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Effects of cold-water immersion on energy expenditure, *ad-libitum* energy intake and appetite in healthy adults

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ABSTRACT

Introduction: Cold-water immersion is a popular method typically used to reduce exercise induced muscle damage and improve health and wellbeing. Despite these benefits, there is emerging evidence to suggest the temperature of the water exposure can influence energy intake in the subsequent hours. The study aim was to investigate the influence of water temperature on energy expenditure and post-water immersion *ad-libitum* energy intake in resting adults. Participants with a range of body masses, but otherwise healthy and physically active males (n = 10) and females (n = 5), participated in three randomised trials in a repeated measures crossover design, with a minimum of 7-days apart. Participants were immersed to sternum level for 30-minutes in either cold-water (16 °C), thermoneutral-water (35 °C) or a no-water thermoneutral ambient air control (26 °C). Participants completed appetite related visual analogue scales throughout and were presented with an *ad-libitum* homogenous pasta meal and asked to eat until 'comfortably full'.

Results: Repeated measures ANOVA showed participants consumed more energy after immersion in cold-water (2783 ± 909 kJ) versus both thermoneutral-water (1817 ± 862 kJ) and thermoneutral ambient air (1894 ± 233 kJ). There were no differences in any of the appetite VAS. Core temperature remained stable throughout the 30 min immersion period across trials, however an after-drop in core temperature was observed for 15 mins following cold-water immersion when compared to both thermoneutral water ($P < 0.001$), and thermoneutral air ($P = 0.004$). Although the exact mechanisms are yet to be elucidated, further research is required to identify if the after-drop in core temperature is a potential mechanism responsible for compensatory food intake post cold-water immersion.

Conclusion: When presented with an *ad-libitum* meal directly after cold-water immersion, participants consumed more in comparison to both thermoneutral water immersion and thermoneutral ambient air. With cold water immersion becoming popular, these findings have practical and clinical relevance for individuals' conscious about body mass management.

Abbreviations

CWI	cold-water immersion
TNWI	thermoneutral water immersion
TNAA	thermoneutral ambient air
TS	thermal sensation

1. Introduction

The beneficial claims of cold-water immersion (CWI) are prolific [1]. Participation in CWI therapy has become more popular, as regular exposure may aid the recovery process after strenuous exercise or sport [2,3], improve mood [4], have positive effects on blood markers of stress [5], strengthen the immune system [6], improve sleep and quality of life [7] and improve overall health and well-being [7,8]. Despite these claims there is burgeoning evidence which highlights that water exposure, in particular the water temperature may cause a person to overeat in the subsequent hours [9] potentially impacting upon body mass loss goals. Thermoneutral mean body temperature is between 36.16–37.02 °C [10]. The thermoneutral zone, is a temperature range perceived as

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comfortable, where resting metabolic rate remains stable [11], core body temperature is consistent, and there is an equilibrium between heat produced and heat lost from the body [12]. The thermoneutral zone in ambient air ranges between 28 °C to 32 °C [13], whereas due to greater thermal exchange is approximately 35–36 °C in water [14,15]. Accordingly, when immersed in cold-water, heat is lost from the body five times more quickly than in air due to greater conductive and convective heat transfer [16]). Although a specific temperature is not defined as 'cold', as some hazardous responses peak between 15 °C and 10 °C it is reasonable to suggest that a water temperature <15 °C is cold [1].

Acute CWI directly reduces skin temperature and subsequently peripheral blood flow, via vasoconstriction, to preserve body temperature [17,18]. Thereafter, to limit hypothermia, heat is generated through a combination of either voluntary or spontaneous physical activity (exercise or fidgeting), non-shivering thermogenesis or involuntary shivering thermogenesis [19]. Several studies have reduced core body temperature and quantified the energy expended through shivering during and after CWI, which is reported to peak at rates equivalent to 40–56% VO_2max ([20]; McInnis et al., 2019). Immediately after CWI, an 'after-drop' or further reduction in core temperature is observed [21] as vasodilation moves colder blood from the periphery to the core, manifesting in a further bout of shivering 5–10 minutes after exiting the water [22]. Ongoing research supports the health benefits of water immersion [7] and given public interest in engaging with passive CWI, more research is needed to understand CWI's specific benefits and concerns.

Appetite may be stimulated after exposure to cold-water, as thermoregulation requires energy [23]. Our study is novel in that it is the first to isolate passive CWI examining the effects of post CWI on appetite and EI, independent of exercise. Halse et al. [9] investigated the acute effect of post-exercise water immersion on subsequent energy intake (EI) in physically trained males. Participants ran on a treadmill for 40 min at an intensity of 70 % VO_{2peak}, after-which were immersed to sternum level for 20 min in either cold-water (15 °C), neutral-water (33 °C), or a no-water control (25 °C). Participants were then provided with an *ad-libitum* buffet meal and results highlighted that EI was higher after both cold-water (4,893 ± 1,554 kJ) and neutral-water (5,167 ± 1,975 kJ) in comparison with the no-water control (4,089 ± 1,585 kJ), suggesting being immersed in water is responsible for the compensation in energy intake.

Although the temperature wasn't manipulated through water immersion, Langveld et al. ;[24] Westerterp-Plantenga et al. [25] & Zakrzewski-Fruer et al. [26] investigated whether acute exposure to cold ambient air, increases short term EI and the results are equivocal. Langveld et al. [24] reported no difference in food intake after spending 2.5 h at 18 °C versus 24 °C ambient air temperature. Westerterp-Plantenga et al. [25] asked participants to spend 3 × 60 hours in a respiration chamber, twice at 16 °C and once at 22 °C. During one of the 16 °C visits, the participants were fed in energy balance for the whole 60-hours, then at the second 16 °C and 22 °C, were fed *ad-libitum*, for the final 24 h of the 60 h session. On the *ad-libitum* days at both ambient temperatures participants were in a positive energy balance, over-eating by 32–34 %. At 16 °C the increase in EI also correlated with reductions in rectal temperature. Zakrzewski-Fruer et al. (2021) demonstrated that after spending 5.5 h at either 10 °C, 20 °C or 30 °C ambient air, participants ate more after both 10 °C and 20 °C versus 30 °C when presented with an *ad-libitum* pasta meal, but there was no difference between 10 °C and 20 °C.

As previous works have either examined water-based exercise [27] or administered temperature change using an environmental chamber [28] the primary basis of our study is to isolate the effects of passive CWI to determine any influence on appetite and subsequent *ad-libitum* EI. We therefore hypothesize that 30 min of CWI set at 16 °C versus both thermoneutral water immersion (TNWI) set at 35 °C and a no-water thermoneutral ambient air (TNAA) control set at 26 °C will increase energy expenditure (EE) and subsequent EI. We also hypothesize *ad-libitum* EI will be higher after both water immersion conditions versus ambient air.

2. Methods

2.1. Ethical approval and participants

This study received approval from Coventry University's Research Ethics Committee (P145446) before any trial-related procedures commenced. Ten males and five females between the ages of 18 and 59 years were recruited from the local community and provided written informed consent. Some participants were in the 'overweight' category based on BMI, but were otherwise healthy and physically active, did not have any diagnosed cardiovascular, pulmonary, or metabolic disease, or any predisposing factors for hypothermia. Participants did not smoke, were not dieting and all met the physical activity guidelines of 150 min of moderate, or 75 min of vigorous intensity physical activity each week [29]. Participants all reported being body mass stable (<2 kg body mass change) in the three months prior to volunteering for the study. All female participants reported being eumenorrheic and not pregnant. As daily average body temperature can increase by approximately 0.4 °C in the luteal phase of the ovulatory cycle [30] we controlled for menstrual cycle by requesting females attend during the follicular phase which was self-reported.

To avoid awareness of the research aims, the participants were provided with information sheets which emphasised that the impact of CWI on EE was being examined. However, they were debriefed about the true aims of the study after the final experimental trial had taken place and it was ascertained that none of the participants were aware of the primary aims. The participants characteristics are detailed in Table 1.

G*Power™ software was used to calculate the required sample size. As there was no comparable study, we carried out a priori power analysis for a repeated-measures analysis of variance to examine main effects with three repeated-measures, which showed that 15 participants would provide greater than 80 % power ($\alpha = 0.05$) to detect a medium effect ($\eta 2 = 0.06$) in the dependent measures of interest (energy intake), with an assumed correlation among repeated measures of 0.5.

2.2. Pre-assessment and familiarisation

Each participant attended the laboratory based on Coventry University's campus for an initial preliminary visit to collect baseline data, assess health status and physical activity and to be familiarised with the study procedures. Participants were introduced to visual analogue scales (VAS) for appetite that were 100-mm in length [31], a four-point bedside shivering assessment scale (BSAS) [32] and the ASHRAE 7-point thermal sensation scale [33]. Participants were asked to insert a rectal thermistor 10cm beyond the anal sphincter [34] and undertake a 10 min cold-water tolerance test, submerged to chest depth (head out only) in a Lazy Spa (St. Lucia AirJet™) set at 16 °C. The temperature of 16 °C was selected as it a) reduced the risk of potential hazardous responses [1], and b) was slightly colder than the study by White et al [35] that demonstrated 40 min of aqua-cycling 20 °C increased EI by 44 %. This procedure was then followed by familiarisation to and consumption of the standardised breakfast snack and *ad-libitum* pasta meal that would be provided on subsequent visits to ascertain no allergies as well as provide an indication of the volume of food that needed to be prepared.

2.3. Experimental design and procedures

Three trials were completed in a randomised order and with a minimum of 7 days washout period between trials. Fig. 1 provides a schematic representation of the study design. Participants were asked to refrain from consuming alcohol and caffeine containing products and undertaking vigorous exercise during the preceding 48 h. Participants were asked to attend the laboratory having fasted for 8–10 h and had a

Table 1
Participants characteristics.

