

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

Marie J. Grigg^a, C. Douglas Thake^a, Judith E. Allgrove^b and David R. Broom^a.

^aMJG, CDT, DRB: Centre for Physical Activity, Sport and Exercise Sciences, Coventry University, CV1 2DS, UK; hutsonm2@uni.coventry.ac.uk (M.J. Grigg), apx223@coventry.ac.uk (D. Thake) and ad5173@coventry.ac.uk (D R. Broom).

^bJEA: Department of Rehabilitation and Sport Sciences, Bournemouth University, Poole, BH12 5BB. jallgrove@bournemouth.ac.uk (J. Allgrove).

* Corresponding author. E-mail address: hutsonm2@uni.coventry.ac.uk (M.J. Grigg).

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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-minute immersion period across trials, however an after-drop in core temperature was observed for 15-minutes 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

Abbreviations: CWI, cold-water immersion; TNWI, thermoneutral water immersion; TNAA, thermoneutral ambient air; TS, thermal sensation

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.

1. INTRODUCTION

The beneficial claims of cold-water immersion (CWI) are prolific (Tipton et al., 2017). Participation in CWI therapy has become more popular, as regular exposure may aid the recovery process after strenuous exercise or sport (Machado et al., 2016; Peake et al., 2017), improve mood (Kelly & Bird., 2021), have positive effects on blood markers of stress (Eimonte et al., 2021), strengthen the immune system (Espeland et al., 2022), improve sleep and quality of life (Cain et al., 2025) and improve overall health and well-being (Cain et al., 2025; Yankouskava et al., 2023). 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 (Halse et al., 2011) potentially impacting upon body mass loss goals. Thermoneutral mean body temperature is between 36.16–37.02°C (Geneva et al., 2019). The thermoneutral zone, is a temperature range perceived as comfortable, where resting metabolic rate remains stable (Ntoumani et al., 2023), core body temperature is consistent, and there is an equilibrium between heat produced and heat lost from the body (Kingma et al., 2014). The thermoneutral zone in ambient air ranges between 28°C to 32°C (Pallubinsky & Schellen., 2019), whereas due to greater thermal exchange is approximately 35 – 36°C in water (Cramer & Jay., 2015; Henderson et al., 2021). 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 (McInnis et al., 2019). 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 (Tipton et al. 2017).

Acute CWI directly reduces skin temperature and subsequently peripheral blood flow, via vasoconstriction, to preserve body temperature (Castellani et al., 2016; Tipton & Bradford, 2014). 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 (Brychta & Chen, 2017). 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% $\dot{V}O_{2max}$ (Haman & Blondin, 2017; McInnis et al., 2019). Immediately after CWI, an 'after-drop' or further reduction in core temperature is observed (Giesbrecht & Bristow, 1992) 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 (Romet, 1988). Ongoing research supports the health benefits of water immersion (Cain et al., 2025) 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 (Yang et al., 2021). 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. (2011) 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-minutes at an intensity of 70% $\dot{V}O_{2peak}$, after-which were immersed to sternum level for 20-minutes 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. (2016); Westerterp-Plantenga et al. (2002) & Zakrzewski-Fruer et al. (2020) investigated whether acute exposure to cold ambient air, increases short term EI and the results are equivocal. Langveld et al. (2016) reported no difference in food intake after spending 2.5-hours at 18°C versus 24°C ambient air temperature. Westerterp-Plantenga et al. (2002) asked participants to spend 3 x 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-hours of the 60-hour 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. (2020) demonstrated that after spending 5.5-hours 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 (Grigg et al., 2022) or administered temperature change using an environmental chamber (Mandic et al., 2019) 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-minutes 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-minutes of moderate, or 75-minutes of vigorous intensity physical activity each week (Gibson-Moore, 2019). 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 eumenorrhic and not pregnant. As daily average body temperature can increase by approximately 0.4°C in the luteal phase of the ovulatory cycle (Baker et al., 2001) 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 ($\alpha = .05$) to detect a medium effect ($\eta^2 = .06$) in the dependent measures of interest (energy intake), with an assumed correlation among repeated measures of 0.5.

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.

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 (Flint et al., 2000), a four-point bedside shivering assessment scale (BSAS) (Badjatia et al., 2008) and the ASHRAE 7- point thermal sensation scale (Buratti et al., 2016). Participants were asked to insert a rectal thermistor 10cm beyond the anal sphincter (Miller et al., 2017) and undertake a 10-minute 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 reduced the risk of potential hazardous responses (Tipton et al., 2017), and b) was slightly colder than the study by White et al (2005) that demonstrated 40-minutes 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. Figure. 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-hours. Participants were asked to attend the laboratory having fasted for 8-10 hours and had a 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-minutes. 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 (Pavlidou et al., 2023) and were given 15-minutes 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-minutes 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-minutes, core body temperature was recorded at 5-minute intervals and subjective measures of appetite, shivering and thermal sensation (TS) were recorded every 10-minutes. 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-minutes. 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.

