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Influence of meal congruency with food reward on energy intake during passive acute cold and heat exposure: a randomised controlled trial

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Influence of meal congruency with food reward on energy intake during passive acute cold and heat exposure: a randomised controlled trial

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Abstract

Background: Military personnel and athletes are characterised by high energy expenditure (EE) and often operate in hot or cold environments, where thermoregulatory demands may further increase EE. If energy intake (EI) does not match these demands, energy deficits may develop. Thermal exposure may also affect EI through changes in appetite and food reward especially for cold and warm foods. Thus, adapting meal serving temperature to the thermal context may help limit such deficits. This study investigated whether congruency between meal serving temperature and environmental temperature influences EI during acute passive cold and heat exposure.

Methods: Thirty participants were randomly assigned to either a cold meal (CM) group or a warm meal (WM) group. Each participant completed three 6-h exposures in a bioclimatic chamber under cold (15 °C), thermoneutral (25 °C), and hot (35 °C) conditions. After 4 h 30 min of exposure, participants received an *ad libitum* main dish corresponding to their allocated group. Food reward was assessed before lunch and subjective appetite was repeatedly assessed throughout the exposure.

Results: Appeal for cold and warm foods increased in the heat and cold conditions, respectively ($p < 0.001$). Subjective appetite decreased during the 90 min preceding the meal in the heat condition ($p < 0.001$), whereas it remained unchanged in the cold condition compared with thermoneutrality. Overall, EI was reduced in the hot condition ($p = 0.006$) and increased in the cold condition ($p = 0.015$). However, the heat-induced reduction in EI was observed only in the WM group, in which the meal was incongruent with the thermal context ($p < 0.001$). EI remained unchanged in the CM group during heat exposure. No specific effect of meal congruency was observed during cold exposure.

Conclusions: This study demonstrated that the heat-induced reduction in EI may be mitigated by serving a congruent meal (i.e. cold). However, meal incongruency (i.e. warm) did not impact EI during cold exposure. These outcomes suggest a practical strategy for limiting energy deficits and optimising ration characteristics in challenging environmental conditions.

Trial Registration: ClinicalTrials.gov, NCT06809296. Registered on 5 February 2025.

Key words: Eating behaviour / Food preference / Appetite / Diet / Meal temperature / Military nutrition / Randomised controlled trial / LFPQ / Energy Balance / appropriateness

Introduction

Military personnel and athletes are characterised by their high energy expenditure (EE) (1,2). A major challenge for these populations is to match EE with adequate energy intake (EI), since insufficient EI may lead to energy deficits. If sustained, these deficits may result in weight loss and impair both cognitive and physical performance (3,4). However, meeting these high energy demands through dietary intake is often difficult because of physiological limits to the ingestion of large amounts of food (5) , as well as logistical and contextual constraints (6,7).

These populations are also frequently required to live and perform in a wide range of climatic conditions (8,9). When environmental conditions exceed the thermoneutral zone (TNZ), energy demands may be further increased by thermoregulatory requirements (2,10,11). Thermal exposures may also directly affect appetite and EI, thereby potentially worsening energy deficits. Field (12–15) and laboratory studies (16–19) suggest that cold exposure generally increases EI, whereas heat exposure may reduce it. However, evidence remains limited and heterogeneous, particularly because of the small number of studies and the lack of homogeneity between protocols (20). This may explain why several studies, especially in the heat (12,14,21), observed no modifications of appetite during these thermal exposures. Interestingly, the modifications of EI have mainly been discussed through alterations in subjective appetite potentially induced by changes in appetite-related hormone levels (19). However, another significant mechanism impacting food choices and thus EI is food reward (22,23). Indeed, our previous studies (21,24) demonstrated that food reward for some food-related characteristics such as fat content or taste (sweet or savoury) was strongly affected by thermal exposure. Not surprisingly, the most impacted characteristic was food serving temperature, with warm foods being more appreciated in cold conditions and cold foods in hot conditions (24). Since participants in the latter study accordingly modulated the quantities of cold and warm foods consumed from the proposed test meals, no modifications in EI during 24 h of exposures to hot and cold environments was found. We therefore hypothesised that thermal exposure-induced modifications of EI do not exclusively depend on alterations of appetite, but mainly on changes of food reward. Thus, the design of the test meal could significantly alter the observed effects of cold or heat exposure.

In this study, we wanted to compare the modifications of EI during a meal served after 4 h 30 min in a cold (15 °C) or hot environment (35 °C) with those observed in a thermoneutral condition (25 °C) between a group receiving a cold meal (CM) and a group receiving a warm meal (WM). We hypothesised that changes in EI in the WM would be accentuated in both extreme thermal conditions, as warm foods are expected to enhance food reward in a cold environment but reduce it in a hot environment. Conversely, because cold foods are likely to be less rewarding in the cold but more rewarding in the heat, EI in the CM is expected to be preserved, or only minimally affected.

These results are important for determining whether 1) it is possible to compensate for the potential anorexigenic effect of an exposure to heat and 2) to clarify the importance of the

temperature of the test meals in protocols assessing the effects of thermal exposures on food intake.

Materials and methods

Participants

Our prior study (24) showed a strong modulation of the LFPQ for cold and warm meal depending on the environmental temperature. Using conventional α (0·05) and 1-β (0·95) levels and with an expected effect size of 1.509 based on our prior study (24), at least eight participants per group were required (G * Power v3.1.9.4). We therefore recruited 30 healthy young adults, including 15 men and 15 women who were randomly assigned to either the cold meal group (CM; n = 15; 8 men and 7 women) or the warm meal group (WM; n = 15; 7 men and 8 women). The randomisation sequence was generated using a computer-based randomisation procedure. Participant flow is presented in the CONSORT flow diagram (Figure 1). The completed CONSORT checklist and TIDieR checklist are provided as Additional files 1 and 2, respectively.

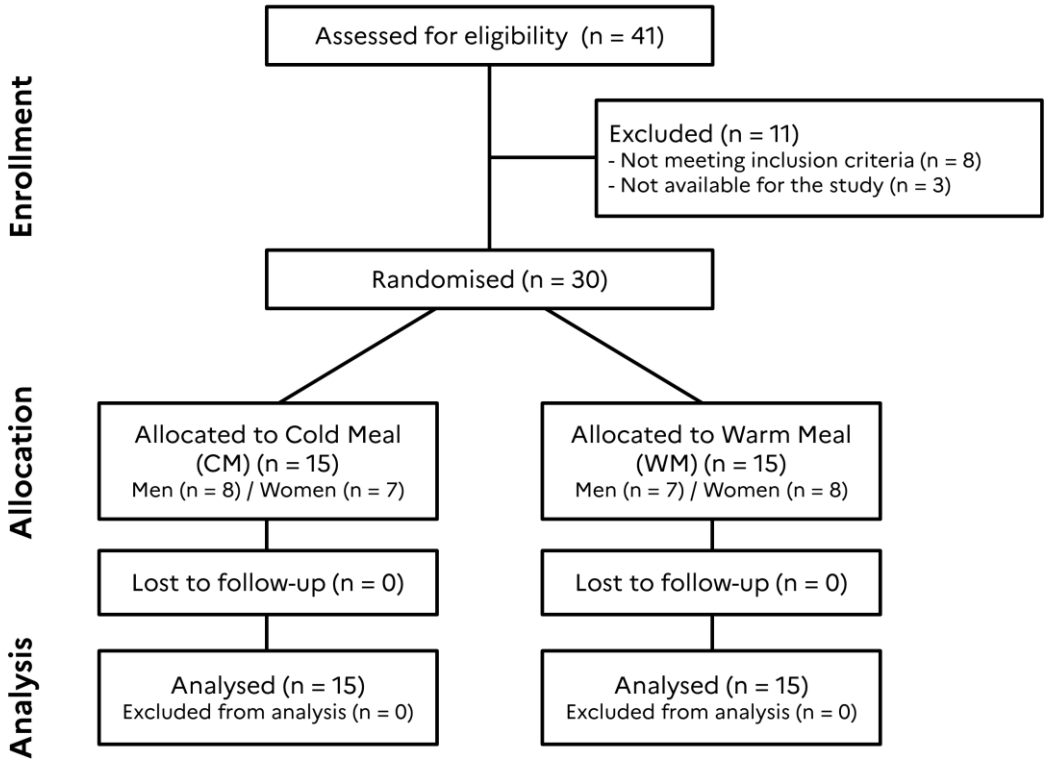


Figure 1 - *CONSORT flow diagram*

Participant characteristics are presented in Table 1.