Characteristics	Male (n = 10)	Range (Min–Max)	Female (n = 5)	Range (Min–Max)	Combined (n = 15)	Range (Min–Max)
Age (years)	42 ± 14	35 (24–59)	37 ± 15	33 (20–53)	39 ± 14	39 (20–59)
RHR (bpm)	64 ± 11	37 (43–80)	62 ± 10	30 (52–82)	64 ± 11	39 (43–82)
MAP (mmHg)	93 ± 9	24 (79–103)	92 ± 18	43 (70–113)	93 ± 11	43 (70–113)
Height (cm)	178 ± 4	12.1 (172.5–184.6)	167 ± 7	15.9 (158.5–174.4)	173 ± 8	26 (158.5–184.6)
Body Mass (kg)	79.5 ± 12.3	34.4 (63.2–97.6)	83.4 ± 12.2	40.4 (56.6–97)	77.7 ± 12.5	41 (56.6–97.6)
BMI (kg.m^2)	25.7 ± 3.9	11.1 (20.9–32)	30.2 ± 6.5	15.5 (22.5–38)	26.7 ± 4.9	17 (20.9–38)
BF (%)	22.3 ± 5.7	21.3 (12.7–34)	31.3 ± 5.9	13 (23–36)	24.9 ± 6.7	23 (12.7–36)
TFEQ-R18 (%)	18.1	3 (17–20)	17.6	2 (17–18)	3 (17 ± 20)	3 (17 - 20)

BF: body fat; BMI: body mass index; BSA: body surface area; MAP: mean arterial pressure; Max: maximum; Min: minimum; RHR: resting heart rate; TFEQ-R18: three factor eating questionnaire–revised 18 questions. Values are presented as mean difference ± standard deviation along with range for each sex and overall.

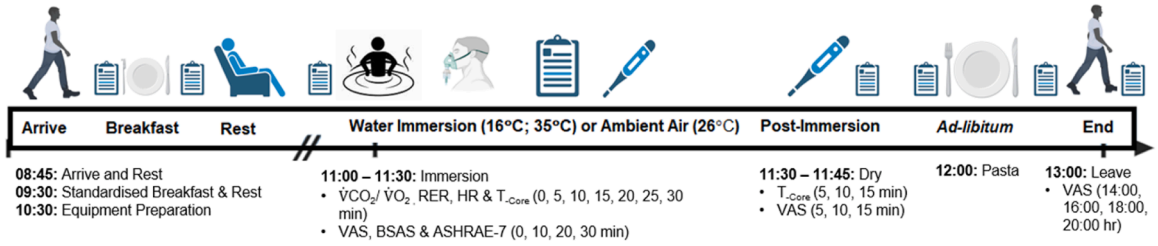


Fig. 1. Schematic representation of the main trial protocol.
ASHRAE-7: 7-point thermal sensation scale; BSAS: bedside assessment shivering scale; HR: heart rate; hr: hour; RER: respiratory exchange ratio; T-Core: core body temperature; VAS: 100 mm visual analogue scale (appetite); VO_2: volume of oxygen; VCO_2: volume of carbon dioxide.

restful night's sleep, arriving at 08:45 by either motorised transport or light exercise. Participants rested quietly in a recumbent position in the laboratory for 30 min. At 09:15 participants were provided with a standardised breakfast equivalent to 20 % of their predicted resting metabolic rate, calculated using Harris-Benedict's revised equation [36] and were given 15 min to consume this. At 09:30 participants then rested quietly for one hour in a recumbent position and at 10:30 changed into their swimwear and were requested to insert a rectal thermistor prior to being fitted with a face mask to enable indirect breath-by-breath calorimetry using an Ultima CCM™. A heart rate monitor (Garmin, 735XT) was worn on the wrist and was used to measure heart rate. At 11:00 participants were immersed to chest depth (xiphoid process) for 30 min in either cold (16 °C), or thermoneutral water (35 °C) or a no-water control, seated on a chair in an environmental chamber set at ambient air temperature (26 °C) and 40 % humidity. During immersion, expired gas was measured for the full 30 min, core body temperature was recorded at 5 min intervals and subjective measures of appetite, shivering and thermal sensation (TS) were recorded every 10 min. At 11:30 participants exited the water and were asked to dry and change into typical loose-fitting clothing and core body temperature was monitored for a further 15 min. At 12:00 participants were presented with an *ad-libitum* homogenous pasta meal and asked to eat until 'comfortably full and satisfied'. Participants were able to leave the laboratory at 13:00 and were briefed to set alarms using a device for 14:00, 16:00, 18:00 and 20:00, and were instructed to go about their day as normal but to text 'subjective measures of appetite' in the order 'hunger, fullness, satisfaction & how much can you eat now' at these specific times to the researcher. All participants were provided with 100 mm VAS for measures to be completed at these specific time points.

2.4. Anthropometrics and body composition measurements

Initial assessments (Table 1) were completed to measure height to the nearest 0.1 cm using a stadiometer (Seca 213 Stadiometer Portable Height Measurement Scale), body mass to the nearest 0.1 kg using a digital scale (Seca 875 Electronic Class III Scale) and body fat percentage was estimated via four subcutaneous fat measurements (triceps, biceps, subscapular and supra-iliac) [37] using skinfold callipers (Baty Harpenden Skinfold Calliper) by an ISAK-accredited practitioner. Body surface area (BSA) was calculated using the DuBois and DuBois method [38] (see equation[1]).

$$BSA = 0.00718xHeight(cm)^{0.725}xWeight(kg)^{0.425}$$

Equation legend[1]: bsa: body surface area; cm: centimetres; kg: kilograms

2.5. Metabolic and cardiorespiratory measurements

Expired VO_2 and VCO_2 were measured every 3-seconds for each 30 min immersion session using indirect calorimetry (Med-Graphics Ultima CCM™). The mean value of oxygen consumption (VO_2 L/min), and carbon dioxide production (VCO_2 L/min), was used to calculate EE using Weir's equation [39] (see equation[2]) multiplied by 30 min to calculate the corresponding kcal/session. Kcal have been converted to kJ (see equation[3])

$$EE(kcal/min) = (3.941xV{\cdot}O_2L/min) + (1.106xV{\cdot}CO_2L/min)$$

Equation legend[2]: EE: energy expenditure; kcal: kilocalories; L: Liters; min: minutes; VCO_2: volume of carbon dioxide; VO_2: volume of oxygen

$$kJ = 1\ kcal * 4.184$$

Equation legend[3]: kcal: kilocalories; kJ: kilojoules

During the initial health screening, blood pressure and resting heart rate were measured using a portable Omron HEM-907 Professional Blood Pressure Monitor (Table 1). Subjective measures of shivering were assessed upon entry and every 10 min during the 30 min exposure using a four-point BSAS (0–none; 1–mild; 2–moderate and 3–severe) and TS was assessed upon entry and every 10 min during the 30 min immersion period using ASHRAE 7- point scale (-3 cold, -2 cool, -1 slightly cool, 0 neutral, +1 slightly warm, +2 warm and +3 hot). All devices were calibrated according to manufacturer guidelines to ensure accuracy of measurement across all visits.

Heart rate was monitored at four time points upon entry and during

immersion (11:00, 11:10, 11:20, 11:30), then for 15 min post immersion every 5 min (11:30, 11:35, 11:40, 11:45) using a Garmin water-based heart rate monitor and heart rate monitor (Garmin 735xt) respectively.

2.6. Energy intake, appetite, and study meals

The revised three-factor eating questionnaire (TFEQ-R18) was completed at baseline, to examine eating behaviour, and to provide the assurance that all participants scored low when questioned on cognitive restraint. The TFEQ-R18 is applicable and able to distinguish between different eating patterns in the general population [40]. The raw scale scores are transformed to a 0–100 scale (see equation[4])

$$TFEQ-R18\ Score\ (\%) = (raw\ score - lowest\ possible\ raw\ score) / (possible\ raw\ score\ range) * 100$$

Equation legend[4]: %: percentage

The standardised breakfast provided 20 % of total daily EE, predicted using the Harris–Benedict equation to calculate basic metabolic rate, multiplied by 1.4 to account for light physical activity [41]. This was then sub-divided into 75 % BelVita™ breakfast strawberry filled soft bake (6.4 % protein, 64.6 % carbohydrates and 29.1 % fat) and 25 % Tesco™ pure orange juice (5.8 % protein, 83.3 % carbohydrates and 10.9 % fat).

Ad-libitum EI was assessed from a homogeneous pasta meal which contained a tomato and basil sauce (14.2 % protein, 75.7 % carbohydrates and 10.1 % fat). Using standardised operating procedures [42]. Ingredients were combined in advance of the trials and then re-heated before serving to participants using a microwave (Kenwood K20MW21 Solo) for 5 min to ensure the temperature was consistent. Pasta volume prepared exceeded expected consumption (2200g; 11655 kJ), and a continual supply of equal portions (50g; 263 kJ) were provided to the participants and eaten in a room with no external influences or food cues. Participants were allowed 30 min to eat the pasta meal and were instructed to eat until 'comfortably full and satisfied'.

The mass of food consumed was determined by subtracting the mass of food remaining, which included any leftovers on the plate or cutlery. Absolute EI was calculated using nutritional information provided by the food manufacturer. Relative energy intake (REI) was calculated by subtracting the EE during the 30 min immersion period from the EI during the homogenous pasta meal (see equation[5]). Subjective perceptions of hunger, fullness, satisfaction, and prospective food consumption (PFC) were assessed using a 100 mm visual analogue scale [31], prior to (09:00) and post (09:30) breakfast, 30 min prior to immersion (10:30) at four time points upon entry and during immersion (11:00, 11:10, 11:20, 11:30), prior to (12:00) and post (12:30) *ad-libitum* pasta meal, and then after leaving the lab (14:00, 16:00, 18:00 and 20:00). The standardised questions being: - how hungry do you feel? ("not hungry at all" to "very hungry"); how full do you feel? ("not full at all" to "very full"); how satisfied do you feel? ("completely empty" to "I cannot eat anymore"); and how much do you think you could eat now? ("nothing at all" to "a lot"). We did not ask participants to alter their dietary intake or physical activity for the remainder of the day and participants were instructed to 'go about their day' as usual.

$$REI = (EI\ ad-libitum - Kcal / Session)$$

Equation legend[5]: REI: relative energy intake; EI: energy intake: Kcal: kilocalories

2.7. Core temperature

Core temperature was measured using a rectal thermistor and a data logger (Eltek Genll GD32) at four time points upon entry and during immersion (11:00, 11:10, 11:20, 11:30), then for 15 min post immersion every 5 min (11:30, 11:35, 11:40, 11:45), to capture any after-drop in core temperature.

