UK Health Security Agency

Additional calorie requirements in extreme cold weather

A rapid evidence summary

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Main messages

1. This rapid evidence summary (search up to 10 August 2023) identified and summarised the available evidence that discussed the additional calorie requirements for a person in the context of extreme cold weather, with an additional focus on how those needs differ for vulnerable groups (63 primary studies).
2. Forty-two experimental studies looked at how energy expenditure changed with different ambient air temperatures for set periods of time, with most studies suggested that colder air temperatures (typically between 16°Celsius (C) and 20°C) increased energy expenditure by around 50 to 200 calories (kcal) per day (1 to 42). However, there was substantial variability in both the experimental protocols (including the air temperature and what the participants did and wore during cold exposure) and the results of these studies, with some studies suggesting much higher energy expenditures during cold exposure.
3. Twenty experimental studies looked at how energy expenditure changed when participants were cooled using temperature-controlled water filled clothing for set periods of time (typically between 0°C and 18°C, or slightly above shivering) (43 to 62). All these studies suggested increased energy expenditure on cold exposure, but again the total amount of energy expenditure was highly variable, with 14 studies suggesting less than 500 kcal per day and 6 studies suggesting more than 1,000 kcal per day. Unlike in the studies that changed the temperature of ambient air, the participants in these studies could not wear clothing to mitigate the effects of cooling and were thus likely much more exposed to the effects of cooling.
4. One modelling study estimated the difference in cold induced thermogenesis (the body's process of heat production) between people who were lean or not, suggesting cold induced thermogenesis at 15°C was lower in overweight or obese individuals than in lean participants (63). This was supported by experimental studies that looked at both lean and overweight or obese participants (3, 4, 13, 23, 27, 35, 54).
5. There was limited evidence from studies comparing men and women. The available evidence indicated that there wasn't a substantial difference in energy expenditure between the sexes (53, 55, 61).
6. Overall, there was evidence that cold exposure increased energy expenditure, with most evidence indicating a modest increase (50 to 200 kcal per day), but others suggesting it could potentially be much more (over 1,000 kcal per day). There was variability between participants even in the same studies.
7. Limited information was available on the additional calorie requirements in response to cold exposure differ for vulnerable groups, as most studies were conducted in healthy, young adults.
8. Risk of bias in the studies was not assessed and so no comment on the reliability of this evidence can be made, however it should be noted that all studies were in a relatively small number of participants.

Purpose

The purpose of this rapid evidence summary was to identify and assess the available evidence that discussed the additional calorie requirements for a person in the context of extreme cold weather, with an additional focus on how those needs differ for vulnerable groups.

Methods

The review questions were:

1. What are the additional calorie requirements for the average man, woman or child in extreme cold weather?
2. How do these requirements differ for vulnerable groups including pregnant women, older people, those with specific medical conditions and other disabilities?

A rapid evidence summary was completed in August 2023, which identified evidence to answer the research questions specified above. A search of Medline, Embase, and Web of Science and Web of Science Core Collection was carried out for literature published prior to 10 August 2023.

Screening on title and abstracts was undertaken in duplicate by 2 reviewers for 20% of the potentially relevant studies, with the remainder completed by one reviewer. Screening on full text was undertaken by one reviewer and excludes were checked by a second reviewer. Disagreement was resolved by discussion. The UN, WHO, and CDC websites were also searched for any other relevant evidence, and a targeted google search was undertaken.

A protocol was produced before the literature search was conducted, including the review questions above, the eligibility criteria, and all other methods, see Annexe A. Several clarifications to, or deviations from, the protocol were made:

- only studies reporting the difference in calories or joules per day (or units that could be converted to calories or joules per day, including watts) were included, therefore, studies only reporting results per m^2 of body surface area or per kg of body mass, or total number of calories or joules without specifying the time period, were excluded (conversions were calculated using 1 Joule = 0.239006 calories)
- studies involving cooling using temperature controlled water filled or perfused clothing or bedding were included, but studies involving part or full body submersion in water were excluded
- studies where the environmental temperatures were not precisely defined were excluded (individual-level temperatures were acceptable if well defined, for example, if participants were cooled to a temperature just above their point of shivering)
- studies looking at cold adaptation (repeated cold exposure over periods of time) were excluded

- studies comparing the same activities in 2 or more temperatures were included regardless of the activities (including physical exercise), so long as it was possible to infer the differential calorie requirements solely for different temperatures.

Evidence

In total, 3,222 studies were screened on title and abstract, of which 257 studies were screened on full text, and 58 were included in this rapid evidence summary. An additional 44 studies were screened from other targeted searches and from searching the reference lists of reviews on similar topics, with 5 further studies meeting the inclusion criteria, resulting in 63 included studies.

Of these, 42 were experimental studies looking at how energy expenditure changed with different ambient air temperatures for set periods of time (1 to 42), 20 were experimental studies looking at how energy expenditure changed when participants were cooled using temperature-controlled water filled clothing for set periods of time (43 to 62), and one was a modelling study estimating the difference in cold induced thermogenesis between people who were lean or not (63).

Study characteristics, including intervention procedures where relevant, and results are provided in Annexe B. If necessary, results from studies were converted to kilocalories (kcal) per day and presented in square brackets (indicating the study did not present results in kcal per day). This was done for studies presenting results in watts, joules (or kJ or MJ) for a specified time period, and calories or kcal for any other specified time period.

Evidence for the effect of different ambient air temperatures on energy expenditure (Table B.1)

There were 42 experimental studies looking at how energy expenditure changed with different ambient air temperatures for set periods of time (1 to 42). Typically, these studies measured energy expenditure, either through indirect calorimetry (for example, through gas exchange) or by using a metabolic measurement system, for at least 2 different air temperatures, set by the researchers using a temperature controlled environment (for example, an environmental chamber). Six studies were conducted in the UK (9, 10, 12, 13, 30, 40), 13 in the rest of Europe (4, 18 to 20, 26 to 28, 31 to 36), 15 in the US and Canada (1 to 3, 5, 7, 8, 11, 14, 16, 21, 23 to 25, 41, 42), 4 in Japan (15, 37 to 39), 3 in Australia (6, 17, 29), and one in Singapore (22).

Studies included between 2 and 75 participants (interquartile range [IQR]: 10 to 22 participants), and most studies included relatively young and fit participants. During their time in the cold environment, the participants were instructed to either remain sedentary, or engage in prescribed activities (physical or otherwise), which were identical regardless of the temperature. Clothing was typically prescribed, with some studies requiring the participant to wear only a bathing suit or jogging shorts, and others allowing whatever clothing was appropriate for the temperatures. The range of temperatures studied varied from between 0°C and 33°C for the warmer temperatures (IQR: 22°C to 27°C), and between -40°C and 22°C for the colder temperatures (IQR: 16°C to 20°C). Participants were in the environments for between less than an hour to up to 84 hours (IQR: 2 hours to 1 day).

All but 5 studies (5, 11, 13, 21, 41) suggested that lower air temperatures increased energy expenditure, typically by between 50 and 200 kcal per day. However, there was often variability between participants even within the studies. There were limited differences in the results of studies looking at longer periods of time, for example, one day and over (4, 10, 11, 20, 21, 26, 29, 31 to 36), and those looking at shorter periods of time, for example, less than 2 hours (5, 6, 15, 18, 19, 22).

The largest difference in energy expenditure was seen in 2 studies reported by Vallerand and others, where participants wore only bathing suits or jogging shorts, and were exposed to temperatures of 29°C then 10°C for around 2 hours each (24, 25). The total additional energy expenditure from the cold temperature was estimated to be around 2,600 kcal per day in both studies.

Five studies looked for differences in the additional energy expenditure from exposure to colder temperatures between participants who had different bodyweight or body mass indexes (BMIs) (3, 13, 23, 27, 35). Four of these studies suggested that leaner participants had more energy expenditure from cold exposure than larger participants (3, 13, 23, 35), although absolute differences varied between the studies. The remaining study suggested overweight participants had more energy expenditure than lean participants (27). Additionally, one study suggested little difference in energy expenditure on cold exposure between people who were overweight with and without diabetes (13).

Of the 5 studies that suggested colder temperatures decreased energy expenditure, 4 reported small average differences in energy expenditure (less than 100 kcal per day) (11, 13, 21, 41), and the remaining study compared very low temperatures (0°C, -20°C, and -40°C) where participants could wear appropriate clothing, and suggested that energy expenditure decreased with decreasing temperature while standing quietly, but increased while walking (5).

Overall, despite marked differences in the temperatures participants were exposed to and the study conditions, the evidence suggested that cold exposure increased energy expenditure. The study that required participants to wear very little recorded a substantially greater increase in energy expenditure. There was also evidence that leaner participants had more energy expenditure than larger participants when exposed to the same cold temperatures.

