Human conscious response to thermal input is adjusted to changes in mean body temperature

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ABSTRACT

Objective and Design: To detect the dependable criteria of behavioural thermoregulation through modelling temperature fluctuations of individuals allowed to freely manipulate inlet water temperature of a liquid conditioning garment (LCG) during 130 min of passive exposure to −20°C interspersed with a 10 min period of moderate exercise at the 65th minute using a double-blind experiment.

Participants: Eleven volunteers (5 women; 23.40 (SD 2.09) years; BMI: 23.24 (SD 2.19)) who lacked previous experience with LCG and cold exposure experiments.

Results: Despite variations in core and skin temperatures, thermal comfort, thermal sensation, and mean body temperature did not fluctuate significantly over time. Participants were able to find a desired level of LCG inlet temperature within 25 minutes which was maintained at similar levels until the 65th minute of the cold exposure. During exercise, LCG inlet water temperature decreased significantly. Regression models demonstrated that mean skin temperature and change in mean body temperature were significantly associated with thermal comfort and thermal sensation. Subsequent models revealed that, although all temperature variables were associated with LCG inlet water temperature, the coefficient of determination mainly depended on mean skin temperature and change in mean body temperature. The involvement of skin temperature was anticipated as the liquid conditioning garment was in contact with the skin.

Conclusions: Humans generate conscious thermoregulatory responses in resting and exercise conditions during exposures to cold environments that are aimed towards maintaining a threshold mean body temperature, rather than temperature changes in individual body regions.

Behavioural thermoregulation is the principal form of thermoregulation used by humans, and is mediated through conscious thermoregulatory response.[1–3] Yet, despite previous attempts, knowledge on the behavioural mechanism controlling thermoregulation remains limited. For instance, it has been shown that mean skin temperature (T_{sk}) per se is not a dependable criterion of behavioural thermoregulation[4] and that the main signal is of internal origin.[5] However, there have been other reports documenting that behavioural thermoregulation is independent of core temperature (T_c)[2] and that thermal pleasantness sensation is a function of both T_{sk} and T_c.[6] On the other hand, recent work on behavioural responses to an increase in body temperature during exercise[7] showed that humans lower their exercise work rate in order to maintain a similar rate of heat storage. According to this premise, T_{sk} seems to carry important information to the brain to regulate exercise behaviour – and thus metabolic rate – independently of rectal temperature.[7 8]

The main challenge in examining behavioural thermoregulation stems from the complexity in the body's responses to different stimuli, as well as the difficulty in explicitly identifying the system of interest and isolating it from other systems within the body, as well as external dynamics. These challenges can be addressed by supplying the body with an additional thermoregulatory system that can be accurately and objectively quantified. When a human is situated in an environment that forces its use, information gained from this hybrid system may provide valuable evidence on the fundamental principles that govern behavioural thermoregulation. Given that liquid conditioning garment systems have been successfully implemented in the past to manipulate thermal balance,[9] we monitored and modelled the fluctuations in temperature of individuals given voluntary control of the inlet temperature of their garments during prolonged passive cold exposure interspersed with a period of moderate exercise. Our purpose in this experiment was to detect the dependable criteria of behavioural thermoregulation based on which the conscious response to thermal input is generated.

METHODS

Participants and procedures

The experimental protocol conformed to the standards set by the Declaration of Helsinki and was approved by the appropriate ethical review board at Dalhousie University. The study adopted a cross-sectional double-blind design. Eleven healthy non-smoking adults (six men, five women; age 23.40 (SD 2.09) years; height: 1.74 (SD 0.09) m; weight: 70.41 (SD 11.74) kg) who had no, or very limited, previous experience with liquid conditioning garments or cold exposure experiments volunteered for the study. Female subjects were tested during the early follicular phase (days 1–6) of their menstrual cycle. Written informed consent was obtained from all participants after full explanation of the procedures involved. However, in order to eliminate psychological bias, the participants were informed of the specific purpose of the study only after the data collection. The information given to them at the beginning was that the purpose of the study was to assess hand function during cold exposure. For this purpose, they completed several hand function assessments during the testing period which were irrelevant to the scope of this study. Participants were given a detailed verbal description of the protocol, followed by extensive familiarisation with all data collection procedures and instruments