2.8. Statistical analysis

Data were analysed using the software package (IBM SPSS Statistics 28.0.0.0). Distribution of data was checked using the Shapiro–Wilks test [43]. Exact P values (to 3 decimal places) are reported except for very small values which are displayed as $P < 0.001$. Effect sizes (ES) are calculated to compare the sizes of effects within a study using partial eta squared η_p^2 where small ($\eta_p^2 = 0.01$), medium ($\eta_p^2 = 0.06$), and large (η_p^2-= 0.14) effects [44]. Mean differences and the respective 95 % confidence intervals (95 % CI) are presented. Energy intake, REI and EE was compared between trials using repeated-measures ANOVA, with post hoc pairwise comparisons using Bonferroni adjustment to determine differences. Core body temperature, shiver intensity, thermal sensation and measures of appetite are compared between trials using a two-way repeated measures ANOVA to compare 'immersion' as a within-subject effect, 'variable over time' as the independent factor, and 'immersion*variable over time' as the interacting term. Mauchly's test determined any within-subject effects, and Greenhouse-Geisser is referred to if the test for sphericity was violated.

3. Results

3.1. Metabolic and cardiorespiratory measurements

3.1.1. VO_2 (L/min)

A main effect of trial was identified for oxygen consumption ($F(1.134, 15.878) = 28.663$, $P < 0.001$, $\eta_p^2 = 0.67$)). VO_2 was higher after CWI (0.356 ± 0.095 L/min) versus both TNWI (0.217 ± 0.452 L/min) (mean difference [95 % CI], 0.139 [0.069 to 0.209] L/min; $P < 0.001$), and TNAA (0.208 ± 0.035 L/min) (mean difference [95 % CI], 0.148 [0.075 to 0.220] L/min; $P < 0.001$). There was no difference in VO_2 when TNWI (0.217 ± 0.452 L/min) was compared with TNAA (0.208 ± 0.035 L/min) (mean difference [95 % CI], 0.009 [- 0.12 to 0.03] L/min; $P = 0.820$, Fig. 2).

3.1.2. Energy expenditure (kJ)

A main effect of trial was identified for EE ($F(1.131, 15.839) = 30.905$, $P < 0.001$, $\eta_p^2 = 0.67$)). Energy expenditure was higher after CWI (224 ± 60 kJ) versus both TNWI (135 ± 27 kJ) (mean difference [95 % CI], 89 [46 to 133] kJ; $P < 0.001$), and TNAA (129 ± 22 kJ); (mean difference [95 % CI], 95 [50 to 140] kJ; $P < 0.001$). There was no difference in EE when TNWI (135 ± 27 kJ) was compared with TNAA (129 ± 22 kJ) (mean difference [95 % CI], 5 [-7 to 19] kJ; $P = 0.771$, Fig. 2).

3.1.3. Bedside shivering assessment scale

A main effect of trial ($F(1.0, 14.0) = 65.113$, $P < 0.001$), time ($F(3, 42) = 17.770$, $P < 0.001$, $\eta_p^2 = 0.82$) and trial*time ($F(2.298, 38.855) = 17.770$, $P < 0.001$) was identified. Between 11:00 and 11:30 shiver intensity was higher in CWI versus both TNWI ($F(1.0, 14.0) = 25.221$, $P < 0.001$) and TNAA ($F(1.0, 14.0) = 25.221$, $P < 0.001$, Fig. 3). Shivering

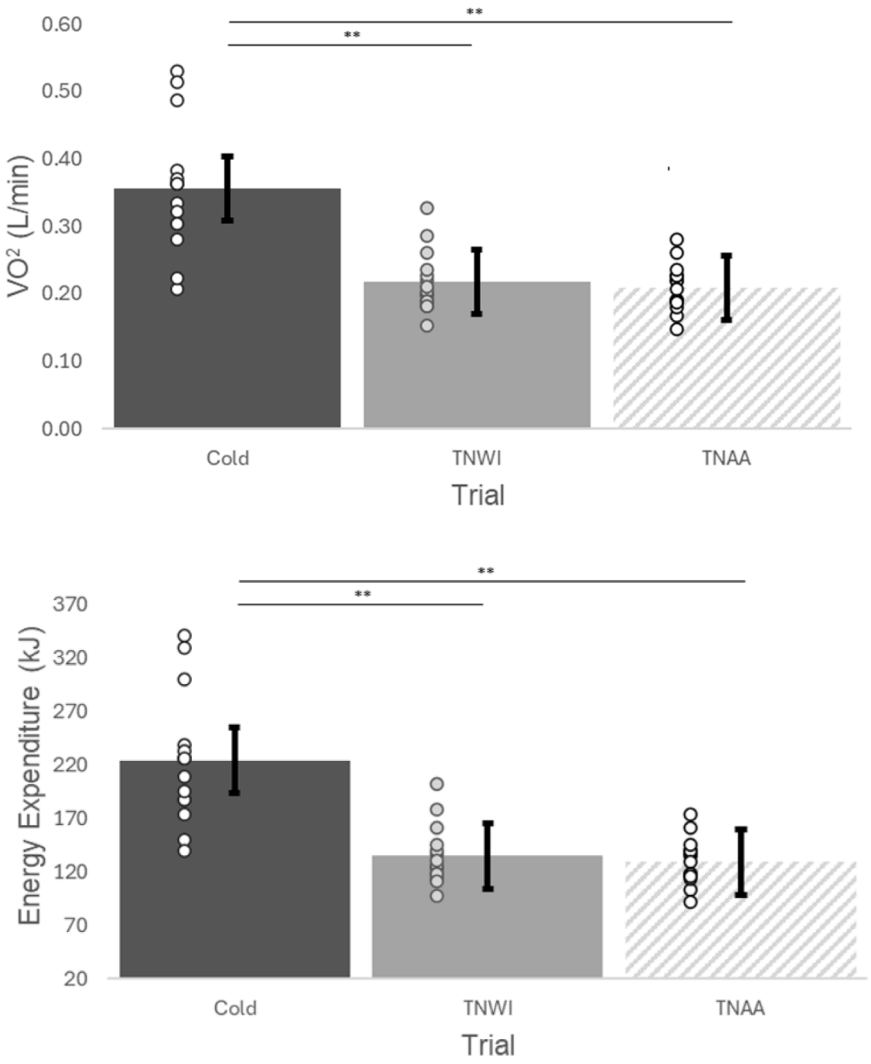


Fig. 2. VO_2 and Energy Expenditure during CWI (16 °C), TNWI (36 °C) and TNAA (26 °C) experimental conditions (n = 15). Data presented as mean ± SD; individual data points are presented for each condition, post hoc analysis using Bonferroni adjustment to determine differences. *, **: significantly different at $P < 0.05$ and $P < 0.001$, respectively. A horizontal line shows start and finish of each time difference.
CWI: cold water immersion, TNWI: thermoneutral water immersion, TNAA: thermoneutral ambient air.

was absent in both TNWI and TNAA.

3.1.4. Thermal sensation

A main effect of trial ($F(2, 28) = 88.309$, $P < 0.001$), time ($F(3, 42) = 4.381$, $P < 0.009$, $\eta_p^2 = 0.86$) but not trial*time ($F(6, 84) = 1.631$, $P = 0.149$) was identified. Between 11:00 and 11:30 TS was perceived to be colder in CWI versus both TNWI ($F(1, 14) = 173.713$, $P < 0.001$) and TNAA ($F(1, 14) = 113.946$, $P < 0.001$). TNAA also felt slightly cooler than TNWI ($F(1, 14) = 4.387$, $P = 0.055$, Fig. 3).

CWI: cold water immersion, TNWI: thermoneutral water immersion, TNAA: thermoneutral ambient air.

3.1.5. Heart rate during immersion

Heart rate did not differ between trials over the 30 min immersion period due to temperature ($F(2, 28) = 0.945$, $P = 0.401$, $\eta_p^2 = 0.63$)), or time ($F(2.007, 28.100) = 0.393$, $P = 0.91$, $\eta_p^2 = 0.91$)) and there were no trial*time differences ($F(3.107, 43.497) = 1.794$, $P = 0.14$, $\eta_p^2 = 0.11$, Fig. 4)).

3.1.6. Heart rate 15 min post immersion

Upon exiting the lazy-spa and 15 min post water immersion, there was a main effect on heart rate due to time ($F(2,28) = 4.211$, $P < 0.02$, $\eta_p^2 = 0.23$)), but not temperature ($F(2,28) = 0.932$, $P = 0.932$, $\eta_p^2 = 0.005$)) or trial*time ($F(2.143, 40.238) = 1.450$, $P = 0.60$, $\eta_p^2 = 0.037$)).

3.2. Energy intake

3.2.1. Energy intake (kJ)

A main effect of trial was identified for EI ($F(1.367, 19.141) = 39.963$, $P < 0.001$, $\eta_p^2 = 0.74$). Energy intake was higher after CWI (2783 ± 909 kJ) versus both TNWI (1817 ± 862 kJ) [95 % CI], 966 [587 to 1345] kJ; $P < 0.001$), and after TNAA (1894 ± 233 kJ) [95 % CI], 889 [512 to 1266] kJ; $P < 0.001$). There was no difference in EI when TNWI (1817 ± 862 kJ) was compared with TNAA (1894 ± 233 kJ) [95 % CI], -77 [-261 to 107] kJ; $P = 0.823$, Fig. 5).