Evidence for the effect of different water filled clothing temperatures on energy expenditure (Table B.2)

There were 20 experimental studies looking at how energy expenditure changed when wearing temperature-controlled water filled clothing for set periods of time (43 to 62). Typically, these studies measured energy expenditure, either through indirect calorimetry (for example, through gas exchange) or by using a metabolic measurement system, for at least 2 different temperatures of water filled clothing. Typically, studies used water perfused cooling vests to control the temperature the participants experienced, but some studies used cooling blankets or water perfused mattresses. Two studies were conducted in the UK (57, 58), 12 in the rest of Europe (43, 44, 47, 48, 51 to 54, 59 to 62), and 6 in the US and Canada (45, 46, 49, 50, 55, 56).

The studies included between 6 and 170 participants (IQR: 10 to 24 participants), and most studies included relatively young and fit participants. During their time in the water cooled clothing, the participants were instructed to remain sedentary in most studies. The range of temperatures studied varied from 19°C to 32°C for warmer temperatures (IQR: 23°C to 26°C), and between 0°C and 18°C for the colder temperatures, but 13 studies set the cold temperature at or slightly above shivering, or kept reducing the temperature to a threshold or until the participants shivered (43, 44, 46 to 48, 51 to 55, 59, 61, 62). The studies examined participants in water cooled clothing for between less than an hour up to 5 hours (IQR: 1 to 2 hours). Unlike the studies investigating change in ambient air temperature, the participants in these studies were not permitted to wear clothing to mitigate the effects of cooling, and were thus much more exposed to the effects of cooling.

All studies suggested that cooling with water filled clothing increased energy expenditure, but the total amount of energy expenditure was highly variable between studies, ranging from 37 kcal per day up to 4,183 kcal per day, with 14 studies suggesting less than 500 kcal per day (41, 43, 44, 46 to 48, 51 to 55, 57, 60, 62) and 6 studies suggesting more than 1,000 kcal per day (45, 49, 50, 56, 58, 59).

Studies that set the cold temperature at or slightly above shivering (43, 44, 46 to 48, 51 to 55, 59, 61, 62) reported similarly variable results, irrespective of participant shivering (41, 45, 49, 50, 56 to 58, 60). Notably, it appeared from these studies that shivering itself may be associated with much higher energy expenditure, as the 4 studies with the highest overall energy expenditure on cold exposure were in those in which participants shivered. These studies suggested extra energy expenditure of:

- 2,099 kcal per day at 16°C for those who shivered, compared with 1,686 kcal per day for those who did not shiver, where all participants had diabetes (58)
- 1,727 kcal per day at 10°C for those who shivered, compared with 1,440 kcal per day for all participants (59)

- 3,067 kcal per day at 10°C, where it was noted that participants shivered (49)
- 4,183 kcal per day at 5°C, where it was noted that participants shivered (50)

Three studies examined differences in energy expenditure on cooling between men and women, but none found systematic differences between the sexes (53, 55, 61). Two studies looked at differences in energy expenditure on cooling between people with and without diabetes. While there was minimal difference between people with and without diabetes (45, 58), the study suggested that people with autonomic neuropathic diabetes may be more prone to shivering and thus more energy expenditure due to a lack of peripheral vasoconstriction (58).

Overall, the studies using water filled clothing to cool participants suggested that col exposure increased energy expenditure, but there was marked variability between the studies, with some suggesting modest increases in energy expenditure and others suggesting extremely large increases.

Evidence for the difference in energy expenditure from modelling studies (Table B.3)

One study used modelling to estimate the difference in cold induced thermogenesis between people who are lean with those who were overweight or obese (63). This study included 40 participants (20 lean, 20 overweight or obese). Heat loss was compared in lean and overweight or obese participants when lying between 2 cold water-perfused mattresses (9°C or 3 to 4°C above shivering).This information was to estimate (using the Scholander-Irving model (64)) cold induced thermogenesis at 15°C in each group of participants. The results suggested that cold induced thermogenesis at 15°C was lower in overweight or obese individuals (449 kcals per degree C per day, 5.9% increase in metabolic rate) than in lean participants (724 kcals per degree C per day, 7.0% increase in metabolic rate, p=0.0042).

Health inequalities

The only available evidence for vulnerable groups were 3 studies in people with diabetes, suggesting a minimal difference in energy expenditure on cold exposure between people with and without diabetes (13, 45, 58). No data was available on the differences of energy requirements between ethnic and social groups.

Limitations

This rapid evidence summary used streamlined systematic methods to accelerate the review process. Most article screening was completed without duplication therefore it is possible relevant studies may have been missed. Due to time constraints critical appraisal was not undertaken which limits our ability to interpret the findings in the context of risk of bias.

Most studies studied short-term changes in energy expenditure due to cold exposure and it is unclear whether these results would extrapolate up to a full day, or longer. However, results from experiments exposing participants to colder air temperatures for shorter (less than 2 hours) and longer (one day or more) time periods did not demonstrate much difference in energy expenditure. The colder air temperatures examined in the included studies were generally warmer than people may be exposed to in extreme cold (between 16°C and 20°C), although clothing and insulated houses may limit extreme cold exposure for many people in the UK. Studies looking at water filled clothing may better simulate exposure to extreme cold, or even overestimate the effects of cold exposure, as appropriate clothing could not be worn and many studies looked specifically at temperatures that caused shivering, or slightly more than shivering. No studies looked specifically at the differences in energy expenditure when wearing different clothes.

Although there was a large number of included studies, all were relatively small, including at most 170 participants, but often less than 25 participants. Most studies included only generally healthy and young people, which may limit generalisability to the general population.

As with all reviews, the evidence identified may be subject to publication bias, whereby null or negative results are less likely to have been published by the authors.

Evidence gaps

No evidence was available on the additional calorie requirement in extreme cold weather for vulnerable groups, except people with diabetes. Evidence was also lacking in people who were older or less healthy, as participants in the included studies were relatively young and healthy. The conclusions from this review therefore may not be generalisable to these groups.

Conclusion

In studies looking at the effect of varying ambient air temperature, most studies suggested that colder air temperatures increased energy expenditure by around 50 to 200 kcal per day. However, there was substantial variability in both the experimental protocols (including the air temperature and what the participants did and wore during cold exposure) and the results of these studies, with some studies suggesting much higher energy expenditures during cold exposure.

All studies looking at cooling participants with water filled clothing also suggested increased energy expenditure on cold exposure, but again the total amount of energy expenditure was highly variable, with 14 studies suggesting less than 500 kcal per day and 6 studies suggesting more than 1,000 kcal per day.

Limited information was available on the additional calorie requirements in response to cold exposure differ for vulnerable groups, as most studies were conducted in healthy, young adults. Risk of bias in the studies was not assessed and so no comment on the reliability of this evidence can be made, however it should be noted that all studies were in a relatively small number of participants.

Acknowledgments

We would like to thank colleagues within the All Hazards Public Health Response division who either reviewed or input into aspects of the review.

Disclaimer

UKHSA's rapid reviews and evidence summaries aim to provide the best available evidence to decision makers in a timely and accessible way, based on published peer-reviewed scientific papers, unpublished reports and papers on preprint servers. Please note that the reviews:

- use accelerated methods and may not be representative of the whole body of evidence publicly available
- have undergone an internal, but not independent, peer review
- are only valid as of the date stated on the review

In the event that this rapid evidence summary is shared externally, please note additionally, to the greatest extent possible under any applicable law, that UKHSA accepts no liability for any claim, loss or damage arising out of, or connected with the use of, this review by the recipient or any third party including that arising or resulting from any reliance placed on, or any conclusions drawn from, the review.

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Annexe A. Protocol

Review question

The review questions for this rapid evidence summary scoping are:

1. What are the additional calorie requirements for the average man, woman or child in extreme cold weather?
2. How do these requirements differ for vulnerable groups including pregnant women, older people, those with specific medical conditions and other disabilities?

This rapid evidence summary will look for evidence that discussed the additional calorie (or nutrition more generally) requirements for a person in the context of extreme cold weather, with an additional focus on how those needs differ for vulnerable groups.

Eligibility criteria

	Included	**Excluded**
Population	Adults and children	Inpatients
Settings	All (except hospital)	Hospital
Context	Extreme cold weather	
Intervention or exposure	Additional calorie intake or nutrition from food necessary for extreme cold weather	Optimal calorie or nutrition intake
Outcomes	• any health complications indicating malnutrition • death • hospitalisation	
Language	English language	Non-English language studies
Date of publication	Up to 10 August 2023	
Study design	• reviews (rapid, systematic or narrative) • primary studies	• editorials • letters • opinion pieces
Publication type	Published and pre-print	

Identification of studies

We will search Medline, Embase, and Web of Science Web of Science Core Collection (editions: Science Citation Index Expanded (SCI-EXPANDED)) to identify any existing evidence related to the review question, published prior to 10 August 2023. See Search strategy below.