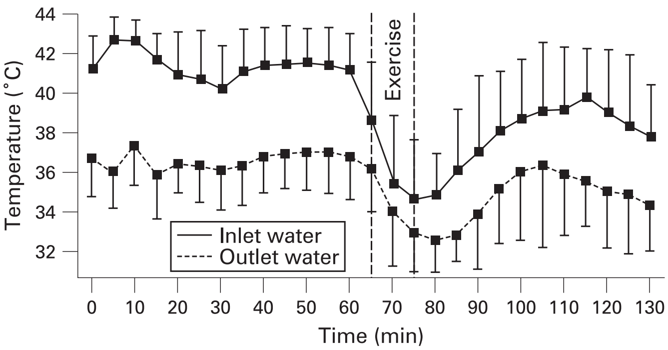

Figure 1 Mean (SD) inlet and outlet temperature of the liquid conditioning garment over time. Values represent 5 minute means derived from data collected every 8 seconds.

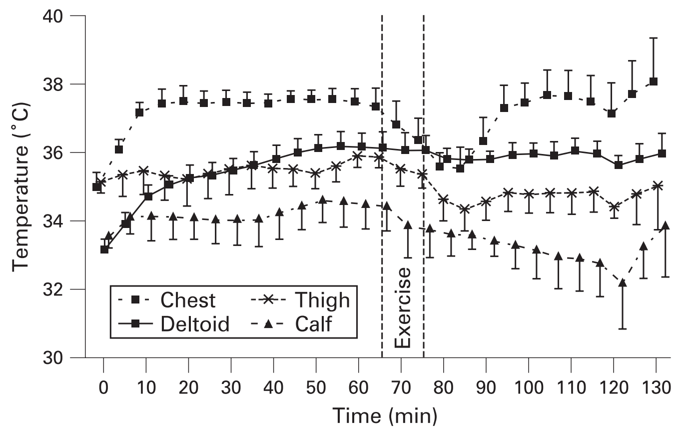

Figure 2 Mean (SD) temperature over time in various skin regions. Values represent 5 minute means derived from data collected every 8 seconds.

during an initial familiarisation session performed at least 3 days prior to testing. Anthropometrical measurements were also performed at this time.

The testing protocol required participants to undergo a cold exposure while wearing a liquid conditioning garment underneath arctic clothing. Subjective thermal comfort (from 0 (extremely uncomfortably cold) to 10 (comfortable) to 20 (extremely uncomfortably warm) with increments of 1) and thermal sensation (from 0 (unbearably cold) to 10 (unbearably hot) with 5 as thermoneutral) were recorded every 32:30 minutes using scales for transient uniform conditions modified from Gagge *et al*,[10] while various thermoregulatory variables (see appropriate section) were recorded continuously throughout. The thermal sensation and thermal comfort models adopted are two of the most commonly used thermal sensation models and have been extensively used in environmental physiology.[11] For reference purposes, baseline measurements for each examined variable were implemented prior to cold exposure while participants relaxed seated in a thermoneutral environment (room temperature: 25°C; relative humidity: 40%) for 20 minutes while wearing as many parts of the clothing ensemble (see below) as they wished.

Testing was conducted by the same investigators and between 09:00 and 14:00 h. Participants were extensively familiarised with the liquid conditioning garment (for detailed description of this system see appropriate section) and the control of its inlet water temperature during an initial session performed at least 3 days prior to testing. They were instructed to consume a light breakfast and adequate amounts of water prior to arriving in the laboratory, having abstained from alcohol and caffeine for 12 h. Ad libitum water ingestion (~25°C) was permitted during data collection. Participants were also advised to avoid physical activity and excessive stressors such as exposure to extreme hot or cold temperatures for 48 h prior to data collection and particularly during the period between awakening and experimentation and during transit from home to the laboratory. Adaptations to low winter-time temperatures may have persisted, as measurements were performed during the months of April and May (mean ambient temperature: 6.7°C (1.5) (Environment Canada)).