3.2.2. Relative energy intake (kJ)

A main effect of trial was identified for REI ($F(1.343, 18.805) = 29.997$, $P < 0.001$, $\eta_p^2 = 0.68$). Relative energy intake was higher after CWI (2558 ± 893 kJ) versus both TNWI (1682 ± 848 kJ) [95 % CI], 877 [477 to 1276]; kJ; $P < 0.001$), and after TNAA (1765 ± 901 kJ); [95 % CI], 797 [405 to 1183] kJ; $P < 0.001$). There was no difference in REI between TNWI (1682 ± 848 kJ) and TNAA (1765 ± 901 kJ); [95 % CI], -82 [-270 to 104] kJ; $P = 0.741$, Fig. 5).

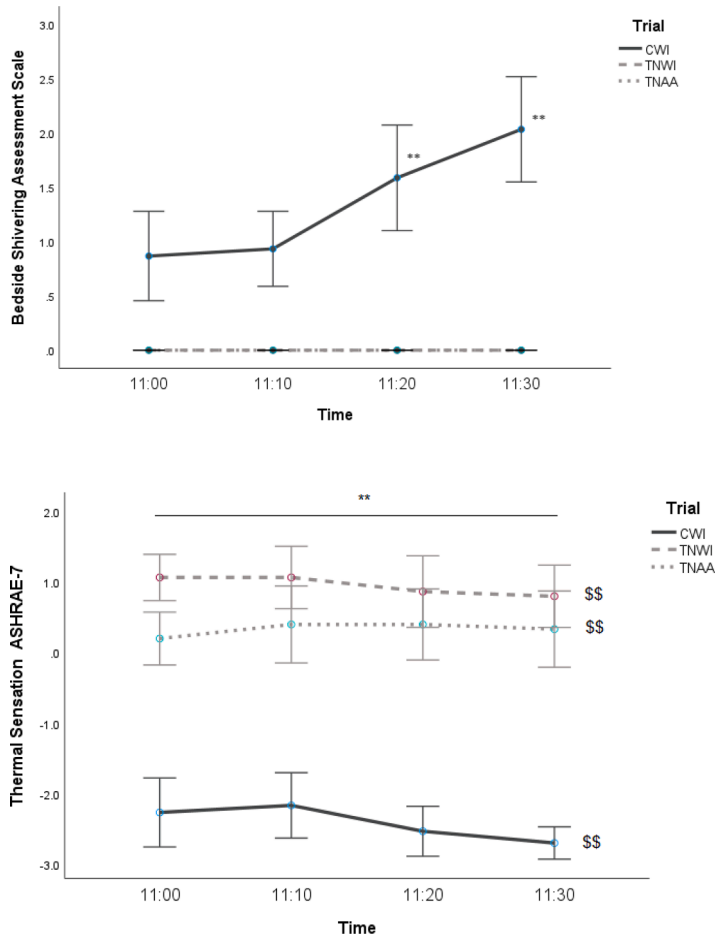


Fig. 3. Bedside Shivering Assessment Scale and ASHRAE-7 thermal sensation in the CWI (16 °C), TNWI (36 °C) and TNAA (26 °C) experimental conditions (n = 15) during 30 min of immersion (*11:00, 11:10, 11:20, 11:30*). Data is presented as mean ± SD and post hoc analysis using Bonferroni adjustment to determine any significant 'time' *, ** or 'trial*time' $, $$ differences at $P < 0.05$ and $P < 0.001$, respectively. A horizontal line shows start and finish of each time difference.

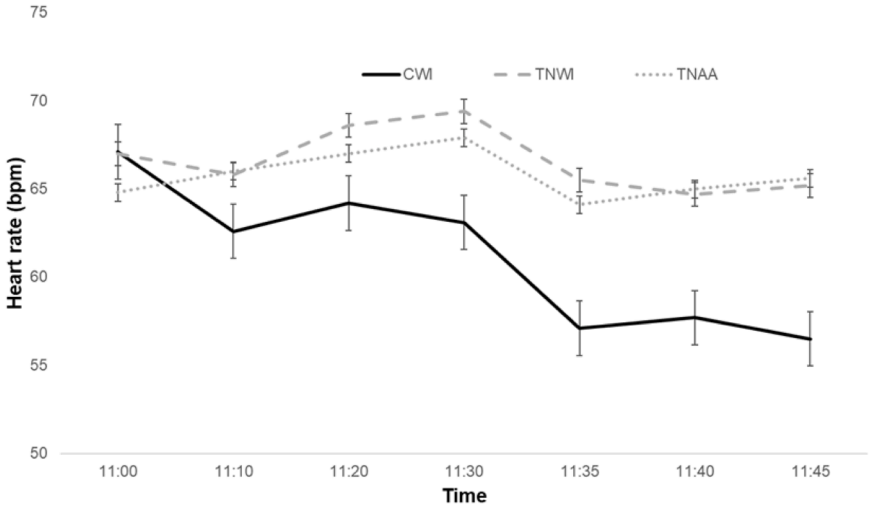


Fig. 4. Heart rate responses during and after CWI (16 °C), TNWI (36 °C) and TNAA (26 °C) experimental conditions (n = 15). Heart rate was measured at four time points during immersion (11:00, 11:10, 11:20, 11:30) and at a further three time points for 15 min post immersion (11.35, 11.40 and 11.45am). Data is presented as mean ± SD and post hoc analysis using Bonferroni adjustment to determine any significant 'time *, ** differences at $P < 0.05$ and $P < 0.001$, respectively.
CWI: cold water immersion, TNWI: thermoneutral water immersion, TNAA: thermoneutral ambient air.

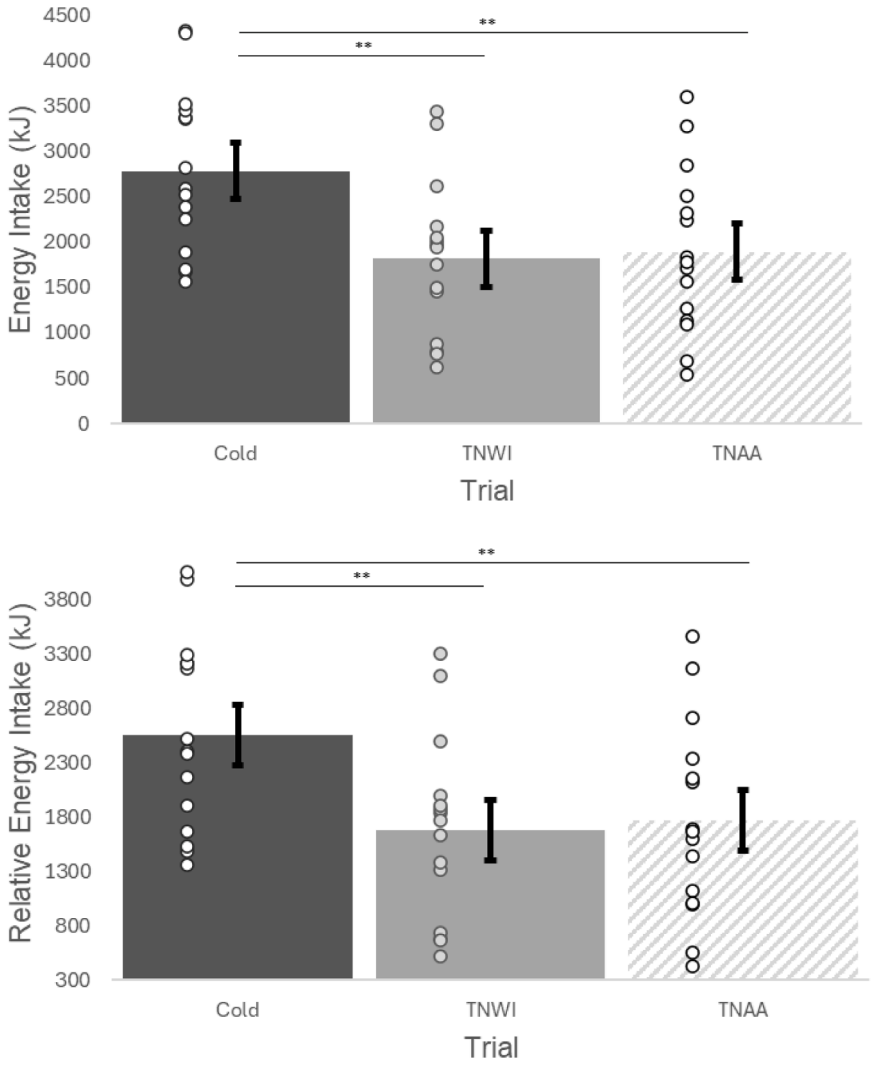


Fig. 5. *Ad-libitum* energy intake and relative energy intake after CWI (16 °C), TNWI (36 °C) and TNAA (26 °C) experimental conditions (n = 15). Energy intake was measured by mean amount of homogenous pasta eaten 30 min post immersion at 12pm. Data presented as mean ± SD; post hoc analysis using Bonferroni adjustment to determine differences. *, **: significantly different at $P < 0.05$ and $P < 0.001$, respectively. A horizontal line shows start and finish of each time difference. CWI: cold water immersion, TNWI: thermoneutral water immersion, TNAA: thermoneutral ambient air.

3.3. Appetite sensations

3.3.1. Hunger, fullness, satisfaction, and prospective food consumption

Ratings of appetite varied over time for hunger, fullness, satisfaction, and PFC ($P < 0.001$). The pattern of change overtime did not vary between trials ($P > 0.05$, Fig. 6).

3.4. Core temperature

3.4.1. Core temperature during immersion

A main effect of time ($F(1.467, 20.543) = 6.440$, $P = 0.01$, $\eta_p^2 = 0.31$)), was identified over the 30 min immersion period, but there was no difference between trial ($F(2, 28) = 0.174$, $P = 0.84$, $\eta_p^2 = 0.01$)) or any trial*time differences ($F(2.166, 30.318) = 1.211$, $P = 0.31$, $\eta_p^2 = 0.08$, Fig. 7)).