Table 1. *Characteristics of participants*

	Cold Meal			*Warm Meal*		
	All	Men (n=8)	Women (n=7)	All	Men (n=7)	Women (n=8)
Age	30.5 ± 6.4	31.4 ± 6.6	29.4 ± 6.5	29.3 ± 6.7	27.1 ± 6.1	31.3 ± 7.0
Height (cm)	172.0 ± 8.9	177.4 ± 6.3	165.9 ± 7.4	171.8 ± 10.2	179.7 ± 7.0	164.9 ± 7.0
Weight (kg)	68.9 ± 11.2	76.4 ± 9.6	60.5 ± 5.1	67.1 ± 15.2	76.1 ± 15.1	59.3 ± 10.7
Body Fat (%)	20.7 ± 4.9	17.7 ± 3.6	24.2 ± 4.1	18.5 ± 7.1	14.6 ± 4.8	21.9 ± 7.3
BMI (kg.m $^{-2}$)	23.2 ± 2.6	24.3 ± 2.7	22.0 ± 2.0	22.5 ± 3.2	23.4 ± 3.1	21.8 ± 3.2

Mean ± SD. BMI: body mass index.

Inclusion criteria were restraint score < 50 based on the Three Factor Eating Questionnaire-R18 (25) without dietary allergies and intolerances, regularly consuming at least three meals per day including breakfast, not following a specific diet, and not taking medication. They were also not eligible if they had been exposed to a hot or cold climate (> 3 consecutive days, mean temperature > 30°C or < 0°C, respectively) in the last 3 months before the study to ensure that participants were not considered heat/cold acclimatised. Given that this study was conducted in winter/spring 2025, they were theoretically exposed to temperature between 5 and 20°C during this period.

Design

The protocol is presented in the Figure 2. Participants participated in three sessions of 6 h 30 separated by at least 1 week in a bioclimatic chamber. Ambient temperatures were fixed at 15, 25, and 35°C at 40% of relative humidity. The session order was randomly allocated and counterbalanced within both groups.

On the day of the experimentation, participants arrived at 7:00 am in the laboratory (22°C) and were equipped with devices used for continuous measurements, such as heart rate (HR), rectal temperature (T_{rec}), and skin temperature (T_{skin}). Participants then dressed in standardised clothing (1 clo): T-shirt (100% cotton), jogging pants (50 % cotton and 50 % polyester), cotton socks, and synthetic sandals. At 8:15 am, a standardised control breakfast was provided. At 8:30 am, participants entered the bioclimatic chamber. Subjective appetite and thermal sensations were assessed throughout the sessions using visual analogue scales (VAS). Body mass fluctuations, total entries (water and food intake) and total losses (urine and sweat loss) were directly measured or calculated. Resting metabolic rate (RMR) was measured one hour before the lunch (12:00 pm) to assess the impact of the environment. Food reward using the Leeds Food Preference Questionnaire (LFPQ) was assessed just before the test meal (12:30 pm). Participants were served an *ad libitum* cold or warm meal depending on their allocated group. Neither group was informed of the existence of the other group. Participants were then allowed to exit the climatic chamber at 3:00 pm.

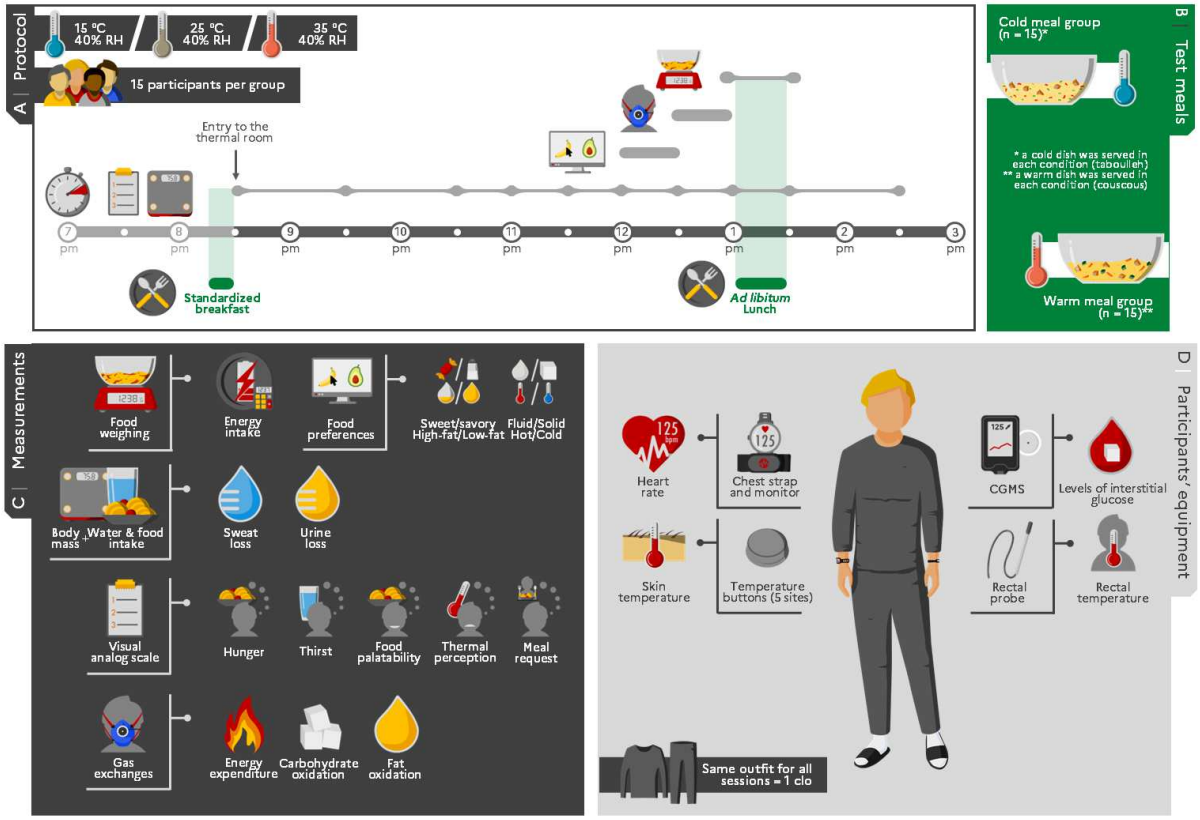


Figure 2 - *Study protocol.*

Period of normalisation

Participants were asked to eat the same dinner the day before each session (quantity, timing and food content). At 8:15 am, the day of experimentation, a standardised control breakfast composed of a cottage cheese, biscuits and a cup of tea or decaffeinated coffee was provided (430 ± 91 kcal; 55 ± 2% of carbohydrates, 32 ± 0 % of lipids, 14 ± 2% of proteins). Participants were asked to eat the same quantity before each session. They were also instructed to drink at least 1.5 litres of water from the previous evening to avoid differences in hydration status and not to perform physical activity on the day before the study. Finally, they were instructed to respect their sleeping habits during the previous two nights.

Regarding menstrual cycle control, complete standardisation of testing within the same phase of the menstrual cycle across all visits (26) was not feasible because of scheduling constraints. However, participants' cycle phases were monitored using self-reported cycle tracking so that menstrual cycle phase was known for each testing session. In line with current methodological recommendations (26), this approach was used to provide partial control of menstrual cycle-related variation. Importantly, data collection was conducted outside the menstrual period to minimise potential confounding from acute menstrual symptoms, such as menstrual pain, fatigue, headache, and gastrointestinal discomfort (27).

Control measurements

Room temperature and relative humidity

The experimental sessions took place in the Institut de Recherche Biomédicale des Armées (IRBA)'s bioclimatic chamber in which both temperature and hygrometry can be acutely regulated (-20 to 60°C and 0 to 100% hygrometry). Two thermal sensors (ibuttons, Maxim Integrated, Sunnyvale, CA, USA) were placed in the area (on the top and the bottom) where participants were seated to measure temperature and hygrometry continuously and to ensure that they matched the desired conditions. The mean temperature (relative humidity) for the three conditions was 15.8 ± 0.5 °C (40.8 ± 2.3 %), 25.6 ± 0.3 °C (39.3 ± 1.0 %), 35.0 ± 0.4 °C (38.5 ± 1.4 %), respectively.

