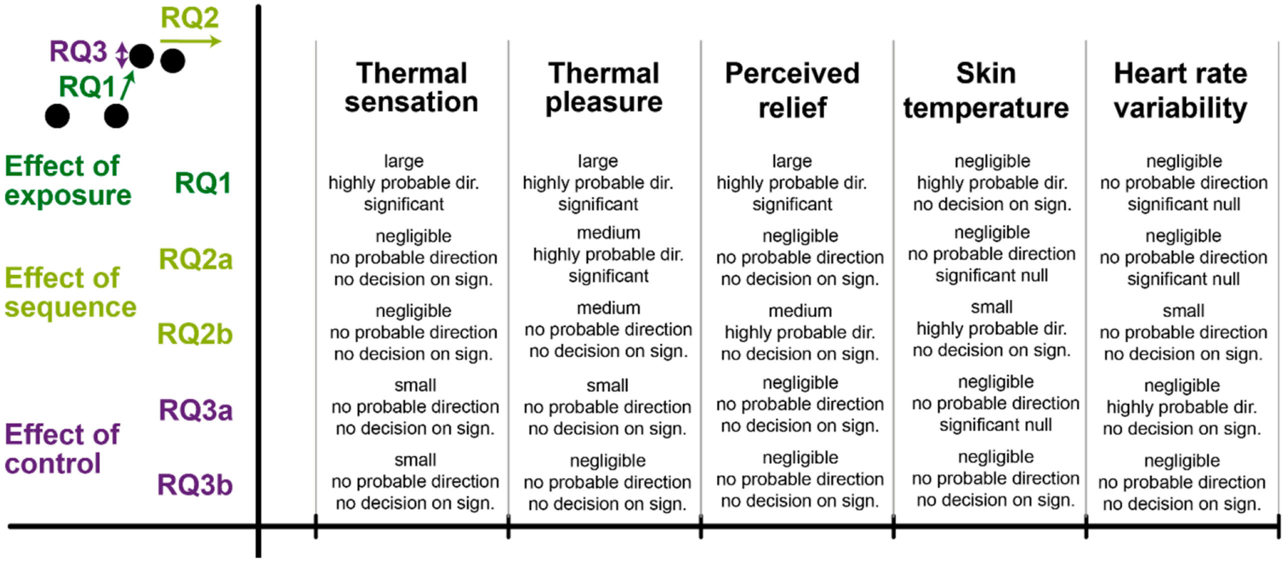
We conclude with reflections and implications related to the content as well as the analysis methodology.

Content related, this study is the first study applying direct measures for perceived thermal pleasure and perceived relief over a small number of repeated cycles of different levels of thermal stress exposure. The results indicate that perceived pleasure and relief can be achieved through such cycles. As mentioned introductory, such conditions might have positive health effects and could support energy efficient HVAC concepts, while acceptance is partly low due to concerns of discomfortable conditions. Given the notion of relief as motivator for reward and learning known from other fields of research [18–20], experiences of cyclic exposures and related perceptions of pleasure and relief could support a transition towards the application of more dynamic conditions and wider temperature ranges than currently found in many buildings. An example could be higher cooling setpoints or naturally ventilated cooling concepts combined with intermittent air movement that deliver perceptible relief and pleasantness.

Thereby, the means of providing such cyclic conditions could be among others ceiling fans as in this study, standing or table fans, cooling chairs, clothing level adjustments or with lower speed of change and depending on indoor and outdoor conditions window openings. As such, the same means considered in recent years as a low-energy, low-cost alternative to air conditioning [e.g.. 57–59] can be applied for such dynamic changes. Whether the experience of pleasure induced through such dynamic changes is strong enough for behavioural changes needs to be investigated in future studies.

CRediT authorship contribution statement

Marcel Schweiker: Writing – original draft, Validation, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Karin Schakib-Ekbatan:** Writing – review & editing, Methodology, Investigation, Data curation, Conceptualization. **Bhavya Swapneel Pathak:** Writing –



		Thermal sensation	Thermal pleasure	Perceived relief	Skin temperature	Heart rate variability
Effect of exposure	RQ1	large highly probable dir. significant	large highly probable dir. significant	large highly probable dir. significant	negligible highly probable dir. no decision on sign.	negligible no probable direction significant null
Effect of sequence	RQ2a	negligible no probable direction no decision on sign.	medium highly probable dir. significant	negligible no probable direction no decision on sign.	negligible no probable direction significant null	negligible no probable direction significant null
	RQ2b	negligible no probable direction no decision on sign.	medium no probable direction no decision on sign.	medium highly probable dir. no decision on sign.	small highly probable dir. no decision on sign.	small no probable direction no decision on sign.
Effect of control	RQ3a	small no probable direction no decision on sign.	small no probable direction no decision on sign.	negligible no probable direction no decision on sign.	negligible no probable direction significant null	negligible highly probable dir. no decision on sign.
	RQ3b	small no probable direction no decision on sign.	negligible no probable direction no decision on sign.	negligible no probable direction no decision on sign.	negligible no probable direction no decision on sign.	negligible no probable direction no decision on sign.

Fig. 7. Overview of results with respect to the five main outcome variables and three research questions (see also Fig. 1). Interpretation is based on the estimate (effect size), probability of direction (PD) and percentage in ROPE (significance).

review & editing, Writing – original draft, Data curation. **Hannah Pallubinsky:** Writing – review & editing, Writing – original draft, Supervision, Data curation. **Susanne Becker:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

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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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.buildenv.2026.114794.

Data availability

Data will be made available on request.

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