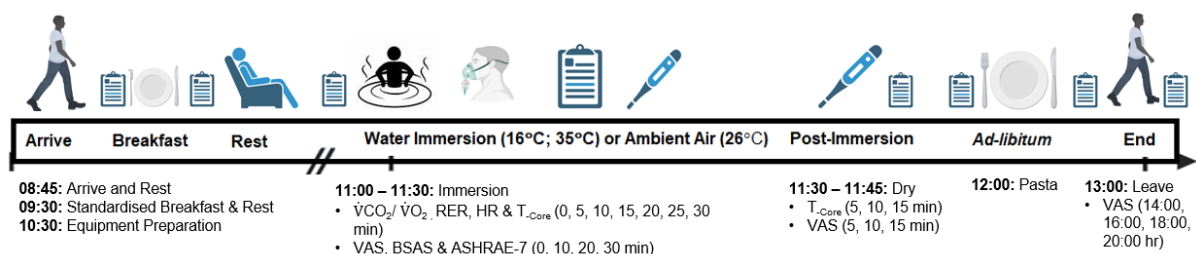


Figure 1. Schematic representation of the main trial protocol.

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: 100mm visual analogue scale (appetite); VO₂: volume of oxygen; VCO₂: volume of carbon dioxide.

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) (Durnin & Womersley. 1974) using skinfold callipers (Baty Harpenden Skinfold Calliper) by an ISAK-accredited practitioner. Body surface area (BSA) was calculated using the DuBois and DuBois method (DuBois & DuBois, 1916) (see equation¹).

$$BSA = 0.00718 \times \text{Height (cm)}^{0.725} \times \text{Weight (kg)}^{0.425}$$

Equation legend¹: bsa: body surface area; cm: centimetres; kg: kilograms

2.5 Metabolic and Cardiorespiratory Measurements

Expired $\dot{V}O_2$ and $\dot{V}CO_2$ were measured every 3-seconds for each 30-minute immersion session using indirect calorimetry (Med-Graphics Ultima CCM™). The mean value of oxygen consumption ($\dot{V}O_2$ L/min), and carbon dioxide production ($\dot{V}CO_2$ L/min), was used to calculate EE using Weir's equation (Weir, 1949) (see equation²) multiplied by 30-minutes to calculate the corresponding kcal/session. Kcal have been converted to kJ (see equation³)

$$EE \text{ (kcal/min)} = (3.941 \times \dot{V}O_2 \text{ L/min}) + (1.106 \times \dot{V}CO_2 \text{ L/min})$$

Equation legend²: EE: energy expenditure; kcal: kilocalories; L: Liters; min: minutes; $\dot{V}CO_2$: volume of carbon dioxide; $\dot{V}O_2$: volume of oxygen

$$kJ = 1 \text{ kcal} * 4.184$$

Equation legend³: 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-minutes during the 30-minute exposure using a four-point BSAS (0 – none; 1 – mild; 2 – moderate and 3 – severe) and TS was assessed upon entry and every 10-minutes during the 30-minute 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-minutes post immersion every 5-minutes (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 (Lauzon et al., 2004). The raw scale scores are transformed to a 0–100 scale (see equation⁴)

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

Equation legend⁴: %: 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 (Harris & Benedict, 1919). 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 (James et al., 2018). Ingredients were combined in advance of the trials and then re-heated before serving to participants using a microwave (Kenwood K20MW21 Solo) for 5-minutes 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-minutes 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-minute immersion period from the EI during the homogenous pasta meal (see equation⁵). Subjective perceptions of hunger, fullness,

satisfaction, and prospective food consumption (PFC) were assessed using a 100-mm visual analogue scale (Flint et al., 2000), prior to (09:00) and post (09:30) breakfast, 30-minutes 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 legend⁵: 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-minutes post immersion every 5-minutes (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 (Mishra et al., 2019). 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 Eta squared η^2 where **small** ($\eta^2 = 0.01$), medium ($\eta^2 = 0.06$), and large ($\eta^2 = 0.14$) effects (Lakens, 2013). 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