Core and skin temperature

Upon their arrival in the bioclimatic chamber, participants were equipped with a rectal probe (Captive, TEA, Vandoeuvre-lès-Nancy, France) in order to measure T_{rec} continuously throughout the sessions. Moreover, participants were also equipped with four cutaneous sensors (ibutton, Maxim Integrated, Sunnyvale, CA, USA), on the upper left chest, on the right biceps, on the 1/3 superior front of the right thigh and on the middle of the left calf. In the present study, mean T_{skin} was calculated using Ramanathan's equation (28): $\mathrm{Tskin} = 0.3(t_{chest} + t_{arm}) + 0.2(t_{thigh} + t_{leg})$.

Body mass modifications

Body mass was measured hourly throughout the study using a scale (Mettler Toledo ICS 425d, Greifensee, Switzerland, accurate to 20 g) located inside the bioclimatic chamber. Fluid intake was recorded by weighing a 1.5-L thermos of water, maintained at 22°C, using a scale (KC120 Mettler Toledo, 7470 Albstadt, Germany). Participants were instructed to drink according to their preference; the thermos was refilled hourly. Urine loss was assessed by weighing immediately before and after each urination. Hourly fluid balance was then calculated from fluid intake, body mass change, and urinary loss, allowing estimation of sweat loss. If participants failed to spontaneously replace fluid loss, they were required to consume the equivalent volume of water to maintain euhydration.

Subjective thermal ratings

Thermal sensation and thermal discomfort ("How do you perceive your thermal environment?") were determined hourly with the ASHRAE 7-point scale (from -3 cold to +3 heat) and with VAS with "very uncomfortable" and "very comfortable" at the left and right ends (29).

Resting energy expenditure

Resting metabolic rate was assessed using indirect calorimetry (Q-NRG, COSMED, Rome, Italy) at 12:00 pm (one hour before the test meal) to assess the impact of the thermal environment on the energy cost of thermoregulation. RMR was calculated by the energy equivalent of O_2 derived from the Weir equation (30) and substrate (fatty acid and glucose) oxidation was calculated using Péronnet & Massicotte equations (31). Non-protein respiratory quotient (RQ) was also calculated using the formula: carbon dioxide production/

oxygen uptake (VCO_2/VO_2). During the measurement, participants were placed in a comfortable lying position during 20 min in dim light. RMR, RQ, and substrate oxidation rates were calculated from a stable sample lasting at least 6 min. Investigators performed regular and frequent visual checks to ensure that the participants were awake during measurements.

Heart rate

HR was continuously measured using a heart chest belt (Polar H10, Polar) connected to a watch (Polar RC3). The period analysed was only the 1-hour mean before meal.

Main measurements

Appetite

Appetite and thirst were assessed hourly until 10:00 am, then every 30 minutes until the end of the test meal at 1:30 pm. Appetite was evaluated across four different dimensions: hunger, desire to eat, fullness and prospective consumption. Each sensation was measured using a 100-mm VAS presented on paper preceded by the following questions: « Are you hungry? », « How strong is your desire to eat? », « How full do you feel? » and « What quantity of food would you be able to eat? ». The first three scales were anchored with « not at all » and « extremely » at the left and right ends, respectively. The last one was anchored with « none » and « a very large quantity ». The distance from the extreme left to the participant's vertical dash represented the rating score expressed in mm (0–100). The composite appetite score (CAS) (32), reflecting the responses to the four VAS, was then calculated as a summary measure of appetite using the following formula: CAS = (hunger + desire to eat + (100-fullness) + prospective consumption)/4. Moreover, every 30 min, from 11:00 am to 1:00 pm, participants were asked their ideal meal timing by indicating a positive or negative duration in min. Thirst was also assessed at the same time points as appetite sensations. Food palatability was assessed using VAS: « Did you like this food? ».

Food reward

Food reward was assessed using LFPQ (22,24,33,34). Two versions were used : the original one comparing appeal for high-fat and low-fat foods (fat appeal) and sweet and savoury foods (taste appeal) using foods usually consumed in France (35) and another version used in our previous study comparing appeal for cold and hot foods/drinks (temperature appeal) and fluid and solid items (texture appeal) (24). The latter was created following the recommendations proposed by Oustric et al. (34). The methodology of food selection is described in the study of Coca et al. (24). This questionnaire was completed 30 min before the test meal.

LFPQ is a two-phase computerised task. One task consists of answering the question « How pleasant would it be to taste this food now? » using 100-point VAS. Food images (n = 16) appeared individually on the screen in a randomised order. Each food image was shown to the participants beforehand to ensure the adequacy between the image and its interpretation. The mean score for each group of foods (low-fat, high-fat, savoury, and sweet for the first questionnaire and hot, cold, fluid, and solid for the second one)

corresponded to explicit liking (EL). The other score reflecting the implicit wanting (IW) was assessed using a covertly timed forced choice procedure. Every image of each of the four food categories was compared with every other image of the three other categories (ninety-six pairs in total). Participants were instructed to indicate which food they most wanted to eat at that moment. The IW score is a combination of reaction time and frequency of selection (34). Each questionnaire required 5–10 min to be completed. EL and IW scores are presented as appeal bias in order to show the relative preference for one dimension (e.g. low fat) in comparison with the opposite one (e.g. high fat). A positive score in this example would indicate a relative preference for high fat and a negative one a preference for low fat, the higher or lower the value, the higher the preference for the respective dimension.

Energy intake

The test meal (lunch) was served *ad libitum* for both groups and consisted of a single component which was identical across all conditions. The CM group (n = 15) received a cold meal of chicken tabbouleh (147 kcal.100g^{-1}; 27 % of carbohydrates, 40% of lipids, 33% of proteins) (~ 6°C) while the WM group (n = 15) received a warm meal of chicken couscous (159 kcal.100g^{-1}, 22% of carbohydrates, 47% of lipids, 30% of proteins) (~ 60°C). These dishes were very comparable in terms of macronutrients' repartition, energy density, and ingredients (poultry meat, wheat semolina, and vegetables). Participants ate without distraction in order to avoid eating while being influenced by other activities (36) and served themselves onto their plate using specific cutlery. Participants were instructed to signal the end of their meal by pressing a button on their desk, allowing us to calculate the meal duration. Thirty minutes after the beginning of the meal, plates were cleared and were weighed. The differences in food weight between before and after the meal corresponded to the consumed quantities. Consumed quantities were then used to calculate EI and macronutrient intake. Relative EI was calculated as EI at 35 °C minus EI at 25 °C, and EI at 15 °C minus EI at 25 °C to assess changes relative to 25 °C.

Statistical analyses

Normality was assessed using the Shapiro–Wilk test. In the case of repeated measurements, repeated-measures ANOVA were used. Thus, VAS scores for appetite and thirst were compared using a 3 × 7 ANOVA (temperature × time), 3 × 10 for thermal sensation and comfort (temperature × time), 3 × 5 for the ideal meal timing (temperature × time), 3 × 2 for HR (temperature × time), 3 × 2 × 2 for EL and IW taste, fat, texture and temperature appeal bias scores (temperature × time × group), 3 × 12 for rectal and skin temperatures (temperature × time), and 3 × 2 for EI (temperature × group). When sphericity was violated (Mauchly's test), Greenhouse–Geisser correction was applied. Post hoc analyses were performed using Holm's tests. Effect sizes were expressed as Cohen's d: > 0.2 (small), > 0.5 (moderate) and > 0.8 (large) (37). Data are presented as means and 95% confidence intervals. Significance was determined as $p < 0.050$; however, in line with current recommendations (38), we reported all results with $p < 0.100$ and post hoc tests were

conducted when the corresponding p value was lower than 0.100. Analyses were performed using JASP software (0.95.4.0 version).