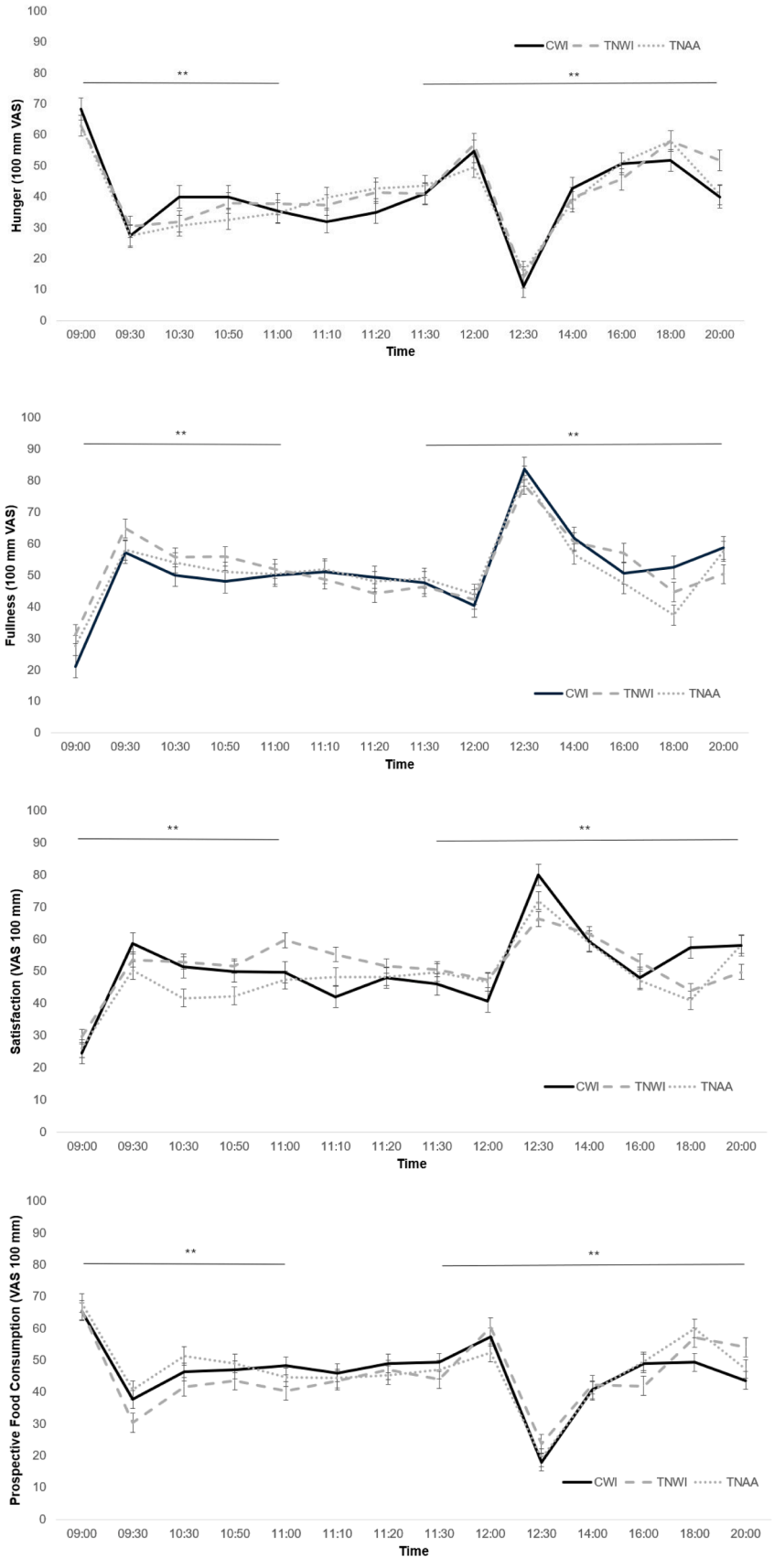
3.4.2. Core temperature 15-min post immersion 'after drop'

All effects are reported as significant at $P < 0.05$. There was a significant main effect of time ($F(1.712, 23.974) = 16.409$, $P < 0.001$, $\eta_p^2 = 0.54$)), trial ($F(2, 28) = 5.372$, $P = 0.01$, $\eta_p^2 = 0.27$)) and trial*time ($F(2.599, 36.384) = 31.991$, $P < 0.001$, $\eta_p^2 = 0.69$)) 15 min post water immersion. Contrasts were performed to compare CWI to both TNWI and TNAA and from time exiting the water (11:30) to 15 min post immersion (11:45). This revealed core body temperature lowered significantly more after CWI versus both TNWI ($F(1, 14) = 91.675$, $P < 0.001$, $\eta_p^2 = 0.86$) and TNAA ($F(1, 14) = 25.021$, $P < 0.001$, $\eta_p^2 = 0.64$, Fig. 7)).

4. Discussion

This study investigated the acute effects of cold-water immersion (CWI) on energy expenditure (EE), *ad-libitum* energy intake (EI), and appetite in healthy adults. Primarily, the results of this study indicate that 30 min of CWI leads to greater EE and post-immersion *ad-libitum* EI (2783 ± 909 kJ) when compared to two thermoneutral conditions, thermoneutral water immersion (TNWI) (1817 ± 862 kJ) and thermoneutral ambient air (TNAA) (1894 ± 233 kJ). No differences between the two thermoneutral conditions were detected. This is an important consideration as CWI could lead to overeating when presented with an *ad-libitum* meal soon afterwards.

These data demonstrate that more energy is expended whilst passively immersed for 30 min in cold-water (224 ± 60 kJ) versus both TNWI (135 ± 27 kJ) and TNAA (129 ± 22 kJ). Water temperatures below thermoneutral cause shivering or non-shivering thermogenesis to occur as the body adjusts to control thermal balance [45]. Peak



(caption on next page)

Fig. 6. *Hunger, fullness, satisfaction, and prospective food consumption prior to and post breakfast and prior to immersion (09:00, 09:30, 10:30), during the 30 min of immersion (11:00, 11:10, 11:20, 11:30),* 60 min leading up to and after ad-libitum meal (11:30, 12.00, 12.30) and during the 6 h leading into the evening (*14.00, 16.00, 18.00, 20.00*) (n = 15). Data is presented as mean ± SD; post hoc analysis, using Bonferroni adjustment to determine significant 'time' *, ** differences at $P < 0.05$ and $P < 0.001$, respectively. A horizontal line shows start and finish of each time difference.
CWI: cold water immersion, TNWI: thermoneutral water immersion, TNAA: thermoneutral ambient air.

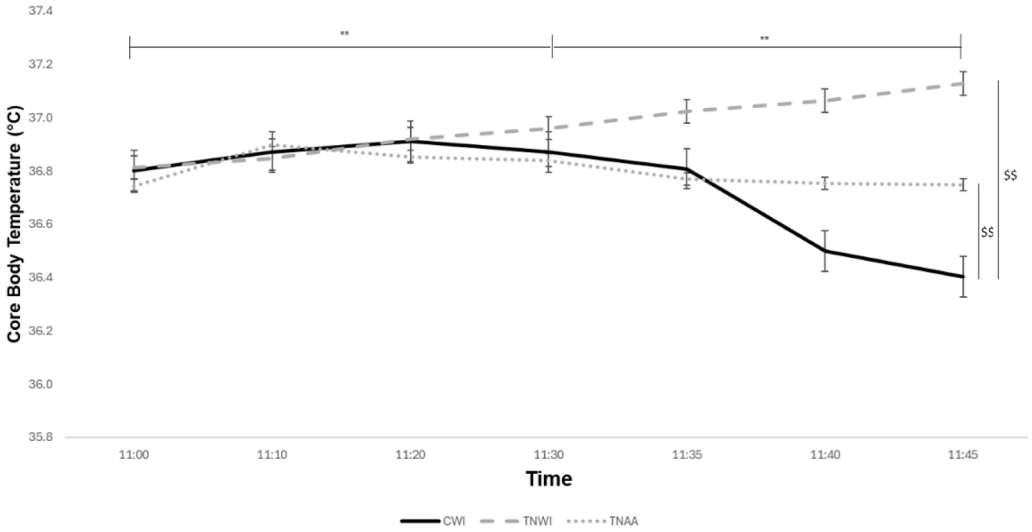


Fig. 7. Thermoregulatory responses during and after CWI (16 °C), TNWI (36 °C) and TNAA (26 °C) experimental conditions (n = 15). Core temperature was measured via rectal thermistor at four time points during immersion (11:00, 11:10, 11:20, 11:30) and at a further three time points for 15 min post immersion (11.35, 11.40 and 11.45am). Data presented as mean ± SD; post hoc analysis using Bonferroni adjustment to determine significant 'time' *, ** or 'trial*time' $, $$ differences at $P < 0.05$ and $P < 0.001$, respectively. A horizontal line shows start and finish of each time difference. A vertical line shows start and finish of each trial difference.
CWI: cold water immersion, TNWI: thermoneutral water immersion, TNAA: thermoneutral ambient air.

shivering rates have been reported to reach 46–50 % of VO_{2max} [46] which for 30 min in an average 70 kg individual would be equivalent to ~753 kJ, [47]. As participants were passively submerged in water much colder than in our study (8 °C) and for approximately 60 min this is much higher than we observed ~224 kJ during 30 min of CWI.