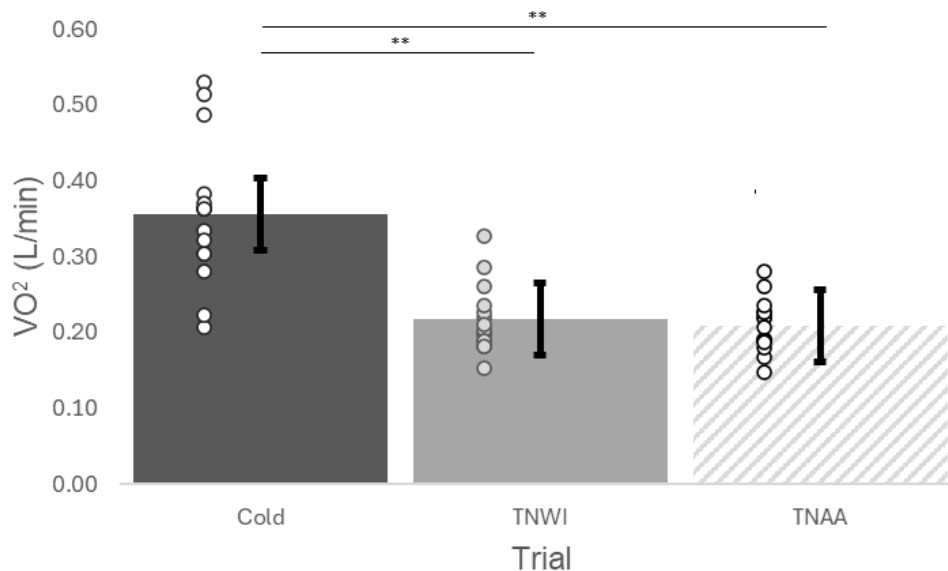
3.1 Metabolic and Cardiorespiratory Measurements

3.1.1 $\dot{V}O_2$ (L/min)

A main effect of trial was identified for oxygen consumption ($F(1.134, 15.878) = 28.663$, $P < 0.001$, $\eta_p^2 = 0.67$). $\dot{V}O_2$ was higher after CWI (0.356 ± 0.095 L/min) versus both TNWI (0.217 ± 0.452 L/min) (mean difference [95% CI], $0.139 [0.069 \text{ to } 0.209]$ L/min; $P < 0.001$), and TNAA (0.208 ± 0.035 L/min) (mean difference [95% CI], $0.148 [0.075 \text{ to } 0.220]$ L/min; $P < 0.001$). There was no difference in $\dot{V}O_2$ when TNWI (0.217 ± 0.452 L/min) was compared with TNAA (0.208 ± 0.035 L/min) (mean difference [95% CI], $0.009 [-0.12 \text{ to } 0.03]$ L/min; $P = 0.820$, Figure 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], $89 [46 \text{ to } 133]$ kJ; $P < 0.001$), and TNAA (129 ± 22 kJ); (mean difference [95% CI], $95 [50 \text{ to } 140]$ 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], $5 [-7 \text{ to } 19]$ kJ; $P = 0.771$, Figure 2).



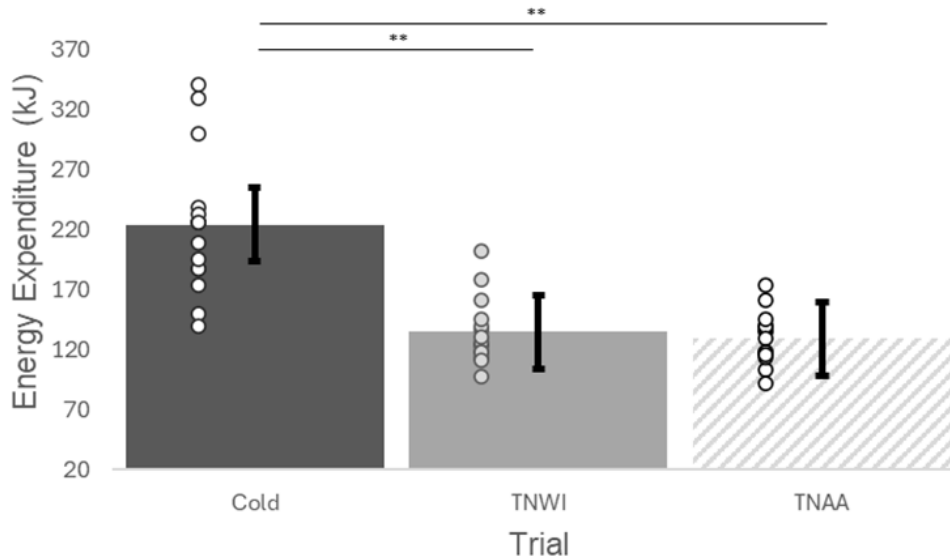


Figure 2. $\dot{V}O_2$ and Energy Expenditure during CWI (16°C), TNWI (36°C) and TNAA (26°C) experimental conditions (n=15). Data presented as mean \pm SD; individual data points are presented for each condition, post hoc analysis using Bonferroni adjustment to determine differences. *, **: significantly 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.