Results

Control measurements

Heart rate, rectal, and skin temperature

Statistical analyses revealed *temperature* effects for HR, T_{rec}, and T_{skin} ($p < 0.001$ for all). Moreover, *time* effects were found for core temperature and T_{skin} ($p < 0.001$ for both). A sex effect was noted for T_{rec} ($p < 0.001$, $d = 0.99$). Finally, *temperature * time* interactions were found for T_{rec} and T_{skin} ($p < 0.001$ for both). Results and details of post hoc tests are presented in Figure 3 for T_{rec} and T_{skin}. HR was higher in the 35 °C condition (76.1 ± 10.7 bpm) than in 15 °C (62.8 ± 11.2 bpm; $p < 0.001$, $d = 1.25$) and 25 °C conditions (65.3 ± 10.5 bpm; $p < 0.001$, $d = 1.01$).

Resting metabolism and body mass modifications

A *temperature* effect was found for all outcomes presented in the table 2 except for urine loss ($p < 0.001$ for all). The details of post hoc analyses are presented in this table.

Table 2 – *Resting metabolism, intake, loss and body mass modification*

	15°C	*25°C*	*35°C*	*15 vs 25*	*15 vs 35*	*25 vs 35*
EE (kcal.min-1)	1.34 ± 0.28	1.05 ± 0.21	1.05 ± 0.18	<0.001 (1.91)	<0.001 (1.93)	
RQ	0.775 ± 0.029	0.806 ± 0.052	0.855 ± 0.084	0.072 (0.50)	<0.001 (1.33)	<0.001 (0.83)
FATox (g.min-1)	0.106 ± 0.028	0.070 ± 0.024	0.053 ± 0.037	<0.001 (1.29)	<0.001 (1.95)	0.009 (0.66)
CHOox (g.min-1)	0.086 ± 0.036	0.098 ± 0.067	0.141 ± 0.075		<0.001 (0.90)	0.004 (0.70)
ΔBM (g)	61 ± 365	291 ± 307	523 ± 355	0.005 (0.67)	<0.001 (1.35)	0.005 (0.68)
Water intake (g)	532 ± 352	594 ± 333	1430 ± 593		<0.001 (2.03)	<0.001 (1.89)
Food intake (g)	476 ± 204	436 ± 191	403 ± 199	0.022 (0.20)	<0.001 (0.37)	0.032 (0.17)
Total intake (g)	1008 ± 376	1030 ± 330	1833 ± 603		<0.001 (1.83)	<0.001 (1.78)
Urine loss (g)	751 ± 418	616 ± 426	649 ± 542			
Sweat loss (g)	135 ± 141	146 ± 92	534 ± 156		<0.001 (3.02)	<0.001 (2.93)
Total loss (g)	885 ± 496	762 ± 435	1184 ± 597		0.005 (0.58)	<0.001 (0.82)

EE: Energy expenditure, RQ: Respiratory quotient, ΔBM: ΔBody mass. *Mean ± SD;* p value (Cohen's d).

Subjective thermal ratings

Temperature and time effects were found for subjective thermal sensation and thermal discomfort ($p < 0.001$ for all). In addition, *temperature * time* interactions were found for thermal sensation ($p = 0.002$) and discomfort ($p < 0.001$). Results and details of post hoc tests are presented in Figure 3 for both subjective thermal assessments.

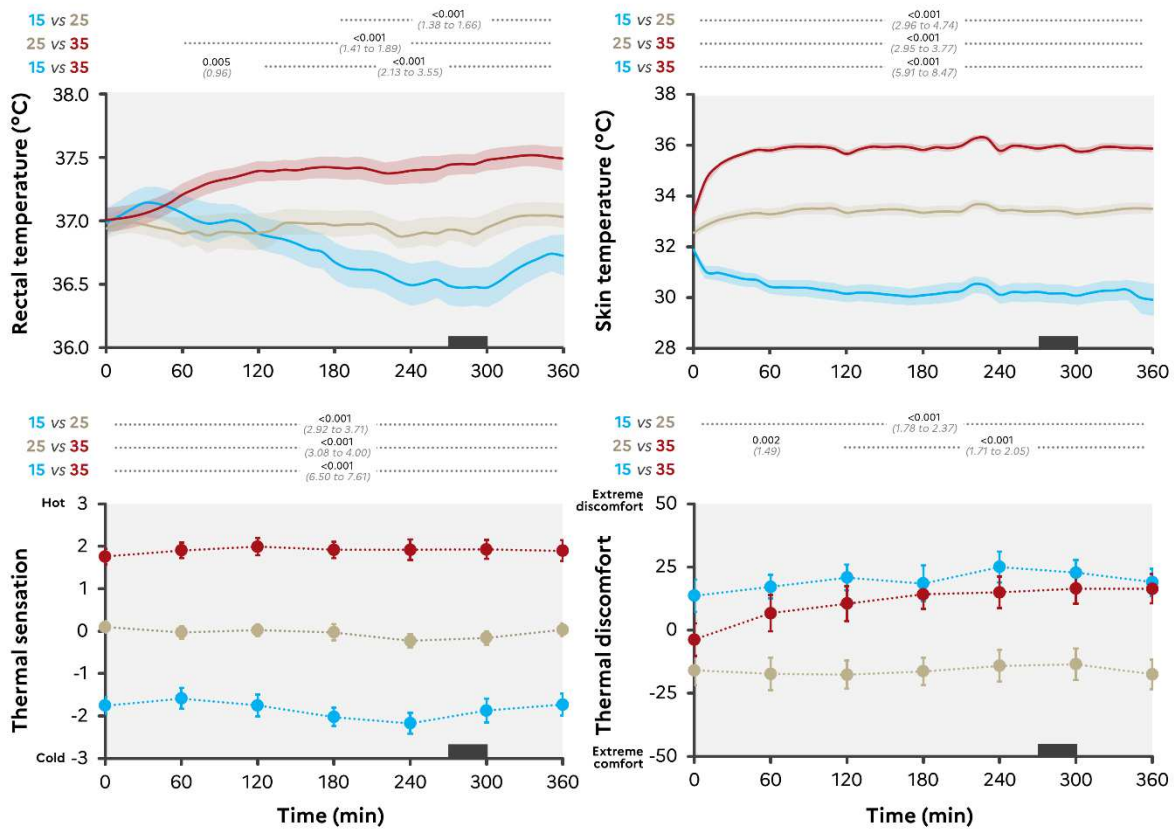


Figure 3 – *Rectal temperature, skin temperature, thermal sensation and discomfort. Data are presented as means and confidence intervals. The blue line and red line represent the cold and heat environments, respectively, whereas the grey line represents the thermoneutral environment.*

Main measurements

Subjective appetite

Temperature effects ($p < 0.001$ for all) and *temperature * time* interactions ($p \leq 0.001$ to 0.022) were found for all VAS except for gastric fullness. Results and details of post hoc tests are presented in Figure 4. Briefly, hunger, desire to eat, prospective consumption, and the composite appetite score were often lower at 35 °C than at 15 and 25 °C mostly between 180 and 270 minutes. Thirst was mainly higher at 35 °C than at 15 and 25 °C between 60 and 300 min.