Screening on title and abstracts will be undertaken in duplicate by 2 reviewers for 20% of the potentially relevant studies, with the remainder completed by one reviewer. Screening on full text will be undertaken by one reviewer and checked by a second. Disagreement will be resolved by discussion.

An information specialist will also run targeted searches on the UN, World Health Organization (WHO), and Centers for Disease Control and Prevention (CDC) websites for any other relevant evidence not found in the literature search, as well as a Google search.

Synthesis of evidence

If reviews providing evidence to answer the research question are identified, these will be summarised. If no reviews are identified, or if the identified reviews are insufficient to answer the review question, identified primary studies will be summarised. Data will be extracted straight into narrative summaries of included studies (reviews, or primary studies). All narrative summaries will be written by one reviewer and checked by a second.

Variations across populations and subgroups, for example cultural variations or differences between ethnic or social groups will be considered, where evidence is available.

Search strategy

Database: Ovid MEDLINE(R) ALL (1946 to 8 August 2023)

1. Extreme Cold Weather/ (137)
2. exp *Cold Temperature/ (28,863)
3. ((extreme* or severe) adj3 (cold or low temperature*)).tw,kf. (2,829)
4. (serious* adj cold).tw,kf. (4)
5. ((cold* or freezing or sub-zero) adj3 temperature*).tw,kf. (10,941)
6. (((low adj3 temperature*) or (freezing or sub-zero)) and (climat* or weather or meteorolog*)).tw,kf. (4,129)
7. (cold adj (spell* or snap*)).tw,kf. (310)
8. hypothermi*.tw,kf. (47,344)
9. Hypothermia/ (15,005)
10. exp Cold Injury/ (2,548)
11. (cold adj (injur* or stress* or exhaust* or shock*)).tw,kf. (10,448)
12. frostbit*.tw,kf. (1,771)

13. (record adj2 cold).tw,kf. (13)
14. Cold-Shock Response/ (1,514)
15. cold* climate*.tw,kf. (1,759)
16. (cold adj2 expos*).tw,kf. (8,410)
17. or/1-16 (105,213)
18. hypocalori*.tw,kf. (2,060)
19. ((calor* or food* or kcal* or kilocal* or energy or macronutrient*) adj3 (restrict* or intake*)).tw,kf. (115,439)
20. *Caloric Restriction/ (4,401)
21. *Energy Intake/ (14,955)
22. ((calor* or food* or kcal* or kilocal* or energy or macronutrient*) adj3 (allocation* or ration*)).tw,kf. (2,797)
23. ((calor* or kcal* or kilocal* or energy or food* or macronutrient*) adj3 (need* or required or requirement*)).tw,kf. (27,347)
24. ((calor* or kcal* or kilocal* or energy or food* or macronutrient*) adj3 (recommend* or guideline*)).tw,kf. (5,517)
25. ((calor* or kcal* or kilocal* or energy or food* or macronutrient*) adj3 (expenditure* or consum*)).tw,kf. (97,460)
26. ((calor* or kcal* or kilocal* or energy or food* or macronutrient*) adj3 (reserve* or turnover*)).tw,kf. (3,746)
27. fat reserve*.tw,kf. (564)
28. *Energy Metabolism/ (41,339)
29. energy metaboli*.tw,kf. (44,635)
30. *Basal Metabolism/ (4,108)
31. basal metaboli*.tw,kf. (5,281)
32. metabolic rate*.tw,kf. (22,170)
33. or/18-32 (302,540)
34. 17 and 33 (4,036)
35. exp animals/ not humans.sh. (5,144,321)
36. 34 not 35 (1,666)

Database: Embase (1974 to 8 August 2023)

1. extreme cold weather/ or "cold wave (weather)"/ (96)
2. cold/ and (air temperature/ or extreme weather/ or severe weather/) (148)
3. *cold/ (8,538)
4. ((extreme* or severe) adj3 (cold or low temperature*)).tw,kf. (3,071)
5. (serious* adj cold).tw,kf. (7)
6. ((cold* or freezing or sub-zero) adj3 temperature*).tw,kf. (11,696)
7. (((low adj3 temperature*) or (freezing or sub-zero)) and (climat* or weather or meteorolog*)).tw,kf. (4,097)
8. (cold adj (spell* or snap*)).tw,kf. (323)
9. hypothermi*.tw,kf. (56,009)
10. exp *cold injury/ (18,165)

11. (cold adj (injur* or stress* or exhaust* or shock*)).tw,kf. (10,985)
12. frostbit*.tw,kf. (1,582)
13. (record adj2 cold).tw,kf. (18)
14. cold shock response/ (950)
15. cold* climate*.tw,kf. (1,696)
16. (cold adj2 expos*).tw,kf. (9,623)
17. or/1-16 (100,469)
18. hypocalori*.tw,kf. (2,894)
19. ((calor* or kcal* or kilocal* or energy or food* or macronutrient*) adj3 (restrict or intake*)).tw,kf. (133,506)
20. *caloric restriction/ (8,419)
21. *caloric intake/ (11,352)
22. ((calor* or kcal* or kilocal* or energy or food* or macronutrient*) adj3 (allocation* or ration*)).tw,kf. (3,416)
23. ((calor* or kcal* or kilocal* or energy or food* or macronutrient*) adj3 (need* or required or requirement*)).tw,kf. (32,665)
24. ((calor* or kcal* or kilocal* or energy or food* or macronutrient*) adj3 (recommend* or guideline*)).tw,kf. (7,369)
25. ((calor* or kcal* or kilocal* or energy or food* or macronutrient*) adj3 (expenditure* or consum*)).tw,kf. (120,668)
26. ((calor* or kcal* or kilocal* or energy or food* or macronutrient*) adj3 (reserve* or turnover*)).tw,kf. (4,056)
27. fat reserve*.tw,kf. (554)
28. *energy metabolism/ or *energy balance/ or *energy consumption/ (26,651)
29. exp *energy expenditure/ (8,283)
30. energy metaboli*.tw,kf. (54,851)
31. exp *metabolic rate/ (4,144)
32. basal metaboli*.tw,kf. (5,404)
33. metabolic rate*.tw,kf. (26,209)
34. or/18-33 (351,633)
35. 17 and 34 (4,302)
36. (exp animal/ or nonhuman/) not exp human/ (7,127,462)
37. 35 not 36 (1,565)

Web of Science Core Collection (Editions: Science Citation Index) (Date of search: 10 August 2023)

KP=(((extreme* or severe) NEAR/2 (cold or "low temperature*"))) OR TI=(((extreme* or severe) NEAR/2 (cold or "low temperature*"))) OR KP=((serious* NEAR/0 cold)) OR TI=((serious* NEAR/0 cold)) OR KP=(((cold* or freezing or sub-zero) NEAR/2 temperature*)) OR TI=(((cold* or freezing or sub-zero) NEAR/2 temperature*)) OR KP=((((low NEAR/2 temperature*) or (freezing or sub-zero)) and (climat* or weather or meteorolog*))) OR TI=((((low NEAR/2 temperature*) or (freezing or sub-zero)) and (climat* or weather or meteorolog*))) OR KP=((cold NEAR/0 (spell* or snap*))) OR TI=((cold NEAR/0 (spell* or snap*))) OR KP=(hypothermi*) OR

TI=(hypothermi*) OR KP=((cold NEAR/0 (injur* or stress* or exhaust* or shock*))) OR TI=((cold NEAR/0 (injur* or stress* or exhaust* or shock*))) OR KP=(frostbit*) OR TI=(frostbit*) OR KP=((record NEAR/1 cold)) OR TI=((record NEAR/1 cold)) OR KP=("cold* climate*") OR TI=("cold* climate*") OR KP=((cold NEAR/1 expos*)) OR TI=((cold NEAR/1 expos*))

AND

KP=(hypocalori*) OR TI=(hypocalori*) OR KP=(((calor* or food* or kcal* or kilocal* or energy or macronutrient*) NEAR/2 (restrict* or intake*))) OR TI=(((calor* or food* or kcal* or kilocal* or energy or macronutrient*) NEAR/2 (restrict* or intake*))) OR KP=(((calor* or food* or kcal* or kilocal* or energy or macronutrient*) NEAR/2 (allocation* or ration*))) OR TI=(((calor* or food* or kcal* or kilocal* or energy or macronutrient*) NEAR/2 (allocation* or ration*))) OR KP=(((calor* or kcal* or kilocal* or energy or food* or macronutrient*) NEAR/2 (need* or required or requirement*))) OR TI=(((calor* or kcal* or kilocal* or energy or food* or macronutrient*) NEAR/2 (need* or required or requirement*))) OR KP=(((calor* or kcal* or kilocal* or energy or food* or macronutrient*) NEAR/2 (recommend* or guideline*))) OR TI=(((calor* or kcal* or kilocal* or energy or food* or macronutrient*) NEAR/2 (recommend* or guideline*))) OR KP=(((calor* or kcal* or kilocal* or energy or food* or macronutrient*) NEAR/2 (expenditure* or consum*))) OR TI=(((calor* or kcal* or kilocal* or energy or food* or macronutrient*) NEAR/2 (expenditure* or consum*))) OR KP=(((calor* or kcal* or kilocal* or energy or food* or macronutrient*) NEAR/2 (reserve* or turnover*))) OR TI=(((calor* or kcal* or kilocal* or energy or food* or macronutrient*) NEAR/2 (reserve* or turnover*))) OR KP=("fat reserve*") OR TI=("fat reserve*") KP=("energy metaboli*") OR TI=("energy metaboli*") OR KP=("basal metaboli*") OR TI=("basal metaboli*") OR KP=("metabolic rate*") OR TI=("metabolic rate*")

1,121 results

Annexe B. Data extraction tables

For consistency between studies, where studies did not provide results as kcal per day, these were calculated from the results provided and given in square brackets, that is, these results were not presented by the studies themselves, but were calculated from data provided by the studies, using 1 joule = 0.239006 calories.