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 ($F(1.0, 14.0) = 25.221, P < 0.001$, Figure 3).**

Shivering 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 ($F(1, 14) = 4.387, P = 0.055$, Figure 3).

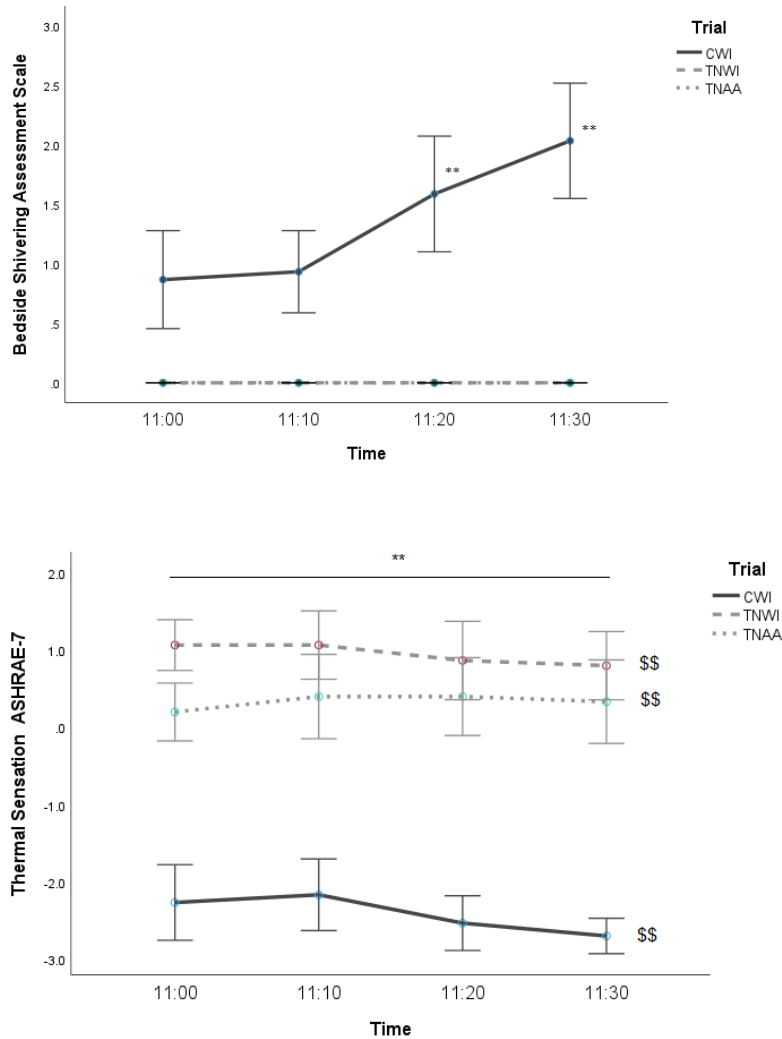


Figure 3. Bedside Shivering Assessment Scale and ASHRAE-7 thermal sensation in the CWI (16°C), TNWI (36°C) and TNAA (26°C) experimental conditions (n=15) during 30-minutes of immersion (11:00, 11:10, 11:20, 11:30). Data is presented as mean \pm SD and post hoc analysis using Bonferroni adjustment to 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.

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-minute 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 ($F(3.107, 43.497) = 1.794$, $P = 0.14$, $\eta_p^2 = 0.11$, Figure 4)).

3.1.6 Heart rate 15-minutes post immersion

Upon exiting the lazy-spa and 15-minutes 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 ($F(2.143, 40.238) = 1.450, P = 0.60, \eta_p^2 = 0.037$).