We asked our participants to rate their shivering intensity during immersion, as either absent, mild, moderate, or severe [32]. Participants did not experience shivering during either of the thermoneutral conditions, however, shivering was rated moderate to severe during cold-water immersion, corresponding with cool to cold perceptions of thermal sensation. The average oxygen consumption during TNWI (0.217 ± 0.045 L/min) versus TNAA (0.208 ± 0.035 L/min) was insignificant and slightly lower than the approximated 3.5 mL O_2/kg/min at rest [48]. In comparison, oxygen consumption was higher when participants were immersed in cold-water (0.356 ± 0.095 L/min). During head-out immersion in water, the increased hydrostatic pressure causes blood to be more centralised around the heart and lungs creating acute changes in cardiac output and gas exchange, more prominent in cold-water [49,50]. Similarly, Choukroun & Varene [51] demonstrated a slightly lower but non-significant reduction in metabolism (0.239 ± 0.053 L/min) during head-out water immersion in 34 °C, in 11 healthy volunteers, which authors concluded was due to water immersion postural support. They noted a rise in oxygen consumption when participants were immersed in a cooler 25 °C water (0.364 ± 0.160 L/min).

We hypothesized cold-water immersion would increase EE with corresponding increases in *ad-libitum* EI. Our findings confirm when compared to both TNWI and TNAA immersion, absolute *ad-libitum* EI was increased by 34 % and 32 % respectively. A small number of studies have researched *ad-libitum* EI following environmental temperature manipulated using ambient air and not water immersion. Langveld et al. [24] and Westerterp-Plantenga et al. [25] reported no difference in EI after exposure, but this may be because experimental temperatures were below that defined as thermoneutral. Zakrzewski-Fruer et al. [26] demonstrated participants also ate a similar amount of food when exposed to both 10 °C and 20 °C, however, when compared to a temperature which more closely reflected TNAA (30 °C) the amount of food consumed was greater. In our study ambient air was set 2 °C below the thermoneutral range, but we didn't detect any differences in immersion VO_2 or EE between thermoneutral water or TNAA. Ratings of thermal comfort were also reported as 'neutral', and shivering was absent. Thermoneutral air could therefore serve as a threshold for energy intake regulation, and we suggest future studies take this into consideration when assigning a thermoneutral control.

Whether compensation in energy intake post CWI affects body mass loss over a longer term is yet to be clarified. Only one chronic training study to date has investigated whether swimming versus land-based cycling altered appetite hormones in adults living with obesity [52]. Participants gradually increased exercise training volume and intensity over a 12-week study period results demonstrating a clear reduction in body mass after both exercise groups (swimming and cycling). As the authors of this study did not measure energy intake, the temperature of the water was not cold 27–28 °C and there was an exercise component, whether compensation occurs longer term after cold water exercise or static immersion requires further investigation.

We also hypothesised that both water immersion conditions would augment EI regardless of the temperature. However, our results ruled out water immersion as a driving mechanism, as *ad-libitum* EI was consistent after both TNWI (1817 ± 862 kJ) and TNAA (1894 ± 233 kJ). Halse et al. [9] post exercise immersion led to increases in *ad-libitum* food intake after both CWI and TNWI when compared to a no-water resting control, but there was no difference between the water immersion trials. It has been suggested that EI may be driven by a reduction in core body temperature [25]. Halse et al. [9] asked participants to exercise prior to the water immersion, which generally results in a more rapid decline in core temperature [53], however, authors reported no significant trial or time interaction in reported tympanic temperature. It

is important to note, using a digital ear thermometer to measure body temperature does not provide the most accurate reflection of core body temperature, particularly during and after exercise [54].

Core body temperature interacts with the brain via specific neural pathways resulting in altered feeding behaviour [55]. The hypothalamic region of the brain is the main regulator of appetite and thermoregulation [56] and contains the arcuate nucleus (ARC) which expresses both anorexigenic A-melanocyte-stimulating hormone (aMSH) and orexigenic agouti-related peptide (AgRP). Although studies have yet to be trialled in humans, Yang et al. [23] demonstrated that ARC^{AgRP} neurons are profoundly activated by cold exposure resulting in hunger dependent feeding behaviour in mice. In our study, participants did eat substantially more after a 30 min bout of CWI, however core body temperature at the end of immersion (11:30), and whilst still in the water, had increased by 0.07 °C. Marginal increases were also observed during both TNWI (0.15 °C) and TNAA (0.10 °C) immersion. This thermoregulatory response is consistent with findings reviewed by Ntoumani et al. [11] who reports core temperature is defended for around 30 min during whole body passive water immersion in temperatures ranging between 15–18 °C due to reduced peripheral blood flow. It is only when a person is removed from the cold-water and during the rewarming process, vasodilation allows warmer blood to perfuse towards the cooler deep tissue establishing a temperature gradient (Giesbrecht & Bristow, 1992). Core temperature will continue to fall for up to 10–30 min, termed the after-drop (Webb, 1986). White et al., [35] reported *ad-libitum* EI increased by 44 % after 40 min of aqua-cycling in cold (20 °C) versus thermoneutral (33 °C) water at 60 % VO_{2max}, but the minimal reduction of 0.3 °C in core temperature was ruled out as a causal factor. The heat generated by the exercising leg muscles most likely led to negligible changes in core temperature as Castellani et al. [45] suggests performing leg only exercise in water at an intensity >60–75 % VO_{2max} mitigates heat lost at the periphery. Although White et al., [35] reported core temperature did decrease significantly 15 min after cold versus neutral water exercise, measurements were still above those taken at baseline. We demonstrated that after our participants exited the cold-water and over a period of 15 min, core temperature had dropped significantly by (-0.50 °C) in comparison to TNWI (-0.02 °C) and which had increased after TNAA (0.10 °C). As the cold-water-induced reduction in core temperature coincided with an increase in food intake, we could speculate that the body is attempting to regulate core temperature via diet induced thermogenesis by overeating.

The thermic effect of food which increases metabolism is greater following a large single meal that contains high energy foods such as carbohydrate and protein [57], comparable to our tomato-based pasta meal. In support of this theory (Westerterp-Plantenga et al., 2001) demonstrated when participants were fed for 24 h in energy balance at 16 °C, both skin and rectal temperature were lower compared to 22 °C. However, when participants were able to eat *ad-libitum* for 24 h in both 16 and 22 °C, only skin temperature decreased, core temperature appeared to be protected by the increase in food intake. Whilst not measuring skin temperature is a limitation, and we suggest that future studies measure both skin and core temperature, we speculate that congruous to the 'temperature gradient theory' that if core temperature has decreased then we will have also seen a reduction in skin temperature. Further investigations are needed to investigate the role of the thermic effect of food in maintaining a thermal balance during and after cold exposure and suggest future research is directed towards tracking oxygen uptake beyond the cold exposure, and during and post the *ad-libitum* meal.

Whilst an acute bout of exercise may cause subsequent increases in calorie intake this does not usually exceed EE [58]. However, it is suggested that cold induced EE may lead to compensatory eating, creating a positive energy balance [16]. To investigate this phenomenon, we calculated REI by subtracting the energy expended during immersion from total EI at *ad-libitum* meal. We identified in comparison to TNWI and TNAA, immersion in cold-water increased REI by 53 % and 47 % respectively but with no difference observed between thermoneutral conditions. Previous studies have also noted REI was greater after swimming versus resting control [59], and swimming versus land-based cycling [60]. Although these findings suggest REI is acutely affected following water-based activities, future studies are needed to assess if this persists over a longer period and to identify the mechanisms responsible.

Finally, we investigated whether increased food intake coincided with increased ratings of appetite. We found that during the 30 min period of immersion, ratings of hunger did not differ between conditions, but participants ate more after CWI. It is documented that perceived hunger may be ineffective in predicting EI [61] which may explain these inconsistent results. In support of this, Langveld et al. [24] demonstrated whilst perceptions of hunger increased over a 2.5 h period of rest in 18 °C versus 24 °C, *ad-libitum* EI remained consistent across trials. Similarly, studies comparing the effects of water-based exercise, on EI show although hunger decreases prior to aqua cycling [62] and during aqua-walking [63] or increases immediately after swimming [60], this seemingly had no bearing on the amount of food eaten at a subsequent *ad-libitum* meal. Our study also monitored participants perceived hunger after leaving the laboratory and into the evening, but hunger scores did not differ between trials. We cannot comment whether an increase in EI persisted into the evening as we did not measure this as an outcome. We recommend future studies report food intake over a longer period, as a study by [64] showed although exercising for 60 min followed by 6 h of rest in cold versus thermoneutral air didn't alter feelings of hunger, more food was consumed at both morning and evening buffet meals.

This study has several strengths. We measured core temperature using an accurate method of measurement and confirm core body temperature remains stable during CWI for at least 30 min in the population studied. All 15 participants, committed to the full trial and individual data demonstrates, with no exceptions all participants ate more food after CWI during the *ad-libitum* meal. Our investigation does have some limitations. We can only comment on short-term compensation and whether this continues over a longer period, for example on the day after immersion, remains to be determined. Secondly, although we identified an after-drop in core temperature following CWI as a potential mechanism responsible for compensatory food intake, we can only speculate the thermic effect of food caused an immediate increase in core body temperature. We suggest future studies extend the assessment of both skin and core body temperature past the immediate post-water immersion to test this hypothesis. Thirdly, heterogeneity in weight status of the sample should be acknowledged, however energy expenditure, energy intake and relative energy intake was higher in all participants, regardless of body mass and weight status. Finally, we cannot rule out any compensation following an acute bout of CWI is due to changes in appetite related hormones. Immersion to chest depth, increases central venous pressure due to the redistribution of circulating blood away from the lower parts of the body [65]. As appetite related hormones are secreted from the intestine and adipose tissue [66], and blood is directed more towards the thoracic cavity during immersion, gut hormone secretion and appetite may be affected. Due to the paucity of data, we therefore suggest measuring short term alterations in hormones such as acylated ghrelin and longer-term alterations in leptin following cold-water exposure.

5. Conclusion

The present work suggests that in healthy adults an acute bout of CWI causes increases in EE with acute compensatory increases in both EI and REI when presented with an *ad-libitum* meal. This is both clinically and practically relevant for individuals who perform frequent bouts of CWI as there is the potential to increase unwanted body mass due to potential overeating in the immediate hours after CWI. However, whether a person continues to consume more following repeated bouts

of CWI needs to be examined specifically, due to a current lack of chronic immersion studies.