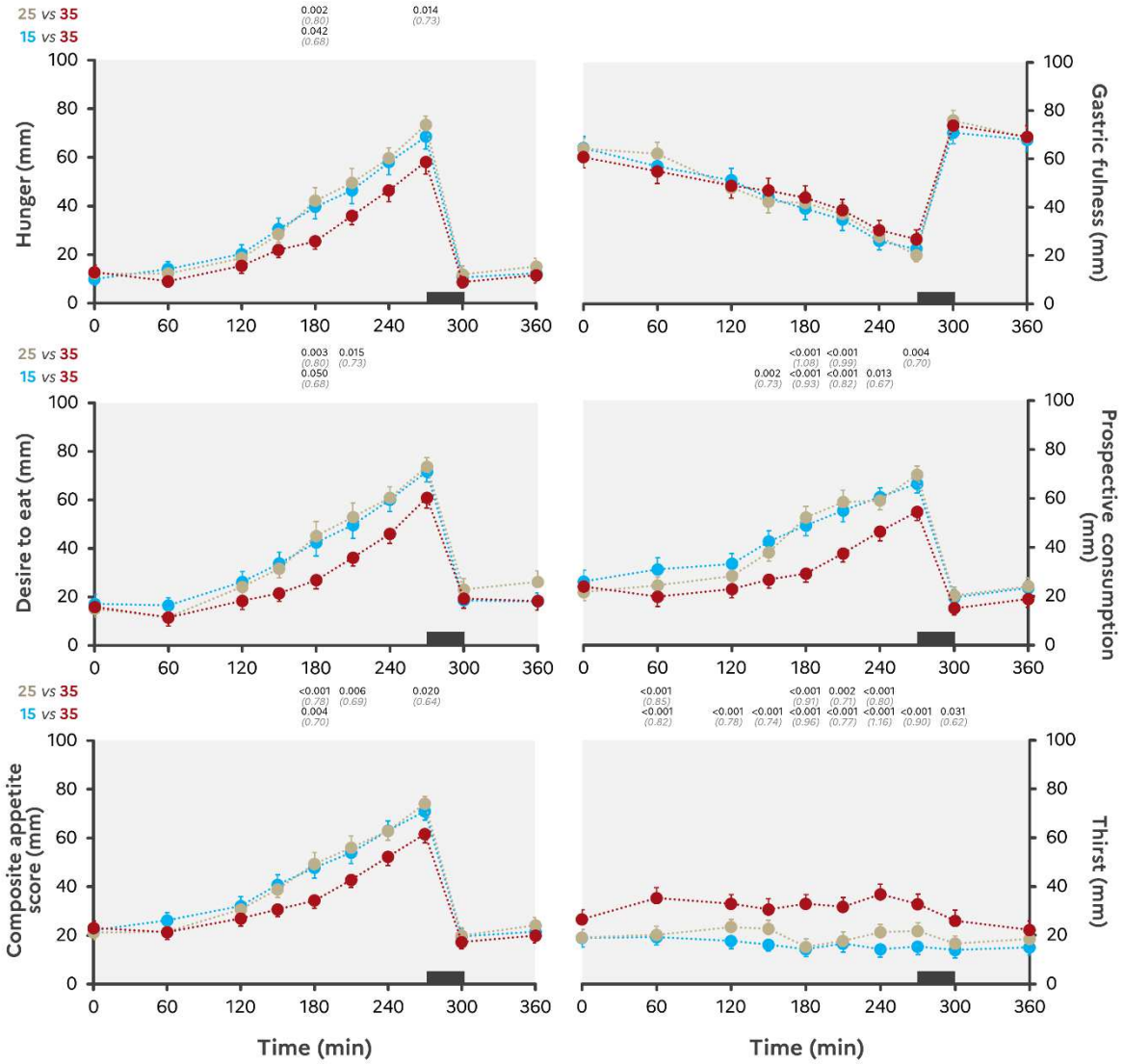


Figure 4 – *Visual analogue scales of hunger, desire to eat, gastric fullness, prospective consumption, composite appetite score, and thirst. Data are presented as means and 95% confidence intervals. The blue line and red line represent the cold and heat environments, respectively, whereas the grey line represents the thermoneutral environment. P values are indicated above each figure followed by Cohen's d scores in brackets.*

A temperature effect ($p = 0.007$) and time effects ($p < 0.001$) were found for the ideal meal timing. Logically, this timing decreased progressively from -120 to 0 min, each timing being lower than the previous one ($p < 0.001$, $d > 0.541$). The timing was higher at 35 °C than 25 and 15 °C (Figure 5) meaning that participants desired starting their meal later at 35 °C compared with other conditions.

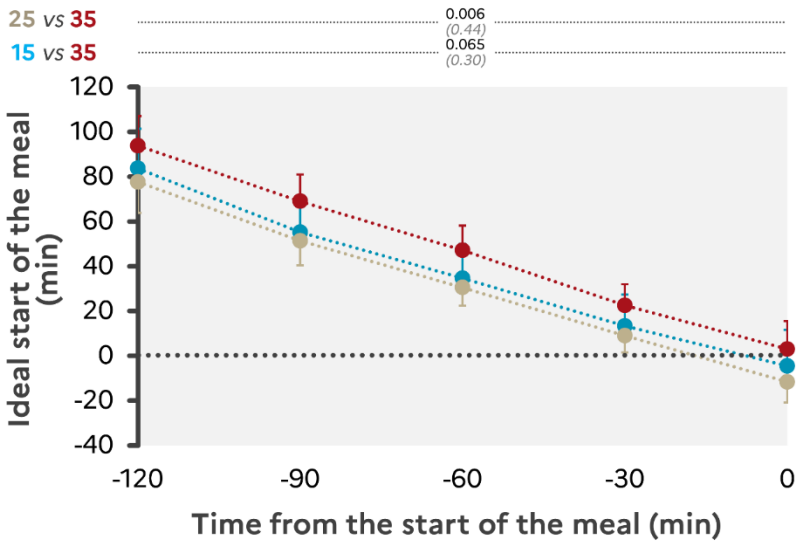


Figure 5 – *Ideal meal timing. Data are presented as means and 95% confidence intervals. Blue line and red line represent the cold and heat environment respectively, whereas grey line represents the thermoneutral. P values are indicated above followed by Cohen's d scores into brackets.*

Food Reward

Temperature effects were found for all biases in EL ($p < 0.021$) and IW ($p < 0.004$). Meal effects were also observed for all biases in EL (p ranging from < 0.001 and 0.056) and IW (p between <0.001 and 0.079) at the exception of IW Fat appeal bias ($p = 0.120$). A group effect was found only for EL Taste appeal bias ($p = 0.010$, $d = 0.636$) and IW Texture appeal bias ($p = 0.029$, $d = 0.488$).

A temperature * group interaction was found for EL ($p = 0.004$) and a tendency for IW ($p = 0.100$) Fat appeal bias.

Results and details of post hoc tests are presented in Figures 6 and 7. Briefly, appeal for high-fat foods and savoury foods mainly decreased at 35 °C compared with 15 and 25 °C (Figure 6). A subtle difference for Fat appeal bias occured between the two groups, the decrease of appeal for high-fat foods (EL and IW) not being observed in the CM group. Then, appeal for cold foods increased at 35 °C and appeal for warm foods increased at 15 °C (Figure 7). Finally, a slight increase in appeal for fluid foods was observed at 35 °C compared with 15 °C only for EL (Figure 7). Regarding IW, this increase compared with 15 and 25 °C was observed

only in the CM group.

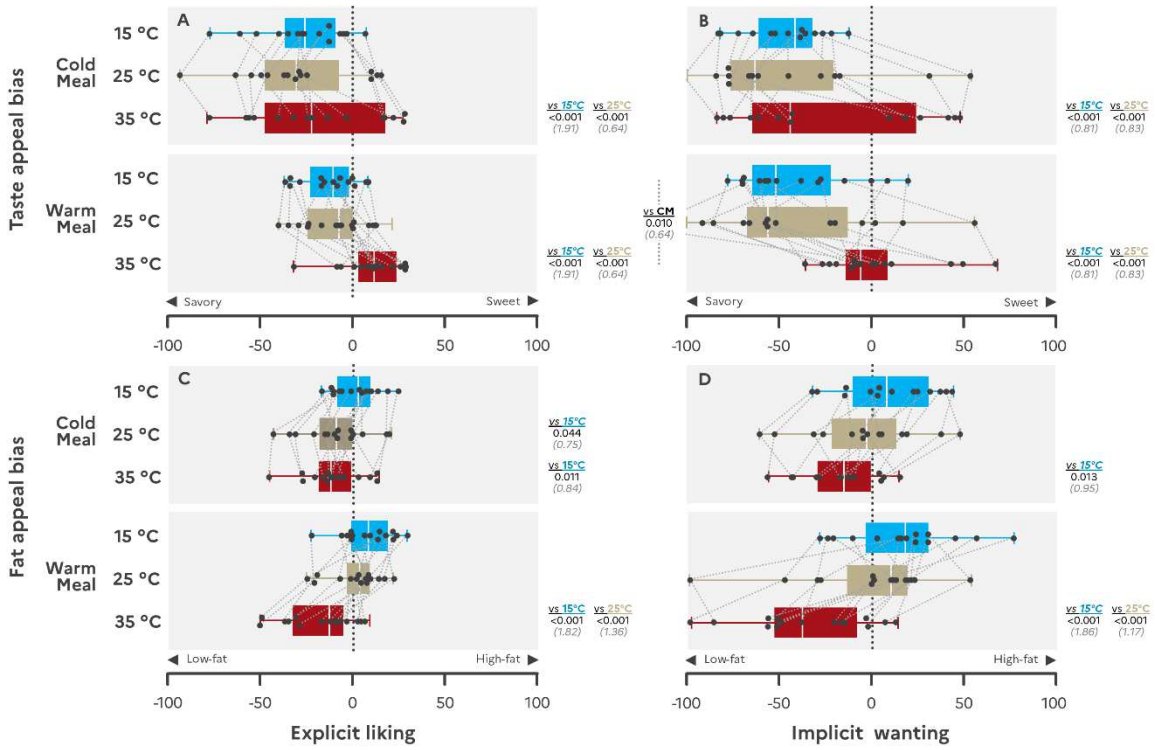


Figure 6 – *Taste (A and B) and Fat (C and D) appeal biases. Data are presented as Box-and-whisker plots. The box encompasses the 25%-75% quartiles and the median is represented by the horizontal line within the box. The whiskers extend to the highest and lowest values. Individual values are represented by dots. Blue and red represent the cold and heat environments, respectively. P values are indicated on the right of each panel, followed by Cohen's d scores in brackets.*