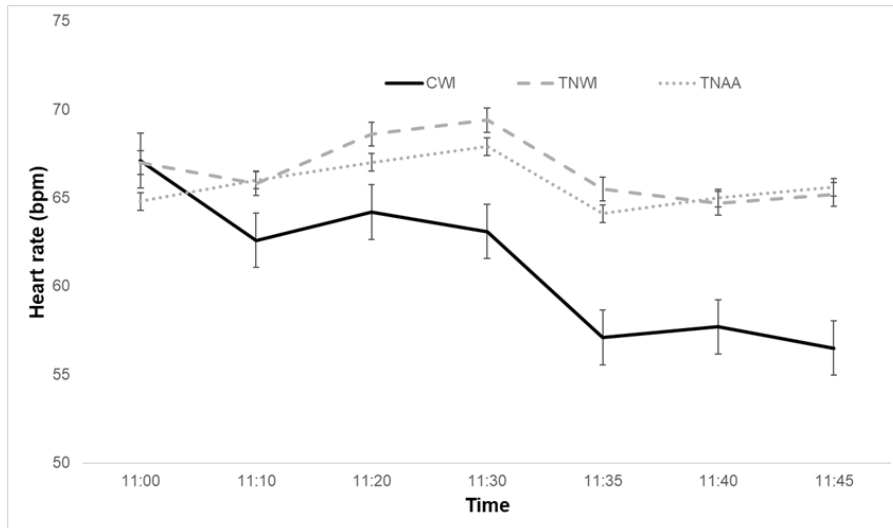


Figure 4. Heart rate responses during and after CWI (16 °C), TNWI (36 °C) and TNAA (26 °C) experimental conditions (n=15). Heart rate was measured at four time points during immersion (11:00, 11:10, 11:20, 11:30) and at a further three time points for 15-minutes post immersion (11.35, 11.40 and 11.45am). **Data is presented as mean \pm 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.

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; $P = 0.823$, Figure 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; $P = 0.741$, Figure 5).