Thermal control

Participants wore a single-piece liquid conditioning garment (Med-Eng, Pembroke, ON, Canada) consisting of 1/8'' diameter Tygon tubing sewn over a close-fitting stretchable hood (6.1 m of tubing), shirt covering the torso and arms (38.1 m of tubing), and pants (25.0 m of tubing). The face, hands, and feet were left uncovered. To promote maximum heat transfer between the skin and the garment, male participants wore only shorts while women also wore a bra. Inlet water temperature of the garment, with a flow rate of ~1 l/min, was controlled by a recirculating chiller/heater (Polyscience, Niles, Illinois, USA) with a resolution of 0.5°C. The water entered the suit through the waist and quickly diffused throughout the entire suit. Inlet temperature was regulated by the participants towards "warmer" or "colder" throughout the cold exposure to subjective thermal comfort without any feedback on suit or body temperature. Specifically, participants were free at any time to request an experimenter situated inside the environmental chamber (experimenter 1) to raise or lower the inlet temperature of the suit. In turn, experimenter 1 carried the participants' requests to another experimenter (experimenter 2) situated outside the environmental chamber through a wireless communication system, but was given no feedback of any kind on how many "units" (of 0.5°C) the temperature was adjusted. Experimenter 1 was instructed to follow precisely the participants' instructions and not influence their decisions regarding inlet temperature change. Thus, both the participants and experimenter 1 were blinded to the exact inlet temperature as well as to the degree of inlet temperature change throughout the experiment.

Cold exposure and protective clothing

During cold exposure participants were seated at rest for 130 min, with a 10 min exercise period at half-time (ie, 65–75 min), inside an environmentally controlled chamber (Conviron GR96, Winnipeg, Canada) with air temperature maintained at −20°C (air velocity 0.05 m/s). During their time inside the chamber, participants wore – over the top of the liquid conditioning garment – commercially available clothing simulating all three layers of the Improved Environmental Clothing System Canadian Forces Arctic clothing ensemble (3.6 clo, 0.556 $m^2/°K/W$). The three-layer system included a fleece garment (first layer), an uninsulated inner parka and pants (second layer), and an insulated outer parka and pants (third layer). In addition standard military mukluks, woollen socks, and a balaclava were also worn, together with a thin pair of long, cotton underpants worn under the fleece pants (additional overall clo value of 0.3 (0.05 $m^2/°K/W$)). The hands were insulated with thin gloves and Arctic mitts.

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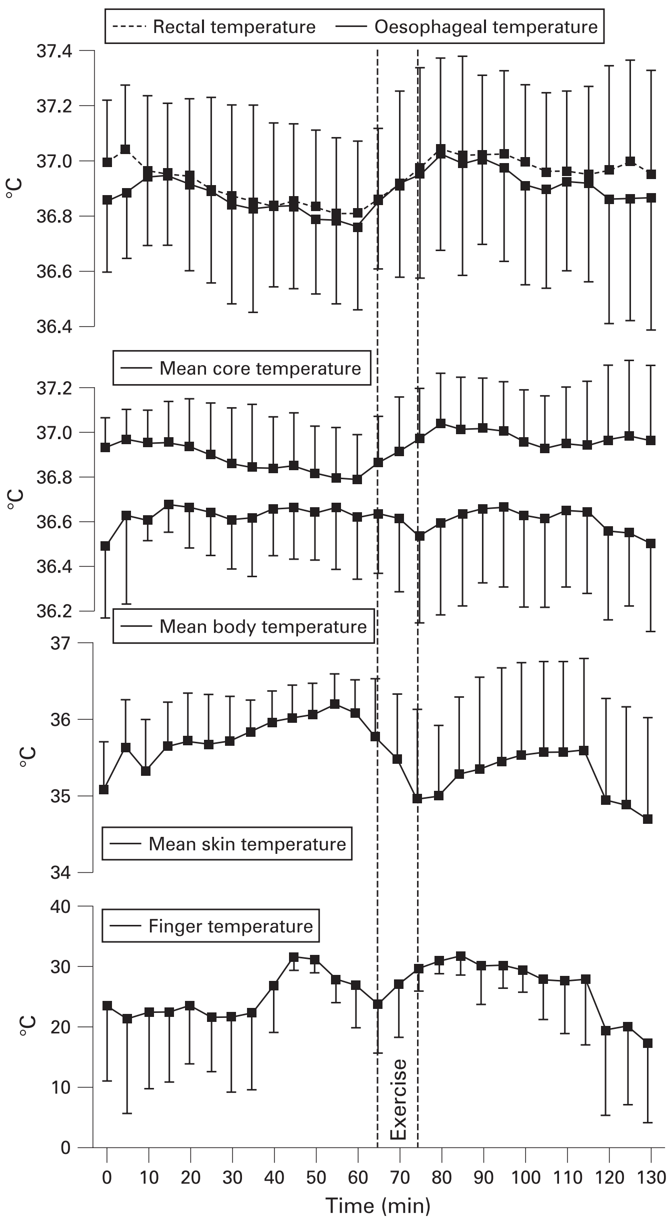

Figure 3 Mean (SD) temperature values over time. Values represent 5 minute means derived from data collected every 8 seconds. "Mean body temperature" is illustrated instead of the "change in mean body temperature" which was used in all statistical analyses as the former is advantageous for graphic comparisons.