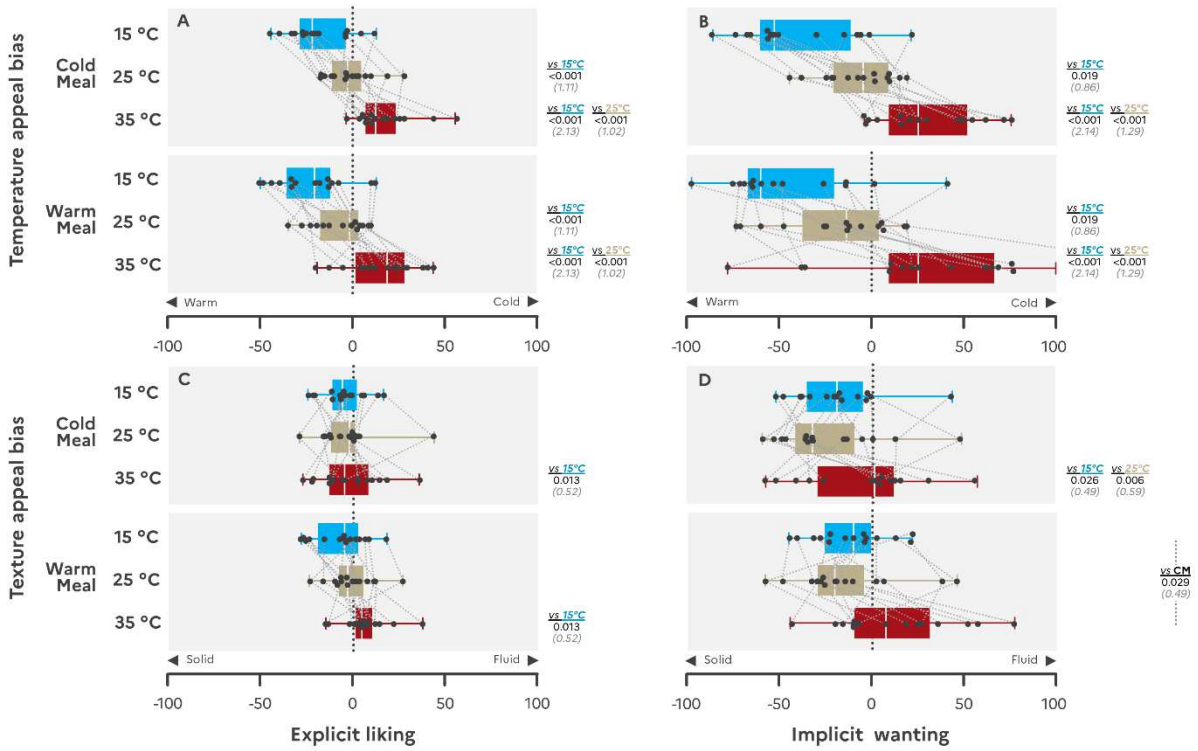


Figure 7 – *Temperature (A and B) and Texture (C and D) appeal biases. Data are presented as Box-and-whisker plots. The box encompasses the 25%-75% quartiles and the median is represented by the horizontal line within the box. The whiskers extend to the highest and lowest values. Individual values are represented by dots. Blue and red represent cold and heat environment respectively. P values are indicated on the right of each panel, followed by Cohen's d scores in brackets.*

Energy intake, meal duration, and palatability

A *temperature* effect was found for energy intake ($p < 0.001$; Figure 8A). Post hoc tests revealed that EI was higher at 15 °C compared to 25 °C and 35 °C, and lower at 35 °C compared to 25 °C. In addition, a *temperature * group* interaction was found ($p = 0.035$), with EI being lower at 35 °C than 15 and 25 °C only in the WM group. Moreover, a tendency for a group effect was found ($p = 0.055$, $d = 0.77$), with EI being higher in the WM than the CM group (Figures 8C and 8D).

A temperature effect ($p < 0.001$, $d = 1.06$), a group effect ($p = 0.041$, $d = 0.64$), and a tendency towards a temperature * group interaction ($p = 0.100$) were found for relative EI (Figure 8B). Post hoc tests revealed that relative EI was higher at 35 °C than at 15 °C in the WM group only, and higher at 35 °C in the WM than at 35 °C in the CM group.

Regarding meal duration, a tendency for a *temperature* effect was found ($p = 0.052$). A tendency for a slight increase in meal duration was observed at 15 °C (12.3 ± 3.8 min) *vs* 25 °C (11.3 ± 3.9 min; $p = 0.064$, $d = 0.237$) and 35 °C (11.3 ± 4.0 min; $p = 0.080$, $d = 0.026$). No effect was found for meal palatability (results not shown).

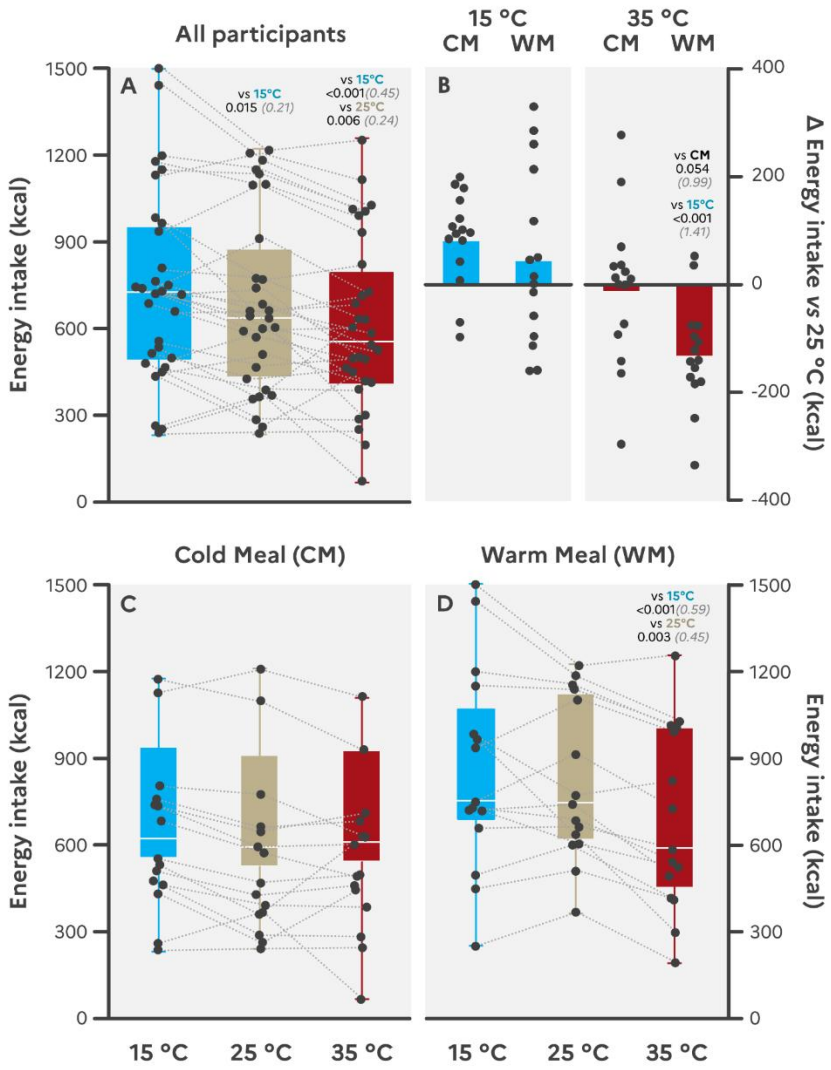


Figure 8 – Relative and absolute *energy intake in different thermal conditions and groups. A: absolute data for all participants, C and D: absolute data in the two different groups, B: difference in energy intake at 15 and 35 °C minus (25 °C) in both groups. Data in Figures A, C, and D, are presented as box-and-whisker plots. The box encompasses the 25%-75% quartiles and the median is represented by the horizontal line within the box. The whiskers extend to the highest and lowest values. Individual values are represented by dots. Blue and red represent the cold and heat environments respectively, whereas grey line represents the thermoneutral environment. The mean is represented in Figure B. Black dots represent individual values. P values are indicated in bold, followed by Cohen's d scores in brackets.*