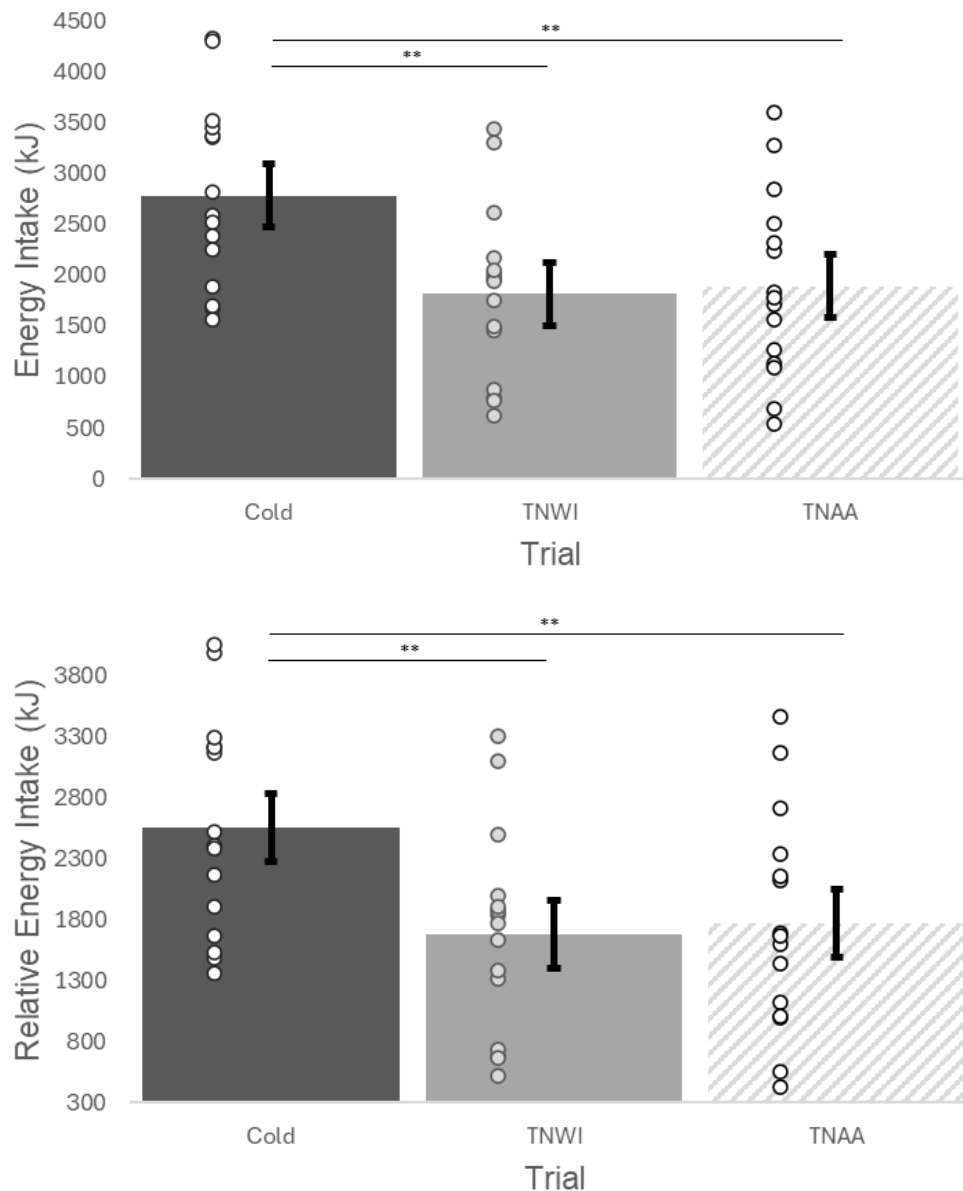


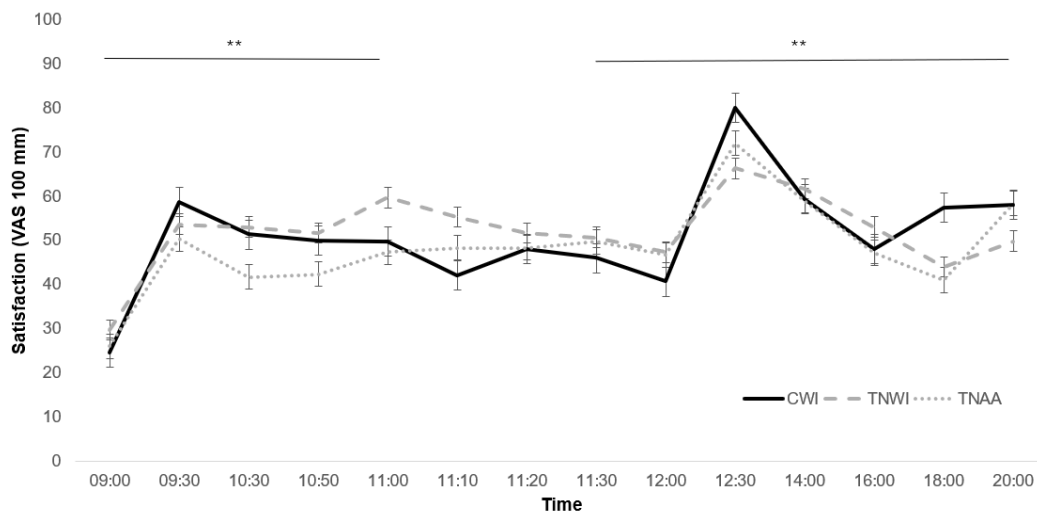
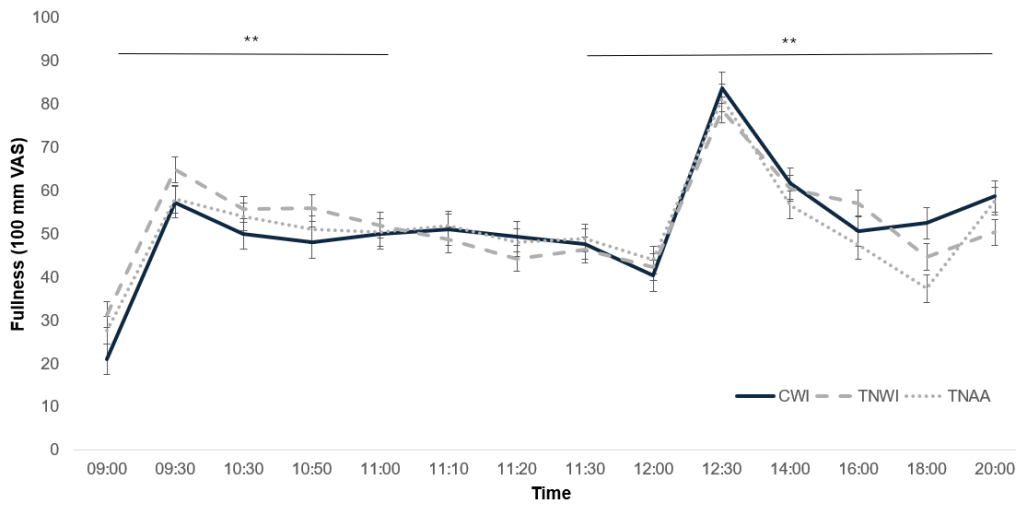
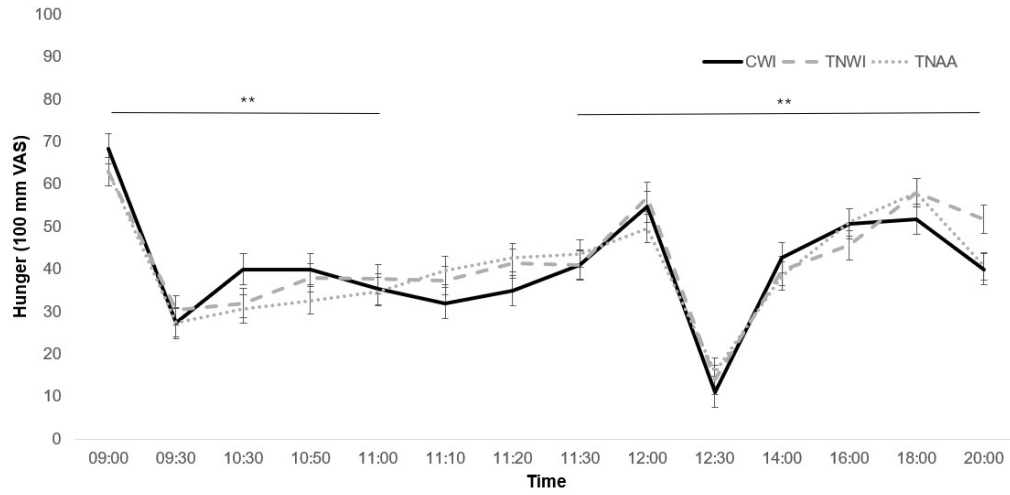
Figure 5. *Ad-libitum* energy intake and relative energy intake after CWI (16°C), TNWI (36°C) and TNAA (26°C) experimental conditions (n=15). Energy intake was measured by mean amount of homogenous pasta eaten 30-minutes post immersion at 12pm. Data presented as mean \pm SD; post hoc analysis using Bonferroni 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 ($P > 0.05$, Figure 6).