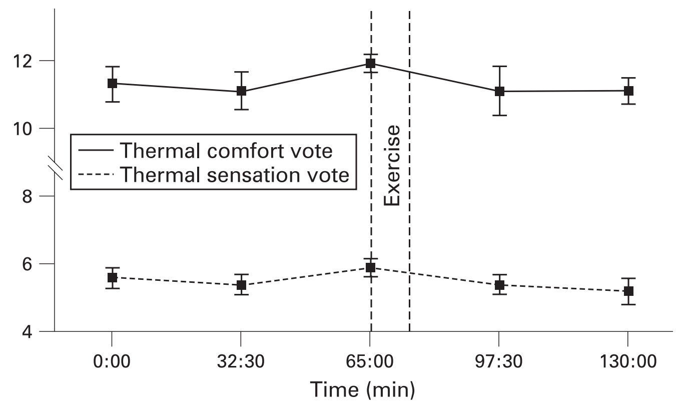

Figure 4 Mean (SD) thermal comfort and thermal sensation over time.

Exercise regimen

To investigate the effects of a sudden perturbation to thermal balance via the addition of endogenous heat, participants were asked to complete a short submaximal exercise protocol during the cold exposure. At 65 min, participants were seated on a stationary Monark cycle ergometer and exercised for 10 minutes at a work load requiring 60% of their age-predicted maximum heart rate (220−age).

Thermoregulatory variables

T_c, T_{sk}, and finger temperatures were recorded throughout cold exposure at 8 sec intervals using a data logger (Smartreader 8 Plus, ACR, Vancouver, Canada) interfaced with a computer so that all variables could be monitored continuously by an investigator situated outside the environmental chamber. Oesophageal temperature was measured with a flexible thermistor (Mon-A-Therm Core, Mallinkrodt Medical, St Louis, USA) placed through the nasal passage into the oesophagus at a distance equal to one-quarter of the standing height.[12] A flexible thermistor (Mon-A-Therm Core, Mallinkrodt Medical) was inserted to a depth of 15 cm beyond the anal sphincter to assess rectal temperature. The oesophageal and rectal temperature values were used separately in statistical analyses and also used to provide a T_c (ie, (oesophageal+rectal)/2). Four ceramic chip skin thermistors (MA-100, Thermometrics, Edison, New Jersey, USA) were attached to the chest, upper arm, thigh, and calf to allow the measurement of T_{sk} using the area-weighting formula of Ramanathan[13]: $T_{sk} = 0.3$ (chest + arm temperature) +0.2 (thigh + leg temperature). Change in mean body temperature (ΔT_b) was calculated as the weighted sum of change in rectal temperature and T_{sk} using a previously described and widely used formula[14]: $\Delta T_b = 0.7$ (change in rectal temperature (rectal temperature at *time t* from the rectal temperature at *time t-1*))+0.3 (change in T_{sk} ("change" calculated as in rectal temperature)). Finger temperature was measured with a thermistor (MA-100, Thermometrics) placed on the pad of the fourth finger of the non-dominant hand. Data for minute-by-minute changes in body heat storage and body heat content in similar experimental conditions can be found in previous papers from our laboratory.[15,16]

Statistical analysis

Due to sample rate differences between temperature data (obtained every 8 seconds) and thermal comfort/sensation data (recorded every 32.30 minutes), analysis was divided into three parts involving 5 minute temperature data, 32 minute temperature+thermal comfort/sensation data and 8 second temperature data, respectively. For the first part of the data analysis, preliminary data transformation involved calculation of 5 minute mean values of all temperature variables which were compared using one-way analysis of variance (ANOVA) followed by post-hoc t tests incorporating a Bonferroni adjustment. For the second part of the data analysis, preliminary data transformations involved calculation of mean values of all examined variables for the baseline and exposure periods in the following manner: one mean value was calculated for baseline using data from t = 6 to 15 min (excluding the first and last 5 minutes in order to retrieve a steady-state value), while temperature data collected during the cold exposure period every 8 seconds were used to calculate 32.30 minute mean values. Thereafter, two simultaneous regression analyses