Acronyms used: BAT = brown adipose tissue, BMI = body mass index, C = Celsius, CI = confidence interval, IQR = interquartile range, kcal = kilocalories, kJ = kilojoules, km = kilometre, MD = mean difference, MJ = megajoules, REE = resting energy expenditure, SD = standard deviation, SE = standard error, W = watt

Table B.1. Experimental studies of the effect of different ambient air temperatures on energy expenditure

Reference	Study location, date	Population	Intervention procedure	Results
Ahmed 2019 (1)	Canada Study date not stated	n=18 Canadian armed forces members (n=4 women, n=14 men) Mean age: 34 years (SD: 11 years) Mean BMI: 26 kg/m^2 (SD: 4 kg/m^2)	4 experimental conditions for 8 hours in an environmental chamber: 1. Sedentary (21°C) 2. Strenuous physical activity, cold (-10°C) 3. Strenuous physical activity, temperate (21°C) 4. Strenuous physical activity, hot (30°C) Strenuous physical activity involved 2 hours of standardised typical military tasks or infantry activities, followed by 2 hours rest, which repeated once Energy intake measured from ad libitum selection Energy expenditure measured using a portable metabolic measurement system (Metamax 3B)	Energy intake over the 8 hours experiment period: • sedentary (21°C): 1,920 kcal (SD: 640) • strenuous physical activity, cold (-10°C): 1,897 kcal (SD: 793) • strenuous physical activity, temperate (21°C): 2,055 kcal (SD: 680) • strenuous physical activity, hot (30°C): 2,005 kcal (SD: 795) • [1,897 – 2,055 = -158 kcal in 8 hours of cold compared with temperate exposure = -474 kcal per day] Energy expenditure over the 8 hours experiment period, estimated from figure: • sedentary (21°C): 412 kcal • strenuous physical activity, cold (-10°C): 1,705 kcal • strenuous physical activity, temperate (21°C): 1,689 kcal • strenuous physical activity, hot (30°C): 1,648 kcal • [1,705 – 1,689 = 16 kcal in 8 hours of cold compared with temperate exposure = 48 kcal per day]
Brychta 2019 (3)	US Study date not provided	n=16 adult men Mean age: 26 years (SD: 4.5 years) Mean BMI: 21.9 kg/m^2 (SD: 1.8 kg/m^2)	1. Lightly clothed and fasted, in a metabolic chamber 2. 4 hours exposure to either a warm temperature: 27.0 (SD: 0.7°C), or coldest tolerated temperature before shivering: 21.3°C (SD: 1.4°C) 3. Given placebo, 20mg pindolol, or 160mg propranolol (only placebo group data extracted) 4. Unclear if participants split between treatment groups or completed all 3 treatments Energy expenditure measurement method not further specified.	Mean metabolic rate, placebo group only: • warm condition (27°C): 1.15 kcal per minute (SD: 0.12 kcal per minute) • cold condition (21°C): 1.28 kcal per minute (SD: 0.16 kcal per minute) • [1,843 – 1,656 = 187 kcal per day more energy expenditure during cold exposure]

Reference	Study location, date	Population	Intervention procedure	Results
Brychta 2019 (2)	US Study date not provided	n=21 adult Caucasian men (n=12 lean, n=9 with obesity) Mean age lean group: 23 years (SD: 5 years) Mean age group with obesity: 29 years (SD: 5 years) Mean BMI lean group: 23.2 kg/m^2 (SD: 1.9 kg/m^2) Mean BMI group with obesity: 34.4 kg/m^2 (SD: 3.4 kg/m^2)	1. 13-day protocol, participants in a room calorimeter for 3 hours per day, fasted, standardised clothing 2. Day 1 to 2: standard room temperature set at 24°C 3. Day 3 to 12: temperature varied from 16°C to 31°C in approximately 1.4°C increments (in a random order) 4. If participant reported intolerable shivering that day's session was stopped and no colder temperatures were used 5. Day 13: participants re-exposed to 16°C or their coldest tolerated temperature if shivering had been reported Energy expenditure measured using indirect respiratory calorimetry.	Mean cold-induced thermogenesis capacity (increase in resting energy expenditure above basal metabolic rate with cold exposure): • lean group: 300 kcal per day (SD: 218 kcal per day) • group with obesity: 125 kcal per day (SD: 146 kcal per day) • cold-induced thermogenesis in the group with obesity was significantly lower than the group without (mean reduction: 6.0%, SD: 7.3%, p=0.01)
Buemann 1992 (4)	Denmark Study date not provided	n=16 women (n=8 'post-obese': history of past resolved obesity, n=8 'controls': no history of obesity Mean age post-obese: 39 years (SD: 3 years) Mean age controls: 37 years (3 years) Mean BMI post-obese: 24.0 kg/m^2 (0.5 kg/m^2) Mean BMI controls: 21.9 kg/m^2 (0.5 kg/m^2)	Two experimental conditions: 1. 16°C and 60% humidity in a respiratory chamber for 24 hours 2. 24°C and 50% humidity during the day and 18°C and 60% humidity at night over 24 hours 3. Participants individually randomised within their groups (post-obese and control) to determine which condition experienced first 4. Same indoor clothing for each experiment, thin blanket provided to cover upper body in 16°C experiment 5. Instructed to report any shivering (but none reported) 6. Energy expenditure estimated for the whole 24 hours, during daytime, during sleep, and post-dinner Energy expenditure measured by open-air circuit calorimetry in a respiratory chamber.	Mean energy expenditure over 24 hours at 16°C: • post-obese group: 349 kJ per hour (SE: 5 kJ per hour) • control group: 368 kJ per hour (SE: 9 kJ per hour) Mean energy expenditure over 24 hours at 24°C: • post-obese group: 342 kJ per hour (SE: 4 kJ per hour) • control group: 360 kJ per hour (SE: 12 kJ per hour) • [post-obese group: 2,002 – 1,962 = 40 kcal per day more energy expenditure during cold exposure] • [control group: 2,111 – 2,065 = 46 per day more energy expenditure during cold exposure] Mean energy expenditure during daytime at 16°C: • post-obese group: 429 kJ per hour (SE: 6 kJ per hour) • control group: 450 kJ per hour (SE: 10 kJ per hour) Mean energy expenditure during daytime at 24°C: • post-obese group: 421 kJ per hour (SE: 8 kJ per hour) • control group: 440 kJ per hour (SE: 15 kJ per hour) Mean energy expenditure during sleep at 16°C: • post-obese group: 247 kJ per hour (SE: 5 kJ per hour)