The correlations between the modifications in palatability and in energy intake between 15 °C or 35 °C compared with 25 °C are presented for each group in Figure 9. These differences at 35 °C were positively correlated within each group (r = 0.694 and p = 0.004 in the WM group and r = 0.627 and p = 0.012 in the CM group; Figure 9B) whereas no association was found at 15 °C (Figure 9A).

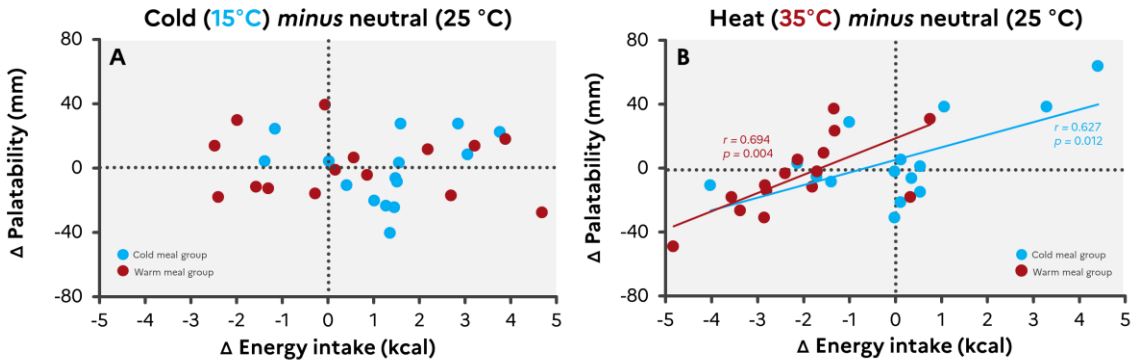


Figure 9 – *Correlations between differences in palatability and energy intake in cold (A) and hot (B) environments (minus the thermoneutral environment) within each group.*

Adverse events

No adverse events requiring study discontinuation were reported during the study.

Discussion

The objective of this study was to investigate the impact of meal congruency based on the serving temperature of foods on EI during exposures to different thermal conditions. Contrary to our hypothesis, meal congruency did not influence EI during cold exposure. In the heat, however, it affected EI, which was lower when the meal was incongruent (warm) but remained stable with a congruent meal (cold). These findings suggest a potential strategy for meal design in hot environments that may help limit the energy deficit commonly observed under such thermal conditions.

Physiological and subjective impact of thermal exposures

In the present study, thermal conditions were rigorously controlled through several measures: 1) participants wore standardised 1-clo clothing, theoretically ensuring thermal comfort around 21 °C and 50% of RH; 2) thermal sensors were used to accurately monitor the thermal environment in the bioclimatic chamber; 3) both cutaneous and core temperatures were recorded to confirm the physiological impact of heat exposure.

Exposures to 15 and 35 °C triggered marked physiological responses: HR, T_{core}, and, T_{skin} were significantly affected by ambient temperature. Moreover, as reported by Langeveld et al. (10) and Unlu et al. (18) under quite similar conditions (18 °C and 19 °C respectively), RMR increased specifically during the cold session, whereas sweat losses were logically higher during the 35 °C session. In addition, participants consistently perceived the 15 and 35 °C conditions as “cold” and “hot”, respectively, and reported both conditions as equally uncomfortable compared with the control 25 °C session.

Regarding RMR modification, our findings suggest different physiological responses to cold and heat exposure compared with thermoneutral conditions. The rise of RMR observed at 15 °C suggests that this condition was below the lower limit of the thermoneutral zone (TNZ) (11), requiring additional thermoregulatory heat production, probably through non-shivering thermogenesis, to maintain T_{core} homeostasis. In contrast, no significant change in RMR was

observed at 35 °C, suggesting that heat exposure did not increase metabolic cost, even though clear physiological and perceptual effects were observed. This suggests that the 35 °C condition induced a compensated heat stress, mainly reflected by evaporative heat loss and thermal discomfort rather than hyperthermia or increased metabolic demand. Therefore, while 15 °C likely felt below the lower boundary of TNZ, the 35 °C condition may be better interpreted as a hot but non-hyperthermic exposure remaining under effective thermoregulatory control. This interpretation is consistent with Pallubinsky et al. (11), who reported stable metabolic rates in humans up to approximately 38 °C.

Effect of cold on hunger and EI

As expected, EI increased by 11.7 ± 24.7% after 4 h 30 min of cold exposure which is consistent with previous studies reporting 8.6 to 13.2% increases in EI using different cold exposures methodologies (liquid conditioned suit (17,39) or ambient exposures (40), with different levels of activity (passive (17,39) or active (17,40)) and in different populations (overweight/obese (39) and healthy individuals (17,40)). This increase may even reach 53% in healthy adults after 30 min of cold-water immersion (16 °C) (16). Nevertheless, even though this cold-induced orexigenic effect was reported in a meta-analysis (20), some studies did not find modifications in EI (10,19,24,41). This lack of effect may be partly explained by the mildness (16-18°C) of these passive cold conditions (10,24,41) and the resulting small differences in temperature between the cold and the thermoneutral conditions (6-8 °C). The absence of clothing standardisation may also have attenuated the effects of cold on EI (19).

However, subjective hunger was not significantly modulated by the cold condition in comparison to the thermoneutral one. This is in line with all studies quoted earlier (16,39,40) and several other previous studies (10,17,41) indicating that passive exposure to cold led to no modification in subjective appetite.

This apparent paradox may reflect the fact that classical hormonal pathways regulating hunger operate over longer timescales (42) and were not altered during a short period of cold exposure (10,24). According to Lal et al. (42), overconsumption in cold conditions during the first hours of exposure could be explained by a compensatory behavioural response triggered by the activation of xiphoid nucleus (within the ventral midline thalamus) driven by the energetic cost of non-shivering thermogenesis. In this state of the literature, it is difficult to know whether these mechanisms also occur in humans and to identify the duration required to observe a concomitant increase in feelings of hunger and EI. We previously observed that hunger levels may increase after 10 days of cold exposure (-30 to -5 °C) during an expedition in Greenland (6,43). However, given the high level of physical activity, it was impossible to link this increase chronic cold exposure alone.

Effect of heat on hunger and EI

Contrary to the cold condition, heat exposure decreased hunger after only 3 h in this environment, which is in accordance with similar studies (19,40,44). Mechanisms identified

in mice may explain this rapid effect. Benevento et al. (45) observed that acute heat exposure activates a brainstem-hypothalamus circuit involving tanycytes. Their stimulation triggers a rapid release of vascular endothelial growth factor A (VEGFA), which inhibits the activity of agouti-related protein neurons (AgRP) in the arcuate nucleus situated in the hypothalamus. The relevance of this mechanism in humans is, to date, only hypothetical.

Subjective appetite may be explained by modifications in the plasma concentrations of appetite-related hormones. However, hormonal changes in response to heat exposure in humans remain poorly understood. In a comparable heat exposure, Zakrzewski-Fruer et al. (19) reported no significant changes following 5 h 30 at 30 °C (vs 20 °C), whereas Coca et al. (24) observed a modest increase in leptin after a 24-h exposure at 32 °C (vs 24 °C). Thus, the decrease in subjective appetite currently remains very poorly associated with modifications in hormone levels in a hot environment.