Table 1 Unstandardised regression coefficients (SE) from hierarchical regression analysis predicting liquid conditioning garment inlet water temperature

DV	R^2	IV: Inlet water temperature			
T_c	0.03	−2.09 (0.55)	−2.55 (0.57)	1.80 (0.51)	1.83 (0.49)
T_{fing}	0.04		−0.06 (0.02)	−0.08 (0.02)	−0.07 (0.01)
T_{sk}	0.38			3.36 (0.16)	3.36 (0.15)
ΔT_b	0.48				13.36 (1.84)
Constant		213.97 (27.99)	240.45 (29.18)	−61.86 (27.72)	−52.49 (26.96)

Note: ANOVA for all models was statistically significant at $p<0.001$. All dependent variables were statistically significant predictors ($p<0.05$). All R^2 change indices were significant at $p<0.05$.
DV: dependent variables; IV: independent variable; R^2: coefficient of determination for each model.

(ie, regression analysis where all independent variables are inserted "at once") were conducted to predict the participants' thermal comfort and thermal sensation (dependent variables) from rectal, oesophageal and finger temperature, as well as T_{sk} and ΔT_b (independent variables) using the aforementioned mean temperature data collected during the cold exposure.

As the first and second parts of the analysis are based on mean values, they have limited capacity in unravelling the dynamical psychophysics problem that our study is investigating. In this light, the third part of the analysis involving only temperature data employed a hierarchical regression analysis (ie, regression analysis where independent variables are inserted in a prespecified sequence to observe changes in regression coefficients amongst models) to predict the participants' chosen inlet water temperature within the liquid conditioning garment (dependent variable) from T_c, T_{sk}, finger temperature and ΔT_b (independent variables) using 8 second temperature data from all subjects collected during the cold exposure. The hierarchy of the independent variables was adjusted so that the initial model included age, gender and T_c, while finger temperature, T_{sk} and ΔT_b were inserted one by one in subsequent models in order to observe differences in regression coefficients. No separate models were calculated for resting, exercise, or recovery conditions given that the purpose of incorporating these different elements was to simulate the perturbations to thermal balance from changes in endogenous heat during real cold exposures. All statistical analyses were performed with SPSS (version 14.0.1, SPSS Inc., Chicago, Illinois) statistical software package. The level of significance was set at $p<0.05$, except for post-hoc tests in which a Bonferroni adjustment was applied.

RESULTS

The first part of the data analysis demonstrated that participants found a desired level of inlet water temperature in approximately 25 min, and maintained it at stable levels until the 65th min of cold exposure (fig 1). During exercise, inlet temperature decreased significantly ($p<0.05$). Overall, ANOVA revealed that inlet water temperature decreased significantly across time ($p<0.05$). Individual readings at different areas of the body (fig 2) as well as T_{sk} and T_c (fig 3) demonstrated significant variation over time ($p<0.05$) and different responses to the suit's heating/cooling and the endogenous heat generated during exercise. Regardless, ANOVA detected no changes over time in subjective thermal comfort and thermal sensation (fig 4) as well as ΔT_b (fig 3) ($p>0.05$).

The simultaneous general linear model revealed that the variables associated with subjective thermal comfort ($R^2=0.22$, $p<0.05$) were the T_{sk} ($\beta=0.67$; $p<0.05$) and the ΔT_b ($\beta=-13.02$; $p<0.05$). When the analysis was repeated for subjective thermal sensation ($R^2=0.50$, $p<0.05$), T_{sk} ($\beta=0.97$; $p<0.001$) and ΔT_b ($\beta=-8.99$; $p<0.05$) were again the only significant predictors.

The second part of the data analysis, employing hierarchical regression analysis to predict the participants' chosen inlet water temperature within the liquid conditioning garment using 8 second temperature data from all subjects collected during the cold exposure, demonstrated statistically significant linear associations with all examined variables (table 1). Yet, it is important to highlight that the coefficient of determination (R^2) which demonstrates the amount of variability explained by each model was increased mainly by the T_{sk} (R^2 change $=0.34$, $p<0.001$) and the ΔT_b (R^2 change $=0.10$, $p<0.001$).