Reference	Study location, date	Population	Intervention procedure	Results
				• control group: 259 kJ per hour (SE: 8 kJ per hour) Mean energy expenditure during sleep at 18°C: • post-obese group: 244 kJ per hour (SE: 4 kJ per hour) • control group: 257 kJ per hour (SE: 8 kJ per hour) Mean energy expenditure post-dinner at 16°C: • post-obese group: 366 kJ per hour (SE: 8 kJ per hour) • control group: 397 kJ per hour (SE: 14 kJ per hour) Mean energy expenditure post-dinner at 24°C: • post-obese group: 349 kJ per hour (SE: 4 kJ per hour) • control group: 378 kJ per hour (SE: 16 kJ per hour)
Cain 1990 (5)	Canada Study date not provided	n=5 men Mean age: 28 years (SD: 5 years) Mean BMI: not provided	1. Ambient temperature -40°C, -20°C, 0°C, and 20°C in an environmental chamber 2. Subjects dressed in appropriate clothing so that they were comfortable at these temperatures (not further specified) 3. Four tests at each ambient condition: standing quietly, walking on a treadmill at 3 km per hour and 0% or 5% slope, walking on a treadmill at 5 km per hour and 5 % slope 4. Each experiment consisted of 10 minutes standing, then 10 minutes at each of the exercise conditions Energy expenditure measured via expired air through facemask into a Beckman Metabolic Measurement Cart.	Mean metabolic rate at 20°C not presented. Mean metabolic rate at 0°C: • standing quietly: 112 W (SD: 16 W) • walking at 3 km per hour and 0% slope: 229 W (SD: 24 W) • walking at 3 km per hour and 5% slope: 320 W (SD: 36 W) • walking at 5 km per hour and 5% slope: 460 W (SD: 57 W) Mean metabolic rate at -20°C: • standing quietly: 77 W (SD: 24 W) • walking at 3 km per hour and 0% slope: 232 W (SD: 32 W) • walking at 3 km per hour and 5% slope: 301 W (SD: 31 W) • walking at 5 km per hour and 5% slope: 497 W (SD: 40 W) Mean metabolic rate at -40°C: • standing quietly: 84 W (SD: 17 W) • walking at 3 km per hour and 0% slope: 241 W (SD: 53 W) • walking at 3 km per hour and 5% slope: 338 W (SD: 53 W) • walking at 5 km per hour and 5% slope: 489 W (SD: 91 W) • [standing quietly at -20°C versus 0°C: 77 – 112 = -35 W = -723 kcal per day energy expenditure] • [standing quietly at -40°C versus 0°C: 84 – 112 = -28 W = -578 kcal per day energy expenditure]

Reference	Study location, date	Population	Intervention procedure	Results
				• [walking at 3 km per hour and 0% slope at -20°C versus 0°C: 232 – 229 = 3 W = 62 kcal per day energy expenditure] • [walking at 3 km per hour and 0% slope at -40°C versus 0°C: 241 – 229 = 12 W = 248 kcal per day energy expenditure] • [walking at 3 km per hour and 5% slope at -20°C versus 0°C: 301 – 320 = -19 W = -392 kcal per day energy expenditure] • [walking at 3 km per hour and 5% slope at -40°C versus 0°C: 338 – 320 = 18 W = 372 kcal per day energy expenditure] • [walking at 5 km per hour and 5% slope at -20°C versus 0°C: 497 – 460 = 37 W = 764 kcal per day energy expenditure] • [walking at 5 km per hour and 5% slope at -40°C versus 0°C: 489 – 460 = 28 W = 578 kcal per day energy expenditure]
Calton 2016 (6)	Australia September 2012 to November 2012	n=22 adults (n=13 women, n=9 men) Mean age: 58 years (SD: 10 years) Mean BMI: 27.8 kg/m^2 (SD: 4.5 kg/m^2)	Randomised cross-over design: 1. 10 to 12 hours after standardised evening meal, standardised clothing (gown) 2. 90 minutes at 20°C in environmental chamber 3. 90 minutes at 25°C in environmental chamber 4. Participants were asked to verbally notify investigators if they started to shiver Resting metabolic rate measured by indirect calorimetry according to a standardised protocol.	Mean resting metabolic rate: • 25°C: 5,938 kJ per day (SD: 1,415 kJ per day) • 20°C: 6,127 kJ per day (SD: 1,467 kJ per day) • mean difference (colder minus warmer): 190 kJ per day (SD: 563 kJ per day) • [190 kJ per day = 45 kcal per day more energy expenditure at 20°C versus 25°C]
Celi 2010 (7)	US Study date not provided	n=25 (n=10 women, n=15 men) Mean age: 29 years (SD: 9 years) Mean BMI: 23.3 kg/m^2 (SD: 2.2 kg/m^2)	Randomised cross-over design: 1. 2-day equilibration diet 2. Randomly assigned to 12-hours in whole room direct calorimeter at either 24°C or 19°C, after a 36-hour recovery crossed over to alternative condition 3. Standardised clothing (hospital scrubs), no blankets provided Energy expenditure measured using a whole room indirect calorimeter.	Mean energy expenditure across 12 hours: • 24°C: 82 kcal per hour (measure of variability not specified but presumed standard deviation: 8.6 kcal per hour) • 19°C: 87 kcal per hour (measure of variability not specified but presumed standard deviation: 9.9 kcal per hour) • [87 – 82 = 5 kcal per hour = 120 kcal per day more energy expenditure in cold exposure]
Chen 2013 (8)	US Study date not provided	n=31 healthy adults, of which 24 were analysed as the remainder had an incomplete set of data (n=10 women, n=13 men)	Randomised cross-over design: 1. 2-day equilibration diet 2. Randomly assigned to 12-hours in whole room direct calorimeter at either 24°C or 19°C, after a 36-hour recovery crossed over to alternative condition	Mean energy expenditure: • 24°C: 70 kcal per hour (SD: 12 kcal per hour) • 19°C: 74 kcal per hour (SD: 12 kcal per hour) • [74 – 70 = 4 kcal per hour = 96 kcal per day more energy expenditure in cold exposure]

Reference	Study location, date	Population	Intervention procedure	Results
		Mean age: 28 years (SD: 7 years) Mean BMI: not provided but was required to be between 20.1 and 26.0 kg/m^2	3. Standardised clothing (hospital scrubs), no blankets provided 4. Also underwent positron emission tomography scanning to determine brown adipose tissue activity Energy expenditure measured using a whole room indirect calorimeter.	
Crabtree 2015 (9)	UK Study date not stated	N=16 adults (n=6 women and n=10 men) Mean age: 50 years (SD: 10.3 years) Mean BMI: 29.9 kg/m^2 (SD: 5.2 kg/m^2)	Ad-libitum energy intake was measured using a buffet style test meal 4 minutes after the participants had exercised under the following conditions: 1. At 20°C; walking on a treadmill for 45 minutes 2. At 8°C; walking on a treadmill for 45 minutes	Total ad-libitum energy intake was statistically significantly higher after exercising at 8°C compared to 20°C ($p < 0.05$) Data extracted from figure: • energy intake was approximately 1,300 kcals after the exercise at 8°C, compared with 1,150 kcals at 20°C • [1,300 – 1,150 = 150 kcal more energy intake during a 30-minute buffet meal]
Dauncey 1981 (10)	UK Study date not stated	N=9 adult women Mean age: 32 years (SE: 4 years) Mean body fat percentage: 21.5% (SE: 1.4%)	Participants were measured using a live-in calorimeter on 2 occasions in environmentally controlled conditions: 1. 30 hours spent at 28°C 2. 30 hours spent at 22°C Energy expenditure was measured as heat production	Mean 24-hour energy expenditure: • 28°C: 7,716 kJ per day (SE: 139 kJ per day) [1,844 kcal per day, SE: 33 kcal per day] • 22°C: 8,258 kJ per day (SE: 188 kJ per day) [1,974 kcal per day, SE: 45 kcal per day] • mean increase of 7% (SE: 1.1%) from 28°C to 22°C • $p < 0.001$ • [1974 – 1844 = 130kcal per day more energy expenditure at 22°C versus 28°C] Mean heat production at rest: • 28°C: 3.899 kJ per minute (SE: 0.112 kJ per minute) • 22°C: 4.329 kJ per minute (SE: 0.152 kJ per minute) • 11% (SE: 3.2%) higher at 22°C versus 28°C • [4.329 – 3.899 = 0.43 kJ per minute = 148 kcal per day more heat production at rest at 22°C versus 28°C]
Hollstein 2020 (11)	US Study date not provided	n=20 adults (n=16 women, n=4 men) Mean age: 37 years (SD: 11 years)	Three experimental conditions: 1. Thermoneutral (mean: 23.6°C, SD: 0.3°C) 2. Cold in isocaloric conditions (mean: 19.0°C, SD: 0.3°C) 3. Thermoneutral fasting (ambient temperature, mean: 23.6°C, SD: 0.3°C) 4. Standardised clothing and 3 blankets provided 5. If shivering was reported, another blanket was provided	Change in 24-hour energy expenditure cold versus thermoneutral: • mean difference = -25 kcal per day, SD: 96 kcal per day