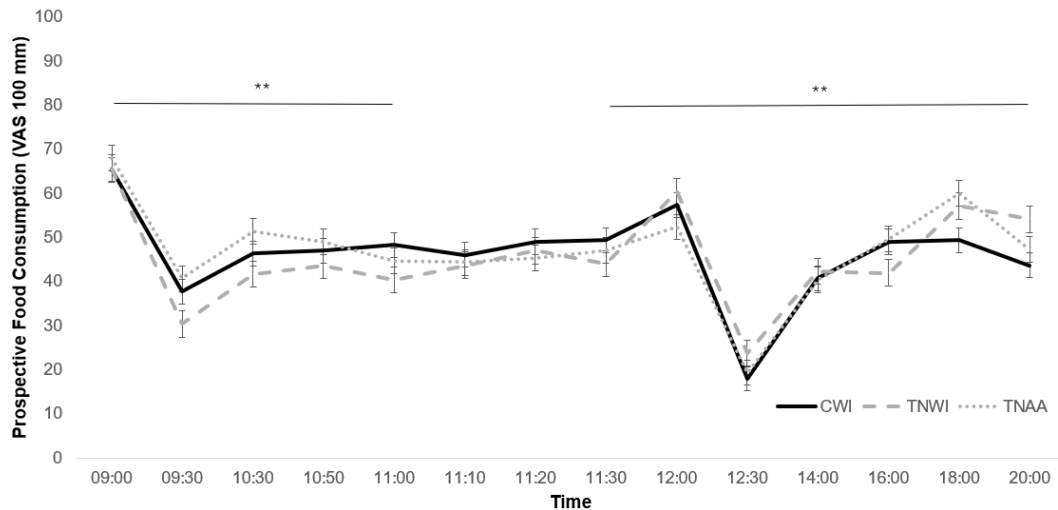


Figure 6. Hunger, fullness, satisfaction, and prospective food consumption prior to and post breakfast and prior to immersion (09:00, 09:30, 10:30), during the 30-minutes of immersion (11:00, 11:10, 11:20, 11:30), 60-minutes leading up to and after ad-libitum meal (11:30, 12:00, 12:30) and during the 6-hours leading into the evening (14:00, 16:00, 18:00, 20:00) (n=15). Data is presented as mean \pm 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.

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-minute 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 ($F(2.166, 30.318) = 1.211, P = 0.31, \eta_p^2 = 0.08$, Figure 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-minutes post water immersion. Contrasts were performed to compare CWI to both TNWI and TNAA and from time exiting the water (11:30) to 15-minutes 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 ($F(1, 14) = 25.021, P < 0.001, \eta_p^2 = 0.64$, Figure 7)).