DISCUSSION

Our findings demonstrate that the human conscious response to thermoregulatory input during both rest and exercise in a cold environment is adjusted to changes in mean body temperature. Despite the fact that the liquid conditioning garment was a single-piece system affecting the entire body simultaneously, there was significant temperature variation in different areas of the body. Also, we found variability in the responses to the suit's heating/cooling and to the endogenous heat generated during exercise across the different areas of the body. The various core and skin areas appeared to counteract one another, resulting in comparatively stable body temperature as well as subjective thermal comfort and thermal sensation across time showing a strong association between conscious thermoregulatory responses (ie, inlet water temperature) and ΔT_b, rather than temperature changes in individual body regions. Indeed, it appears that ΔT_b remained constant, in contrast to T_c and T_{sk} (fig 3), which appeared relatively volatile with opposing trends. Concomitantly, the present regression analyses indicated that ΔT_b was the only variable significantly associated with thermal comfort and thermal sensation, as well as the most significant predictor of inlet water temperature. Although T_{sk} also showed strong associations with inlet temperature, thermal comfort and thermal sensation, this result was anticipated given that the garment and tubing were in contact with the skin and thus had a major influence on its temperature. This knowledge can contribute to our understanding of the thermoregulatory system of resting and exercising healthy humans under a prolonged exposure to harsh environmental conditions. Therefore, the current findings have valuable practical implications for the control of liquid conditioning garments used underneath protective clothing as well as other engineering applications germane to severe thermal environments faced by athletes as well as certain military occupational specialities, pilots, firefighters and other emergency responders.[9 16 17]

Previous reports in the germane literature suggested that autonomic effector response thresholds depend upon the

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What is already known on this topic

Behavioural thermoregulation is the principal form of thermoregulation used by humans and is mediated through conscious thermoregulatory response, but knowledge on the behavioural mechanism controlling thermoregulation remains limited. Mean skin temperature, core temperature and rate of heat storage have all been proposed as the dependable criteria of behavioural thermoregulation.

What this study adds

Through a novel method that quantified accurately and objectively the human behavioural thermoregulatory response, we found that humans generate conscious thermoregulatory responses in resting and exercise conditions during exposures to cold environments that are aimed towards maintaining a threshold mean body temperature, rather than temperature changes in individual body regions.

integration of T_c and T_{sk}.[2 6] Our results support this notion demonstrating that behavioural thermoregulatory responses attempt to maintain thermoneutrality by achieving a compromise between T_{sk} and T_c rather than T_c alone. This view is further strengthened by the finding that, in the pre-exercise period, T_c drifted steadily downward while T_{sk} drifted steadily upward so that they mathematically equalised one another and resulted in minimal changes in mean body temperature. The mid-exposure exercise bout significantly increased T_c and should have normally resulted in substantial heat gain (we have previously recorded a heat gain of approximately 137 W for a 75 kg individual from this exercise bout in similar settings).[15] However, in response to the increased metabolic rate, the participants selected a lower inlet water temperature and thus achieved a lower T_{sk}, with T_c and T_{sk} almost perfectly equalising one another again (for a 75 kg individual, based on the average ΔT_b at the end of the exercise regimen, body heat content was decreased by 1.3 W). Recent work on behavioural responses to an increase in body temperature during exercise[7] showed that individuals lower their exercise work rate in order to maintain a similar rate of heat storage. Our findings are in line with this finding, demonstrating that individuals lowered inlet water temperature during exercise, resulting in minimal ΔT_b.

It should be noted that the current ΔT_b values are the product of thermometric calculations based on standard mean core and skin temperature weighting coefficients, a method that is inferior in accuracy compared with calorimetry. However, thermometric calculations are generally accepted as valid and sensitive to change[16] and it is important to remember that the aim in the present experiment was to investigate the association between conscious thermoregulatory responses (ie, inlet water temperature) and thermal balance (ie, ΔT_b, T_c and T_{sk}) across time, not cross-sectionally between different variables. Therefore, the effects of thermometry, if any, were constant across time and, therefore, did not influence our conclusions. Our experimental design would be further strengthened by including a separate paired-control condition with individuals serving as their own controls while sitting quietly in a thermoneutral environment. Within these limits, we conclude that humans generate conscious thermoregulatory responses in resting and exercise conditions during exposure to cold environments that are aimed towards maintaining a threshold mean body temperature, rather than temperature changes in individual body regions.

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Competing interests: None.

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