Reference	Study location, date	Population	Intervention procedure	Results
		Mean BMI: 31.0 kg/m^2 (SD: 7.6 kg/m^2)	Energy expenditure estimated using an open-circuit, indirect, whole-room calorimeter.	
Langeveld 2016 (12)	UK April 2012 to September 2012	n=10 Caucasian, healthy, non-smokers (n=5 women, n=5 men) Mean age men: 45 years (SD: 5 years) Mean age women: 34 years (SD: 7 years) Mean BMI men: 22.4 kg/m^2 (SD: 0.8 kg/m^2) Mean BMI women: 22.9 kg/m^2 (SD: 0.9 kg/m^2)	Participants studied twice 2 weeks apart, once under thermoneutral conditions and once under mild cold exposure. 1. Stayed overnight in a temperature-controlled room at thermoneutral conditions (24°C) 2. The following morning either stayed in these thermoneutral conditions or moved to the mild cold condition room (18°C) 3. Measurements including calorimetry taken every 20 minutes for 2.5 hours Resting energy expenditure measured by indirect calorimetry: ventilated canopy respiratory gas exchange.	Increase in baseline energy expenditure in 18°C versus 24°C: • mean difference = 48 kJ (SD: 14 kJ) over 150 minutes • [48*9.6 = 460.8 kJ per day = 110 kcal per day increased energy expenditure in mild cold conditions]
Lean 1988 (13)	UK Study date not provided	n=16 adult women (n=5 overweight and diabetic women [A], n=5 overweight women without diabetes [B], n=6 normal weight women without diabetes[C]) Mean age group A: 55 years (SD: not provided) Mean age group B: 44 years (SD: not provided) Mean age group C: 32 years (SD: not provided) Mean BMI group A: 35.4 kg/m^2 (SD 2.6 kg/m^2) Mean BMI group B: 33.8 kg/m^2 (SD: 2.2 kg/m^2)	All participants exposed to 2 experimental conditions: 1. 12 hours overnight exposure to 28°C in calorimeter room 2. 12 hours overnight exposure to 22°C in calorimeter room Participants wore a thin cotton gown and slept with a single cotton sheet. Energy expenditure measured using a calorimeter room with an analytical precision of 0.38 Watts over a 3-hour measurement.	Mean sleeping energy expenditure at 28°C: • group A (overweight and diabetic): 78.2 W (SE 9.2 W) • group B (overweight): 74.0 W (SE 4.7 W) • group C (controls): 66.0 W (SE 2.9 W) Mean sleeping energy expenditure at 22°C: • group A (overweight and diabetic): 75.1 W (7.7 W) • group B (overweight): 72.4 W (4.2 W) • group C (controls): 68.4 W (3.1 W) Percentage change in sleeping energy expenditure between 28°C and 22°C: • group A (overweight and diabetic): -3.5% • group B (overweight): -2.0% • group C (controls): +3.8% • [group A 1,551 kcal per day (75.1 W) – 1,615 kcal per day (78.2 W) = MD of -64kcal per day] • [group B 1,495 kcal per day (72.4 W) – 1,528 kcal per day (74.0 W) = MD of -33 kcal per day]

Reference	Study location, date	Population	Intervention procedure	Results
		Mean BMI group C: 23.1 kg/m^2 (SD: 1.2 kg/m^2)		• [group C 1,412 kcal per day (68.4 W) – 1,363 kcal per day (66.0 W) = MD of 49 kcal per day]
Lee 2013 (14)	US Study date not provided	n=12 healthy adults (n=5 women, n=7 men) Mean age: 32 years (SD: 11 years) Mean BMI: 23 kg/m^2 (SD: 3 kg/m^2)	Randomised, single-blind, cross-over study. Two experimental conditions (participants randomized to initial condition, then repeated with the alternative condition after 36-hour recovery period). 1. Overnight fast 2. Wore hospital scrubs with no additional blankets 3. Standardised physical activity and diet during the study 4. 24°C or 19°C for 12 hours (whole-room temperature) Energy expenditure measured using a whole-room indirect calorimeter.	Mean total energy expenditure over 12 hours: • 24°C: 802 kcal (SD: 104 kcal) • 19°C: 847 kcal (SD: 116 kcal) • [1,694 kcal – 1,604 kcal = 90 kcal per day more energy expenditure in the colder condition]
Matsushita 2021 (15)	Japan Study date not provided	n=23 healthy adult men Age range: 20 to 29 years BMI range 19.3 to 24.1 kg/m^2	1. Brown adipose tissue (BAT) activity estimated using FDG-PET/CT, and participants divided into low and high-BAT activity groups 2. Light clothing, relaxed on a bed 3. Energy expenditure measured at 27°C and again after 90 minutes of 19°C (cold-room) 4. Cold-induced thermogenesis measured as the difference in energy expenditure at 19 and 27°C 5. Measurements taken morning and evening to look for diurnal variation Energy expenditure estimated via a respiratory gas analyser connected to a ventilated hood.	Mean cold-induced thermogenesis (energy expenditure at 19°C minus energy expenditure at 27°C): Morning: • high brown adipose tissue activity group: 152 kcal per day (SD: 167 kcal per day) • low brown adipose tissue activity group: -10 kcal per day (SD: 133 kcal per day) Evening: • high brown adipose tissue activity group: 75 kcal per day (SD: 154 kcal per day) • low brown adipose tissue activity group: 36 kcal per day (SD: 155 kcal per day)
Munten 2021 (41)	Canada Study dates not stated	N=11 adults (n=4 women, n=7 men) Mean age: 23 years (SD: 3 years) Mean BMI: 26.4 kg/m^2 (SD: 1.9 kg/m^2)	Energy expenditure was measured using indirect calorimetry in an environmental chamber under the following conditions: 1. High-intensity interval exercise under thermoneutral conditions (21°C) 2. High-intensity interval exercise under cold conditions (0°C)	No statistically significant difference in energy expenditure between thermoneutral and cold conditions (p=0.476).
Murray 1986 (42)	Canada Study dates not stated	N=24 adult women Mean age: 21.4 years (SD: 2.3 years)	Energy expenditure was measured using indirect calorimetry under 3 experimental conditions, with 200 minutes of treadmill walking and stepping in each: 1. Five days of exercise at 15°C 2. Five days of exercise at -20°C while inhaling air at 18°C	There were no statistically significant differences in energy expenditure between the 3 conditions: • mean energy expenditure at 15°C: 10.9 MJ per day (SD: 5.0 MJ per day) [2,605 kcal per day, SD: 1,195 kcal per day]

Reference	Study location, date	Population	Intervention procedure	Results
		Mean body fat percentage: 26.7 % (SD: 5.5%)	3. Five days of exercise at -20°C Participants wore Arctic clothing and boots in both -20°C experimental conditions. For each of the 3 conditions, participants completed 9-day dietary recalls from 36 hours pre-exercise to 48 hours post-exercise	• mean energy expenditure at -20°C while inhaling warm air: 11.3 MJ per day (SD: 5.2 MJ per day) [2,700 kcal per day, SD: 1,243 kcal per day] • mean energy expenditure at -20°C: 11.4 MJ per day (SD: 5.3 MJ per day) [2,725 kcal per day, SD: 1,267 kcal per day] • [2,725 – 2,605 = 120 kcal per day more energy expenditure in -20°C versus 15°C] • [2,700 – 2,605 = 95 kcal per more energy expenditure in -20°C inhaling warm air versus 15°C] There were no statistically significant differences in dietary intake between the experimental conditions on experiment days: • mean energy intake at 15°C: 9.1 MJ per day (SD: 1.6 MJ per day) [2,174 kcal per day, SD: 382 kcal per day] • mean energy intake at -20°C while inhaling warm air: 7.9 MJ per day (SD: 1.5 MJ per day) [1,888 kcal per day, SD: 359 kcal per day] • mean energy intake at -20°C: 8.6 MJ per day (SD: 1.2 MJ per day) [2,055 kcal per day, SD: 287 kcal per day] • [2,055 – 2,174 = -199 kcal per day: 119 fewer calories consumed at -20°C versus 15°C] • [1,888 – 2,174 = -286 kcal per day: 286 fewer calories consumed at -20 whilst breathing warm air versus 15°C]
Muzik 2013 (16)	US Study date not stated	N=25 adults (n=15 women, n=10 men) Mean age: 30 years (SD: 7 years) Two groups: High and low brown-adipose tissue (based on the presence or absence of F-FDG uptake)	Resting energy expenditure was measured using indirect calorimetry under the following conditions: 1. room temperature (25°C) 2. under cold stress (15.5°C), temperature lowered to 15.5°C with 2 fans to induce cold air flow	High brown adipose tissue: • daily energy expenditure increased from 1,452 kcal per day at 25°C, to 1,689 kcal per day at 15.5°C (percentage increase of 17.4%, SD: 15%, p=0.02) • [1,689 – 1,452 = 237 kcal per day increased energy expenditure in cold condition] Low brown adipose tissue • little difference in daily energy expenditure between conditions (1,676 kcal per day at 25°C, 1,643 kcal per day at 15.5°C, p > 0.05) • [1,643 – 1,676 = -33 kcal per day energy exposure in cold condition]
Pathak 2018 (17)	Australia	N=20 adults (n=16 women, n=4 men)	Resting energy expenditure was measured using indirect calorimetry in a temperature-controlled chamber under 3 conditions:	Mean resting energy expenditure:

Reference	Study location, date	Population	Intervention procedure	Results
	Study date not stated	Individuals were grouped by markers of metabolic syndrome; with MetS (3 or more markers of metabolic syndrome) or without MetS (without metabolic syndrome) With MetS (n=9; n=6 women, n=3 men): • mean age: 62 years (SD: 3.8 years) • mean BMI: 30.1 kg/m^2 (SD: 5.9 kg/m^2) Without MetS (n=10 women, n=1 man): • mean age: 57 years (SD: 13.5 years) • mean BMI: 25.1 kg/m^2 (SD: 3.01 kg/m^2)	1. 20°C 2. 25°C 3. 27°C	• 20°C: 247 kJ per hour (SE: 5 kJ per hour) in the with MetS group, and 221 kJ per hour (SE: 4.5 kJ per hour) in the without MetS group ($p < 0.05$) • [1,416.8 kcal per day, SE: 28.7 kcal per day and 1,267.7 kcal per day, SE: 25.8 kcal per day, respectively] • 25°C: 234 kJ per hour (SE: 5 kJ per hour) in the with MetS group, and 220 kJ per hour (SE: 4.5 kJ per hour) in the without MetS group ($p < 0.05$) • [1,342.3 kcal per day, SE: 28.7 kcal per day and 1,262.0 kcal per day, SE: 25.8 kcal per day, respectively] • 27°C: 224 kJ per hour (SE: 5 kJ per hour) in the with MetS group, and 217 kJ per hour (SE: 4.5 kJ per hour) in the without MetS group ($p > 0.05$) • [1,284.9 kcal per day, SE: 28.7 kcal per day and 1,244.7 kcal per day, SE: 25.8 kcal per day, respectively] • [MetS group: 1,416.8 – 1,284.9 = 132 kcal per day more energy expenditure in 20°C versus 27°C] • [Group without MetS: 1,267.7 – 1,244.7 = 23 kcal per day more energy expenditure in 20°C versus 27°C]
Sanchez-Delgado 2019 (18)	Spain October and November 2016	N=44 adults (n=29 women, n=15 men) Mean age: 22.1 years (SD: 2.1 years) Mean BMI: 25.6 kg/m^2 (SD: 5.2 kg/m^2)	Resting energy expenditure was measured using indirect calorimetry under 2 conditions: 1. In a warm room (23.2°C, SD: 0.7°C) 2. In a cold room (19.7°C, SD: 0.4°C) Resting energy expenditure measured using a neoprene face mask hooked up to either a CCM Express or Ultima Cardi02 metabolic cart (MCG diagnostics)	Mild cold exposure statistically significantly increased resting energy expenditure ($p < 0.001$), data extracted from figure: • from approximately 1,578 kcal per day before cold exposure, to approximately 1,796 kcal per day at 30 and 1,854 kcal per day at 65-minutes cold exposure • [1,854 – 1,578 = 218 kcal per day more resting energy expenditure at 19.7°C versus 23.2°C]
Sanchez-Delgado 2020 (19)	Spain October 2016 to January 2018	N=75 adults (n=48 women, n=27 men)	Resting energy expenditure was measured using indirect calorimetry under 2 conditions: 1. In a warm room (23.2°C, SD: 0.7°C) 2. In a cold room (19.7°C, SD: 0.4°C) Resting energy expenditure measured using a neoprene face mask hooked up to either a CCM Express or Ultima Cardi02 metabolic cart (MCG diagnostics)	Mild cold exposure statistically significantly increased resting energy expenditure ($p < 0.001$); data extracted from figure: • from 1.1 kcal per minute to 1.3 kcal per minute after 65 minutes of cold exposure • [1,872 – 1,584 = 288 kcal per day more resting energy expenditure at 19.7°C versus 23.2°C]

Reference	Study location, date	Population	Intervention procedure	Results
Schrauwen 2002 (20)	Netherlands Study date not stated	N=10 males Mean age: 24.4 years (SE: 1.6 years) Mean body fat percentage: 19% (SE: 2%) BMI range: 20.2 to 27.4 kg/m^2	Resting energy expenditure was measured using whole-room indirect calorimetry. The measurement period was 60 hours. Each participant was measured under 2 conditions: 1. 22°C 2. 16°C Participants were given a 'normal' western diet (36% of energy intake came from fat, 49% from carbohydrate and 15% from protein)	24-hour energy expenditure: • 24-hour energy expenditure was statistically significantly higher at 16°C (12.8 MJ per day, SE: 0.6 MJ per day) than at 22°C (11.9 MJ per day, SE: 0.7) (p < 0.005) • [3,059.3 - 2,844.2 = 215 kcal per day more energy expenditure in the colder condition] • at 16°C, 24-hour energy expenditure was statistically significantly higher on day 2 (12.8 MJ per day, SE: 0.6 MJ per day) compared to day one (11.9 MJ per day, SE: 0.5 MJ per day) (p < 0.01) • [3,059.3 - 2,844.2 = 215 kcal per day kcal per day more energy expenditure on day 2 cold exposure versus day 1] Sleeping energy expenditure: • sleeping energy expenditure was higher at 16°C (7.6 MJ per day, SE: 0.3 MJ per day) compared to 22°C (7.4 MJ per day, SE: 0.3 MJ per day) (p=0.06) • [1,816.4 - 1,768.6 = 48 kcal per day more sleeping energy expenditure in the colder condition] • at 16°C, sleeping energy expenditure was higher (not significant) on day 2 (7.6 MJ per day, SE: 0.3 MJ per day) compared to day one (7.5 MJ per day, SE: 0.3 MJ per day) (p=0.1) • [1,816.4 - 1,792.5 = 24 kcal per day more sleeping energy expenditure on day 2 cold exposure versus day 1]
Spealman 1948 (21)	US Study date not stated	n=2 Mean age and mean BMI not stated	Summer experiment: 1. Warm period 33°C for 4 days 2. Cold period 21°C for 6 days 3. Original room temperature for 4 days Winter experiment: 1. Cold period 21°C for 2 days 2. Warm period 33°C for 7 days	Summer experiment: Subject 1: • mean caloric intake during warm period: 2,650 kcal • mean caloric intake during cold period: 2,630 kcal • mean caloric intake at original room temperature: 2,170 kcal • [2,630 – 2,650 = -20 kcal per day comparing cold and warm period] Subject 2: • mean caloric intake during warm period: 2,280 kcal • mean caloric intake during cold period: 2,140 kcal • mean caloric intake at original room temperature: 2,220 kcal • [2,140 – 2,280 = -140 kcal per day comparing cold and warm period]

Reference	Study location, date	Population	Intervention procedure	Results
				Winter experiment: Subject 1: • mean caloric intake during warm period: 2,650 kcal • mean caloric intake during cold period: 2,710 kcal • [2,710 – 2,650 = 60 kcal per day comparing cold and warm period] Subject 2: • mean caloric intake during warm period: 2,660 kcal • mean caloric intake during cold period: 2,490 kcal • [2,490 – 2,660 = -170 kcal per day comparing cold and warm period]
Tay 2020 (22)	Singapore Study dates not stated	n=17 Chinese males Mean age: 24 years (SE: 0.52 years) Mean BMI: 21.7 kg/m^2 (SE: 0.63 kg/m^2)	1. 45 minutes in thermoneutral environment (24°C) 2. 45 minutes in cold chamber (18°C)	Mean resting energy expenditure: • during thermoneutral environment = 1,486 kcal per day (SD: 144 kcal per day) • during cold exposure = 1,687 kcal per day (SD: 274 kcal per day) • percentage change = 201 kcal per day (13.14%), p<0.0001 • [1,687 – 1,486 = 201 kcal per day comparing cold thermoneutral environments] Mean cumulative energy expenditure: • during thermoneutral environment = 48.9 kcal (SD: 4.4 kcal) • during cold exposure = 53.4 kcal (SD: 7.7 kcal) • percentage change = 4.4 kcal (9.12%), p<0.0001
Tikuisis 1991 (23)	Canada Study dates not stated	n=13 male participants Age (range): 30 to 42 years Mean BMI not stated	1. 0.5 hour rest at room temperature (21 to 22°C) 2. 2 hours in a cold room (10°C)	Metabolic rate, data extracted from figure: Lean participants (less than 15% body fat): • room temperature: 75 W • 115 minutes in cold room: 173 W • [173 W – 75 W = 3,272 – 1,549 kcal per day = 1,723 kcal per day] Normal body fat participants (more than 15% body fat): • room temperature: 80 W • 115 minutes in cold room: 152 W • [152 W – 80 W = 3,139 – 1,652 kcal per day = 1,487 kcal per day]