Ethical statement

This study was conducted in accordance with the Declaration of Helsinki and received approval from Coventry University's Research Ethics Committee (P145446) before any trial-related procedures commenced.

CRediT authorship contribution statement

Marie J. Grigg: Writing – review & editing, Writing – original draft. **C. Douglas Thake:** Supervision. **Judith E. Allgrove:** Supervision. **David R. Broom:** Supervision.

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. Lazy spa provided the inflatable water-tub but was not involved in the trial design or interpretation of the findings.

Data availability

Data will be made available on request.

References

[1] M.J. Tipton, N. Collier, H. Massey, J. Corbett, M. Harper, Cold water immersion: kill or cure? Exp. Physiol. 102 (11) (2017) 1335–1355, https://doi.org/10.1113/EP086283.

[2] A.F. Machado, P.H. Ferreira, J.K. Micheletti, A.C. de Almeida, I.R. Lemes, F. M. Vanderlei, J. Netto Junior, C.M. Pastre, Can water temperature and immersion time influence the effect of cold water immersion on muscle soreness? A systematic review and meta-analysis, Sports Med. 46 (4) (2016) 503–514, https://doi.org/10.1007/s40279-015-0431-7.

[3] J.M. Peake, L.A. Roberts, V.C. Figueiredo, I. Egner, S. Krog, S.N. Aas, K. Suzuki, J. F. Markworth, J.S. Coombes, D. Cameron-Smith, T. Raastad, The effects of cold water immersion and active recovery on inflammation and cell stress responses in human skeletal muscle after resistance exercise, J. Physiol. 595 (3) (2017) 695–711, https://doi.org/10.1113/JP272881.

[4] J.S. Kelly, E. Bird, Improved mood following a single immersion in cold water, Lifestyle Med. (2021).

[5] M. Eimonte, H. Paulauskas, L. Daniuseviciute, N. Eimantas, A. Vitkauskiene, G. Dauksaite, R. Solianik, M. Brazaitis, Residual effects of short-term whole-body cold-water immersion on the cytokine profile, white blood cell count, and blood markers of stress, Int. J. Hyperth. 38 (1) (2021) 696–707, https://doi.org/10.1080/02656736.2021.1915504. PMID: 33910456.

[6] D. Esperland, L. de Weerd, J.B. Mercer, Health effects of voluntary exposure to cold water - a continuing subject of debate, Int. J. Circumpolar. Health 81 (1) (2022) 2111789, https://doi.org/10.1080/22423982.2022.2111789.

[7] T. Cain, J. Brinsley, H. Bennett, M. Nelson, C. Maher, B. Singh, Effects of cold-water immersion on health and wellbeing: a systematic review and meta-analysis, PLoS. One 20 (1) (2025) e0317615, https://doi.org/10.1371/journal.pone.0317615. Jan 29PMID: 39879231; PMCID: PMC11778651.

[8] A. Yankouskaya, R. Williamson, C. Stacey, J.J. Totman, H. Massey, Short-term head-out whole-body cold-water immersion facilitates positive affect and increases interaction between large-scale brain networks, Biol. (Basel) 12 (2) (2023), https://doi.org/10.3390/biology12020211.

[9] R.E. Halse, K.E. Wallman, K.J. Guelfi, Postexercise water immersion increases short-term food intake in trained men, Med. Sci. Sports Exerc. 43 (4) (2011) 632–638, https://doi.org/10.1249/MSS.0b013e3181f55d2e.

[10] I.I. Geneva, B. Cuzzo, T. Fazili, W. Javaid, Normal body temperature: a systematic review, Open. Forum. Infect. Dis. 6 (4) (2019) ofz032, https://doi.org/10.1093/ofid/ofz032.

[11] M. Ntoumani, B. Dugue, E. Rivas, K. Gongaki, Thermoregulation and thermal sensation during whole-body water immersion at different water temperatures in healthy individuals: a scoping review, J. Therm. Biol. 112 (2023) 103430, https://doi.org/10.1016/j.jtherbio.2022.103430.

[12] B.R. Kingma, A.J. Frijns, L. Schellen, W.D van Marken Lichtenbelt, Beyond the classic thermoneutral zone: including thermal comfort, Temp. (Austin) 1 (2) (2014) 142–149, https://doi.org/10.4161/temp.29702.

[13] H. Pallubinsky, L. Schellen, W.D van Marken Lichtenbelt, Exploring the human thermoneutral zone – a dynamic approach, J. Therm. Biol. 79 (2019) 199–208, https://doi.org/10.1016/j.jtherbio.201812.014.

[14] M.N. Cramer, O. Jay, Biophysical aspects of human thermoregulation during heat stress, Aut. Neurosci. 196 (2016) 3–13, https://doi.org/10.1016/j.autneu.2016.03.001.

[15] M.E.T. Henderson, L.G. Halsey, The metabolic upper critical temperature of the human thermoneutral zone, J. Therm. Biol. 110 (2022) 103380, https://doi.org/10.1016/j.jtherbio.2022.103380.

[16] K. McInnis, F. Haman, E. Doucet, Humans in the cold: regulating energy balance, Obes. Rev. 21 (3) (2020) e12978, https://doi.org/10.1111/obr.12978.

[17] J.W. Castellani, A.J. Young, Human physiological responses to cold exposure: acute responses and acclimatization to prolonged exposure, Aut. Neurosci 196 (2016) 63–74, https://doi.org/10.1016/j.autneu.2016.02.009.

[18] M. Tipton, C. Bradford, Moving in extreme environments: open water swimming in cold and warm water, Extrem. Physiol. Med. 3 (2014) 12, https://doi.org/10.1186/2046-7648-3-12. Jun 11PMID: 24921042; PMCID: PMC4052348.

[19] R.J. Brychta, K.Y. Chen, Cold-induced thermogenesis in humans, Eur. J. Clin. Nutr. 71 (3) (2017) 345–352, https://doi.org/10.1038/ejcn.2016.223.

[20] F. Haman, D.P. Blondin, Shivering thermogenesis in humans: origin, contribution and metabolic requirement, Temp. (Austin) 4 (3) (2017) 217–226, https://doi.org/10.1080/23328940.2017.1328999.

[21] G.G. Giesbrecht, GK. Bristow, A second postcooling afterdrop: more evidence for a convective mechanism, J. Appl. Physiol. 73 (4) (1985) 1253–1258, https://doi.org/10.1152/jappl.1992.73.4.1253, 1992 OctPMID: 1447067.

[22] TT. Romet, Mechanism of afterdrop after cold water immersion, J. Appl. Physiol. 65 (4) (1985) 1535–1538, https://doi.org/10.1152/jappl.1988.65.4.1535, 1988 OctPMID: 3182516.

[23] S. Yang, Y.L. Tan, X. Wu, J. Wang, J. Sun, A. Liu, L. Gan, B. Shen, X. Zhang, Y. Fu, J. Huang, An mPOA-ARC(AgRP) pathway modulates cold-evoked eating behavior, Cell Rep. 36 (6) (2021) 109502, https://doi.org/10.1016/j.celrep.2021.109502.

[24] M. Langeveld, C.Y. Tan, M.R. Soeters, S. Virtue, G.K. Ambler, L.P. Watson, P. R. Murgatroyd, V.K. Chatterjee, A. Vidal-Puig, Mild cold effects on hunger, food intake, satiety and skin temperature in humans, Endocr. Connect. 5 (2) (2016) 65–73, https://doi.org/10.1530/EC-16-0004.

[25] M.S. Westerterp-Plantenga, W.D. van Marken Lichtenbelt, H. Strobbe, P. Schrauwen, Energy metabolism in humans at a lowered ambient temperature, Eur. J. Clin. Nutr. 56 (4) (2002) 288–296, https://doi.org/10.1038/sj.ejcn.1601308. AprPMID: 11965504.

[26] J.K. Zakrzewski-Fruer, R.N. Horsfall, D. Cottrill, J. Hough, Acute exposure to a hot ambient temperature reduces energy intake but does not affect gut hormones in men during rest, Br. J. Nutr. 125 (8) (2021) 951–959, https://doi.org/10.1017/S0007114520002792.

[27] M.J. Grigg, C.D. Thake, J.E. Allgrove, J.A. King, A.E. Thackray, D.J. Stensel, A. Owen, D.R. Broom, Influence of water-based exercise on energy intake, appetite, and appetite-related hormones in adults: a systematic review and meta-analysis, Appetite 180 (2023) 106375, https://doi.org/10.1016/j.appet.2022.106375.

[28] I. Mandic, M. Ahmed, S. Rhind, L. Goodman, M. L'Abbe, I. Jacobs, The effects of exercise and ambient temperature on dietary intake, appetite sensation, and appetite regulating hormone concentrations, Nutr. Metab. (L.) 16 (2019) 29, https://doi.org/10.1186/s12986-019-0348-5.

[29] H. Gibson-Moore, UK chief medical officers' physical activity guidelines 2019: what's new and how can we get people more active? Nutr. Bull. 44 (4) (2019) 320–328, https://doi.org/10.1111/nbu.12409.

[30] F.C. Baker, D. Mitchell, H.S Driver, Oral contraceptives alter sleep and raise body temperature in young women, Pflugers. Arch. 442 (5) (2001 Aug) 729–737, https://doi.org/10.1007/s004240100582.

[31] A. Flint, A. Raben, J.E. Blundell, A. Astrup, Reproducibility, power and validity of visual analogue scales in assessment of appetite sensations in single test meal studies, Int. J. Obes. Relat. Metab. Disord. 24 (1) (2000) 38–48, https://doi.org/10.1038/sj.ijo.0801083.

[32] N. Badjatia, E. Strongilis, E. Gordon, M. Prescutti, L. Fernandez, A. Fernandez, M. Buitrago, J.M. Schmidt, N.D. Ostapkovich, S.A. Mayer, Metabolic impact of shivering during therapeutic temperature modulation: the bedside shivering assessment scale, Stroke 39 (12) (2008) 3242–3247, https://doi.org/10.1161/STROKEAHA.108.523654.