Moreover, when both groups were merged, EI decreased by 8.1% ± 30.0% in the hot condition. This is consistent with this reduction in hunger reported above, as well as with previous studies. For instance, Zakrzewski-Fruer et al. (19) reported decreases in both subjective hunger and EI (-26.4%) after 5.5 h at 30 °C (vs 20 °C). Similarly, Li et al. (46) observed a 17.1% reduction of EI after 60 min of a combined torso and foot heat exposure and Wasse et al. (40) observed an almost-significant reduction in EI (-11.8 %, $p = 0.08$) at 30 °C compared with 20 °C. By contrast, Faure et al. (47) did not observe modifications in hunger feelings and EI after 1.5 h at 31 °C compared to 22 °C. This divergence may be related to the shorter exposure duration in that study, as 3 h of exposure was required in the present study to reduce hunger.

Interestingly, whereas the cold-induced increase in EI appeared to occur independently of modifications of hunger feeling, the heat-induced decrease in EI seems to be more closely associated with a reduction in subjective hunger. This suggests that these opposite responses are not simply mirrored, but rather involve distinct and subtler mechanisms.

Food reward

The thermal exposure-induced changes in food reward are beginning to be well understood. Most of the previous studies have been conducted in our research facility where we assessed the effects of passive heat and cold exposure under controlled conditions (21,24) as well as in a cold environment , using a paper-based version of the LFPQ (48). In the current study, both EL and IW were significantly affected by thermal exposure across all food reward dimensions, highlighting once again their dependence on the thermal environment. Specifically, heat exposure increased food reward for low-fat, sweet, and fluid foods, whereas cold exposure slightly enhanced preferences for high-fat foods. More importantly, as expected, food temperature was the food characteristic most affected by thermal exposure. In a previous study, Coca et al. (24) observed that food reward for cold and warm foods was drastically increased during hot and cold exposures, respectively. These modifications were accompanied by concordant increases or decreases in the intake of the cold and warm components of the meals in the cold and hot conditions. These findings

confirmed the validity of the present study's design, indicating that some food propositions were indeed more congruent with the thermal environment (a warm meal at 15 °C and a cold meal at 35 °C) than others (a cold meal at 15 °C and a warm meal at 35 °C).

Other studies have reported similar effects. Motoki et al. (49) observed that the perceived warmth of savoury foods was positively associated with palatability in thermoneutral conditions (20-23 °C). However, this association became negative in hot conditions (27-30 °C). Recently, Li et al. (17,46) reported that 60 min of cold (cooling vest) or hot (hot vest and foot bath) exposures affected the consumption of foods and beverages based on their temperature. Thus, warm items were more consumed after cold exposure and less consumed after heat exposure, and cold items less consumed after cold exposure, indicating that modifications in food reward/preferences may be reflected in actual food choices and intake.

All these results confirmed that passive thermal exposures alter food reward, which, even in the absence of changes in hunger, may modulate food intake and ultimately influencing EI (12).

Congruency

At the whole-group level, hunger remained stable during cold exposure but was followed by an increase in EI, whereas heat exposure reduced subjective hunger and produced a parallel reduction in EI. These responses are consistent with most of the current literature regarding thermal influences on appetite and EI. However, the analysis at a group-specific level, based on the congruency of the meal, revealed different thermal exposure-induced effects on EI.

Under cold conditions, and contrary to our hypothesis, the modifications of EI compared with the thermoneutral condition were similar in both groups indicating that participants tended to eat more when exposed to cold, independently of the congruency of the meal. We previously observed (24), and others also reported (17), that the increases in food reward for warm foods resulted in a higher intake of these foods when participants could choose between items served at different temperatures. We were the first to observe that EI tend to increase (+8 to 12%; $p > 0.063$) over two consecutive meals at 32 °C compared with 24 °C, mainly due to a greater consumption of the cold components of the meals (+20%) (24).

Very interestingly, the present study suggests that even if food reward is strongly modified by cold exposure and even if the food choices may be altered when multiple options are available, people are encouraged to eat more food regardless of their congruency despite no increase in subjective appetite when they are presented as the only dish of the meal. The underlying mechanisms remain to be identified. However, as presented earlier, Lal et al. (42), in a mouse model, proposed that the cold-induced increase in EI obeys the primary physiological imperative to compensate for the high level of energy production in the brown adipose tissue through enhanced dopaminergic activity within reward-related neural circuits. We assume that this effect would override any influence of the food congruency

based on the temperature of the proposed foods, thereby explaining the similar EI across groups in the cold.

Interestingly, food congruency affected EI during heat exposure. Indeed, we observed that when the meal was congruent with the modulated food reward (i.e. Cold Meal), the decrease in EI was totally prevented despite lower levels of subjective appetite. In addition, when the meal was incongruent (i.e. Warm Meal), EI decreased in accordance with previous studies in which only a warm meal was served (19) and with the decrease in subjective appetite. The fact that the congruency of the served meal did not exert the same effect in the cold and heat conditions may potentially be explained by the different neural pathways. In contrast to the cold condition, the decrease in hunger would not be associated with the reward-related neural system, but rather with hypothalamic pathways (45). We hypothesise that the dopaminergic activity within the reward system may act additively with the thermal-induced anorexigenic effects already present, potentially mitigating or exacerbating these effects. Figure 9 highlights these different modifications between cold and heat. Indeed, cold-related modifications in the palatability of the meal were not associated with the cold-related modifications in EI in both groups indicating that EI increased independently of a better appreciation of the meal. However, those modifications were positively correlated at 35 °C, strongly suggesting that decreases in the palatability of the WM in the heat may explain its low consumption while the increase in palatability of the CM positively influenced its consumption.

Conclusion

First, we observed, in agreement with most of the literature, that thermal environments exert distinct effects on subjective appetite, EI, and food reward. Cold exposure increased EI despite stable levels of hunger, reflecting a possible compensatory metabolic response to the energetic cost of thermoregulation. In contrast, heat exposure reduced both hunger and EI, which is consistent with a hypothalamus-mediated anorexigenic effect. Second, we demonstrated the existence of an effect of the congruency between the serving temperature of the meal and the thermal exposure-induced modifications in food reward on EI. Interestingly, this phenomenon occurred only in the heat but not in the cold. Thus, while EI was similarly increased during cold exposure in both groups, EI was largely decreased during heat exposure only when a warm meal (incongruent) was served, indicating that serving a cold meal (congruent) may help prevent energy deficits in these thermal conditions.

Although the mechanisms remain to be identified, these observations illustrate that the nature of the foods served to athletes, military personnel, or other individuals exposed to heat could mitigate or worsen EI in this environment, cold foods having the potential to strongly reduce the anorexigenic response. Moreover, these findings indicate that researchers must anticipate the potential impact of their test meal on EI when assessing the effects of thermal exposure on appetite.

List of abbreviations

CAS: Composite appetite score

CM: Cold meal

EB: Energy Balance

EE: Energy Expenditure

EI: Energy Intake

EL: Explicit Liking

HR: Heart Rate

IW: Implicit Wanting

LFPQ: Leeds food preference questionnaire

RMR: Resting metabolic rate

RQ: Respiratory quotient

TNZ: Thermoneutral zone

Trec: Rectal temperature

Tskin: Skin Temperature

VAS: Visual analogue scale

WM: Warm meal

Declarations

Ethics approval and consent to participate

This study was conducted according to the guidelines laid down in the Declaration of Helsinki, and all procedures were approved by the French National Ethics Committee Île-de-France X (2024-A02285-42). Written informed consent was obtained from all participants who received financial remuneration for study completion.

Consent for publication

Not applicable

Availability of data and materials

The datasets used and analysed during the current study are not publicly available due to ethical and privacy restrictions but are available from the corresponding author on reasonable request.

Competing interests

The authors declare no competing interests.

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Authors' contributions

K. C. and M. C. designed the study. M. C., M. E., S. B., A. G., B. L., B. T., P-E. T-D., S. L., C. B., L. B., M. L-N., A. M., and K. C. carried out the study and collected the data. M. C. and K. C. processed data and conducted the statistical analyses. K. C. designed the figures. M. C., and K. C. drafted the initial manuscript. All authors reviewed and revised the manuscript, approved the final manuscript as submitted and agree to be accountable for all aspects of the work.

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