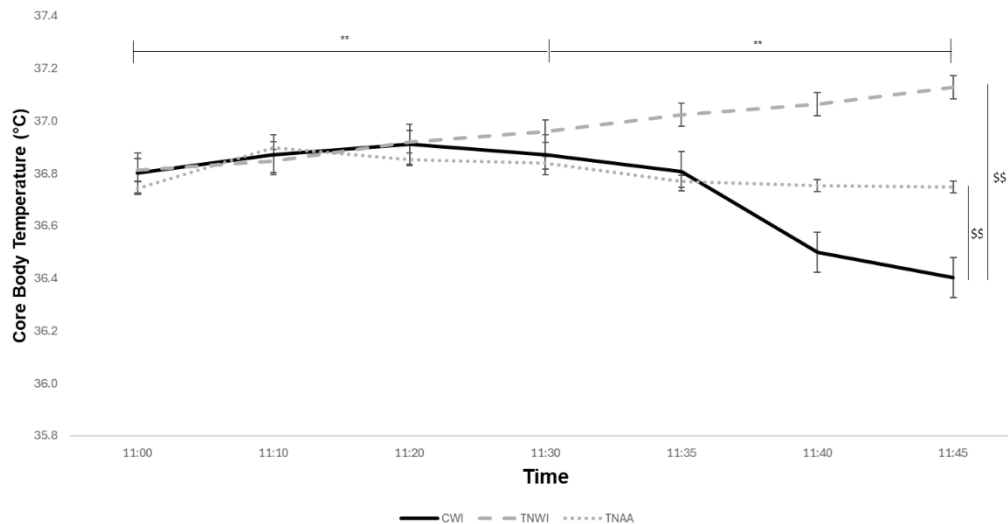


Figure 7. Thermoregulatory responses during and after CWI (16 °C), TNWI (36 °C) and TNAA (26 °C) experimental conditions (n=15). Core temperature was measured via rectal thermistor at four time points during immersion (11:00, 11:10, 11:20, 11:30) and at a further three time points for 15-minutes post immersion (11.35, 11.40 and 11.45am). Data presented as mean \pm 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.

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-minutes 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-minutes 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 (Castellani et al., 2006). Peak shivering rates have been reported to reach 46–50% of $\dot{V}O_{2max}$ (Eyolfson et al., 2000) which for 30-minutes in an average 70 kg individual would be equivalent to ~ 753 kJ, (Jette et al., 1990). As participants were passively submerged in water much colder than in our study (8°C) and for approximately 60-minutes this is much higher than we observed ~ 224 kJ during 30-minutes of CWI.

We asked our participants to rate their shivering intensity during immersion, as either absent, mild, moderate, or severe (Badjatia et al., 2008). 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 (Franklin et al., 2017). 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 (Andrade et al., 2012; Derion et al., 1992). Similarly, Choukroun & Varene (1990) 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. (2016) and Westerterp-Plantenga et al. (2001) reported no difference in EI after exposure, but this may be because experimental temperatures were below that defined as thermoneutral. Zakrzewski-Fruer et al. (2020) 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 $\dot{V}O_2$ 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 (Fico et al., 2021). 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. (2011) 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 (Westerterp-Plantenga et al., 2002). Halse et al. (2011) asked participants to exercise prior to the water immersion, which generally results in a more rapid decline in core temperature (Scott et al., 2004), 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 (Moran & Mendal, 2002).

Core body temperature interacts with the brain via specific neural pathways resulting in altered feeding behaviour (Tan & Knight, 2018). The hypothalamic region of the brain is the main regulator of appetite and thermoregulation (Charlot et al., 2017) and contains the arcuate nucleus (ARC) which expresses both anorexigenic A-melanocyte-stimulating hormone (αMSH) and orexigenic agouti-related peptide (AgRP). Although studies have yet to be trialled in humans, Yang et al. (2021) 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-minute 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. (2023) who reports core temperature is defended for around 30-minutes 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 minutes, termed the after-drop (Webb, 1986). White et al., (2005) reported *ad-libitum* EI increased by 44% after 40-minutes of aqua-cycling

in cold (20°C) versus thermoneutral (33°C) water at 60% $\dot{V}O_{2max}$, 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. (2006) suggests performing leg only exercise in water at an intensity >60-75% $\dot{V}O_{2max}$ mitigates heat lost at the periphery. Although White et al., (2005) reported core temperature did decrease significantly 15-minutes 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-minutes, 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 (Calcagno et al., 2019), comparable to our tomato-based pasta meal. In support of this theory (Westerterp-Plantenga et al., 2001) demonstrated when participants were fed for 24-hours 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-hours 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 (Tobin et al., 2021). However, it is suggested that cold induced EE may lead to compensatory eating, creating a positive energy balance (McInnis et al., 2020). 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 (King et al., 2011), and swimming versus land-based cycling (Thackray et al., 2020). 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-minute 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 (Holt et al., 2017) which may explain these inconsistent results. In support of this, Langveld et al. (2016) demonstrated whilst perceptions of hunger increased over a 2.5-hour 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 (Metz et al., 2021) and during aqua-walking (Ueda et al., 2018) or increases immediately after swimming (Thackray et al., 2020), 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 (Wasse et al., 2013) showed although exercising for 60-minutes followed by 6-hours 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-minutes 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 (Park et al., 1999). As appetite related hormones are secreted from the intestine and adipose tissue (Heisler & Lam, 2017), 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.

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.

Declaration of 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.

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