[33] C. Buratti, D. Palladino, P. Ricciardi, Application of a new 13-value thermal comfort scale to moderate environments, Appl. Energy 180 (2016) 859–866, https://doi.org/10.1016/j.apenergy.2016.08.043.

[34] K.C. Miller, L.E. Hughes, B.C. Long, W.M. Adams, D.J. Casa, Validity of core temperature measurements at 3 rectal depths during rest, exercise, cold-water immersion, and recovery, J. Athl. Train. 52 (4) (2017) 332–338, https://doi.org/10.4085/1062-6050-52.2.10.

[35] L.J. White, R.H. Dressendorfer, E. Holland, S.C. McCoy, MA. Ferguson, Increased caloric intake soon after exercise in cold water, Int. J. Sport Nutr. Exerc. Metab. 15 (1) (2005) 38–47, https://doi.org/10.1123/ijsnem.15.1.38. FebPMID: 15902988.

[36] E. Pavlidou, S.K. Papadopoulou, K. Seroglou, C. Giaginis, Revised Harris-Benedict equation: new human resting metabolic rate equation, Metabolites. (2) (2023) 13, https://doi.org/10.3390/metabo13020189.

[37] J.V. Durnin, J. Womersley, Body fat assessed from total body density and its estimation from skinfold thickness: measurements on 481 men and women aged from 16 to 72 years, Br. J. Nutr. 32 (1) (1974) 77–97, https://doi.org/10.1079/bjn19740060.

[38] D. Du Bois, E.F. Du Bois, Clinical calorimetry: tenth paper A formula to estimate the approximate surface area if height and weight be known, Arch. Intern. Med. (Chic) XVII (6_2) (1916) 863–871, https://doi.org/10.1001/archinte.1916.00080130010002.

[39] JB. Weir, New methods for calculating metabolic rate with special reference to protein metabolism, J. Physiol. 109 (1-2) (1949) 1–9, https://doi.org/10.1113/jphysiol.1949.sp004363. AugPMID: 15394301; PMCID: PMC1392602.
[40] B. de Lauzon, M. Romon, V. Deschamps, L. Lafay, J.M. Borys, J. Karlsson, P. Ducimetiere, M.A. Charles, Fleurbaix Laventie Ville Sante Study, G., The Three-Factor Eating Questionnaire-R18 is able to distinguish among different eating patterns in a general population, J. Nutr. 134 (9) (2004) 2372–2380, https://doi.org/10.1093/jn/134.9.2372.
[41] J.A. Harris, FG. Benedict, A biometric study of human basal metabolism, Proc. Natl. Acad. Sci. U.S.A. 4 (12) (1918) 370–373, https://doi.org/10.1073/pnas.4.12.370. DecPMID: 16576330; PMCID: PMC1091498.
[42] L.J. James, T. Maher, J. Biddle, D.R. Broom, Eating with a smaller spoon decreases bite size, eating rate and ad libitum food intake in healthy young males, Br. J. Nutr. 120 (7) (2018) 830–837, https://doi.org/10.1017/S0007114518002246.
[43] P. Mishra, C.M. Pandey, U. Singh, A. Gupta, C. Sahu, A. Keshri, Descriptive statistics and normality tests for statistical data, Ann. Card. Anaesth. 22 (1) (2019) 67–72, https://doi.org/10.4103/aca.ACA_157_18.
[44] D. Lakens, Calculating and reporting effect sizes to facilitate cumulative science: a practical primer for t-tests and ANOVAs, Front. Psychol. 4 (2013) 863, https://doi.org/10.3389/fpsyg.2013.00863.
[45] J.W. Castellani, A.J. Young, M.B. Ducharme, G.G. Giesbrecht, E. Glickman, R. E. Sallis, Prevention of cold injuries during exercise, Med. Sci. Sports Exerc. 38 (11) (2006) 2012–2029, https://doi.org/10.1249/01.mss.0000241641.75101.64.
[46] D.A. Eyolfson, P. Tikuisis, X. Xu, G. Weseen, GG. Giesbrecht, Measurement and prediction of peak shivering intensity in humans, Eur. J. Appl. Physiol. 84 (1-2) (2001) 100–106, https://doi.org/10.1007/s004210000329. Jan-FebPMID: 11394237.
[47] M. Jette, K. Sidney, G. Blumchen, Metabolic equivalents (METS) in exercise testing, exercise prescription, and evaluation of functional capacity, Clin. Cardiol. 13 (8) (1990) 555–565, https://doi.org/10.1002/clc.4960130809.
[48] B.A. Franklin, J. Brinks, K. Berra, C.J Lavie, N.F Gordon, L.S. Sperling, Using Metabolic Equivalents in Clinical Practice, Am. J. Cardiol. 121 (3) (2018) 382–387, https://doi.org/10.1016/j.amjcard.2017.10.033.
[49] A.D. de Andrade, J.C. Junior, T.L. Lins de Barros Melo, C.S. Rattes Lima, D. C. Brandao, J. de Melo Barcelar, Influence of different levels of immersion in water on the pulmonary function and respiratory muscle pressure in healthy individuals: observational study, PhysiOther. Res. Int. 19 (3) (2014) 140–146, https://doi.org/10.1002/pri.1574.
[50] T. Derion, H.J.B. Guy, Effects of age on closing volume during head-out water immersions, Respir. Physiol. 95 (3) (1994) 273–280, https://doi.org/10.1016/0034-5687(94)90090-6.
[51] M.L. Choukroun, P. Varene, Adjustments in oxygen transport during head-out immersion in water at different temperatures, J. Appl. Physiol. 68 (4) (1985) 1475–1480, https://doi.org/10.1152/jappl.1990.68.4.1475, 1990 AprPMID: 2112126.
[52] B.G. Fico, M. Alkatan, H. Tanaka, No changes in appetite-related hormones following swimming and cycling exercise interventions in adults with obesity, Int. J. Exerc. Sci. 13 (2) (2020) 1819–1825.
[53] C.G. Scott, M.B. Ducharme, F. Haman, GP. Kenny, Warming by immersion or exercise affects initial cooling rate during subsequent cold water immersion, Aviat. Space Env. Med. 75 (11) (2004) 956–963. NovPMID: 15558995.
[54] D.S. Moran, L. Mendal, Core temperature measurement: methods and current insights, Sports Med. 32 (14) (2002) 879–885, https://doi.org/10.2165/00007256-200232140-00001. PMID: 12427049.
[55] C.L. Tan, Z.A. Knight, Regulation of body temperature by the nervous system, Neuron 98 (1) (2018) 31–48, https://doi.org/10.1016/j.neuron.2018.02.022.
[56] K. Charlot, C. Faure, S. Antoine-Jonville, Influence of hot and cold environments on the regulation of energy balance following a single exercise session: a mini-review, Nutrients 9 (6) (2017), https://doi.org/10.3390/nu9060592.
[57] M. Calcagno, H. Kahleova, J. Alwarith, N.N. Burgess, R.A. Flores, M.L. Busta, N. D. Barnard, The thermic effect of food: a review, J. Am. Coll. Nutr. 38 (6) (2019) 547–551, https://doi.org/10.1080/07315724.2018.1552544.
[58] S.Y. Tobin, M.A. Cornier, M.H. White, A.K. Hild, S.E. Simonsen, E.L. Melanson, T. M. Halliday, The effects of acute exercise on appetite and energy intake in men and women, Physiol. Behav. 241 (2021) 113562, https://doi.org/10.1016/j.physbeh.2021.113562.
[59] J.A. King, L.K. Wasse, D.J. Stensel, The acute effects of swimming on appetite, food intake, and plasma acylated ghrelin, J. Obes. 2011 (2011), https://doi.org/10.1155/2011/351628.
[60] A.E. Thackray, S.A. Willis, A.P. Sherry, D.J. Clayton, D.R. Broom, M. Demashkieh, J.A. Sargeant, L.J. James, G. Finlayson, D.J. Stensel, J.A. King, An acute bout of swimming increases post-exercise energy intake in young healthy men and women, Appetite 154 (2020) 104785, https://doi.org/10.1016/j.appet.2020.104785.
[61] G.M. Holt, L.J. Owen, S. Till, Y. Cheng, V.A. Grant, C.J. Harden, B.M. Corfe, Systematic literature review shows that appetite rating does not predict energy intake, Crit. Rev. Food Sci. Nutr. 57 (16) (2017) 3577–3582, https://doi.org/10.1080/10408398.2016.1246414.
[62] L. Metz, L. Isacco, N. Fearnbach, B. Pereira, D. Thivel, M. Duclos, Energy intake and appetite sensations responses to aquatic cycling in healthy women: the WatHealth study, Nutrients. (4) (2021) 13, https://doi.org/10.3390/nu13041051.
[63] S.Y. Ueda, H. Nakahara, E. Kawai, T. Usui, S. Tsuji, T. Miyamoto, Effects of walking in water on gut hormone concentrations and appetite: comparison with walking on land, Endocr. Connect. 7 (1) (2018) 97–106, https://doi.org/10.1530/EC-17-0323.
[64] L.K. Wasse, J.A. King, D.J. Stensel, C. Sunderland, Effect of ambient temperature during acute aerobic exercise on short-term appetite, energy intake, and plasma acylated ghrelin in recreationally active males, Appl. Physiol. Nutr. Metab. 38 (8) (2013) 905–909, https://doi.org/10.1139/apnm-2013-0008.
[65] K.S. Park, J.K. Choi, YS. Park, Cardiovascular regulation during water immersion, Appl. Hum. Sci. 18 (6) (1999) 233–241, https://doi.org/10.2114/jpa.18.233. NovPMID: 10675972.
[66] L.K. Heisler, D.D. Lam, An appetite for life: brain regulation of hunger and satiety, Curr. Opin. Pharmacol. 37 (2017) 100–106, https://doi.org/10.1016/j.coph.2017.09.002.