Reference	Study location, date	Population	Intervention procedure	Results
Vallerand 1989 (24)	Canada Study dates not stated	n=7 male participants Mean age: 32.5 years (SE: 1.5 years) Mean body mass: 76.6 kg (SE: 2.1 kg)	1. Warm environment (29°C) 2. Cold exposure (10°C) for 2 hours (wearing only bathing suit or jogging shorts)	Mean energy expenditure: • warm environment: 617.8 kJ (SE: 28.0 kJ) • cold exposure: 1,519.4 kJ (SE: 150.6 kJ) • p value for difference < 0.01 [1,519.4 – 617.8 kJ in 2 hours = 4,357.7 – 1,771.9 kcal per day = 2,585.9 kcal per day]
Vallerand 1990 (25)	Canada Study dates not stated	n=7 males Mean age= 32.5 years (SE: 1.5 years) Mean BMI not stated	1. Once in warm environment (29°C) in a climatic suite for 160 minutes 2. Twice in cold environment (10°C) for 160 minutes (wearing only bathing suit or jogging shorts)	Mean energy expenditure: • warn environment = 885.4 kJ (SE 10.4 kJ) • cold environment 1 = 2,104 kJ (SE 197.9 kJ) • cold environment 2 = 2,083 kJ (SE 197.9 kJ) • 2.5 fold increase in energy expenditure after cold exposure (p<0.01) • [2,104 – 885.4 kJ in 160 minutes = 4,526 – 1,905 kcal per day = 2,621 kcal per day] • [2,083 – 885.4 kJ in 160 minutes = 4,481 – 1,905 kcal per day = 2,576 kcal per day]
Van Marken Lichtenbelt 2002 (26)	Netherlands November 1998 to March 1999	n=9 Caucasian males Mean age: 23.8 years (SD: 5.1 years) Mean BMI: 22.7 kg/m^2 (SD: 2.1 kg/m^2)	1. Once in thermoneutral environment (22°C) for 60 hours in respiration chamber 2. Twice in cold environment (16°C) for 60 hours each time	24 hours mean energy expenditure: • fed in energy balance (22°C) = 12.17 MJ per day (SD: 1.97 MJ per day) • fed in energy balance (16°C) = 12.91 MJ per day (SD: 2.01 MJ per day) • [12.91 – 12.17 MJ per day = 3,086 – 2,909 kcal per day = 177 kcal per day] 24 hours mean energy intake: • fed in ad libitum (22°C) = 12.90 MJ per day (SD 1.9778) • fed in ad libitum (16°C) = 13.38 MJ per day (SD 2.06) • [13.38 – 12.90 MJ per day = 3,198 – 3,083 kcal per day = 115 kcal per day]

Reference	Study location, date	Population	Intervention procedure	Results
Van Marken Lichtenbelt 2009 (27)	Netherlands October 2007 to December 2008	n=24 male participants Lean subjects mean age = 24.3 years (SD: 3.6 years), range 20 to 32 years Overweight subjects mean age = 23.5 years (SD: 3.4 years), range 18 to 30 years Lean subjects mean BMI = 23.2 kg/m^2 (SD: 1.2 kg/m^2), range 21.3 to 24.5 kg/m^2 Overweight subjects mean BMI = 30.3 kg/m^2 (SD: 4.2 kg/m^2), range 25.4 to 38.7 kg/m^2	1. Rested in supine position under thermoneutral environment (22°C) for 1 hour 2. Cold exposure in climate chamber (16°C) for 2 hours 3. Energy expenditure was measured by respiratory gas analyser	Mean resting metabolic rate: Lean group (BMI less than 25): • thermoneutral environment = 8.46 MJ in 24 hours (SD: 0.93 MJ in 24 hours) • cold exposure = 9.62 MJ in 24 hours (SD: 1.36 MJ in 24 hours), p<0.001 • [9.62 – 8.46 MJ per day = 2,299 – 2,022 kcal per day = 277 kcal per day] Overweight group (BMI more than 25): • thermoneutral environment = 8.16 MJ in 24 hours (SD: 0.29 MJ in 24 hours) • cold exposure = 9.56 MJ in 24 hours (SD: 0.66 MJ in 24 hours), p<0.001 • [9.56 – 8.16 MJ per day = 2,285 – 1,950 kcal per day = 335 kcal per day]
Van Ooijen 2004 (28)	Netherlands Study dates not stated	n=20 (10 females and 10 males) Mean age: 26 years (SD: 5 years) BMI range: 17 to 32 kg/m^2	1. One hour at ambient temperature (22°C) 2. 3 hour cold exposure (in a room cooled from 22°C to 15°C in 45 minutes) Experiment conducted in summer and winter	Metabolic rate: In summer: • ambient temperature = 4.7 kJ per minute (SD: 0.7 kJ per minute) • cold environment = 5.1 kJ per minute (SD: 0.8 kJ per minute) • 7.0% increase (SD: 10.5%) • [5.1 – 4.7 kJ per minute = 1,755 – 1,618 kcal per day = 138 kcal per day] In winter: • ambient temperature = 4.7 kJ per minute (SD: 0.7 kJ per minute) • cold environment = 5.3 kJ per minute (SD: 0.9 kJ per minute) • 11.5% increase (SD: 9.1%) • [5.3 – 4.7 kJ per minute = 1,824 – 1,618 kcal per day = 206 kcal per day]
Warwick 1990 (29)	Australia Study dates not stated	N=10 participants (6 females and 4 males)	All subjects were exposed to 2 temperatures (28°C and 20°C) randomly for 24 hours in a calorimetry	24 hours mean energy expenditure: • at 28°C = 8.77 MJ per day (SD: 0.93 MJ per day) • at 20°C = 9.17 MJ per day (SD: 0.67 MJ per day) • p<0.02

Reference	Study location, date	Population	Intervention procedure	Results
		Mean age = 23.1 years (SD: 5.2 years) Mean BMI = 27.6 kg/m^2 (SD: 6.8 kg/m^2)		• mean percentage difference = 5.0% (SD: 5.5 %) • [9.17 – 8.77 MJ per day = 2,192 – 2,096 kcal per day = 96 kcal per day] 24 hours mean energy expenditure (basal metabolic rate): • at 28°C = 1.24 MJ per day (SD: 0.08 MJ per day) • at 20°C = 1.30 MJ per day (SD 0.11 MJ per day) • p<0.02 Daytime energy expenditure (16 hours): • at 28°C = 6.67 MJ per day (SD: 0.67 MJ per day) • at 20°C = 6.97 MJ per day (SD: 0.41 MJ per day) • p<0.05 Overnight energy expenditure (8 hours): • at 28°C = 2.11 MJ per day (SD: 0.31 MJ per day) • at 20°C = 2.20 MJ per day (SD: 0.34 MJ per day) • p<0.05
Wasse 2013 (30)	UK Study date not provided	n=10 healthy, active adult men Mean age: 23 years (SD: 3 years) Mean BMI: 23.1 kg/m^2 (SD: 1.6 kg/m^2)	Data extracted for the 'cool study' only. 1. Two 7-hour trials in an environmental chamber (order randomised) 2. 20°C and 10°C, relative humidity kept constant at 50% 3. Overnight fast, clothing not standardised 4. 60-minute treadmill run at intensity sufficient to elicit 65% of maximal oxygen uptake, followed by 6 hours rest Foods presented in excess of expected consumption at 2 and 5.5 hours and energy intake measured	Mean energy intake increased by 1,450 kJ (SD: 2,345 kJ) in the 10°C condition versus the 20°C condition (time period during which this energy was consumed not specified). [1,450 kJ = 347 kcal excess energy intake over 7 hours at 10°C versus 20°C, potentially equivalent to 1,190 kcal per day]
Westerterp-Plantenga 2002 (31)	Netherlands Study date not provided	n=9 adult men Mean age: 24 years (SD: 5 years) Mean BMI: 22.7 kg/m^2 (SD: 2.1 kg/m^2)	Randomised within-subject design: 1. 3 60-hour experiments in respiratory chamber, 2 at 16°C and one at 22°C 2. Standardised clothing, standardised daily activities protocol, fixed meal and snack times 3. At 22°C and one 16°C experiment, participants were fed in energy balance for the first 24 hours then allowed to eat freely for the second 24 hours (unclear for additional 12 hours)	Mean energy expenditure when participants fed in energy balance: • 22°C: 12.2 MJ per day (SD: 2.2 MJ per day) • 16°C: 12.9 MJ per day (SD: 2.0 MJ per day) • [12.9 – 12.2 = 0.7 MJ per day = 167 kcal per day more energy expenditure during cold exposure when fed at energy balance] Mean energy expenditure when allowed to eat freely: • 22°C: 12.9 MJ per day (SD: 1.9 MJ per day) • 16°C: 13.4 MJ per day (SD: 2.0 MJ per day)

Reference	Study location, date	Population	Intervention procedure	Results
			4. In the additional 16°C experiment participants were fed in energy balance for the whole 60-hour duration Energy expenditure calculated from oxygen consumption and carbon dioxide production via the respiratory chamber.	• [13.4 – 12.9 = 0.5 MJ per day = 120 kcal per day more energy expenditure during cold exposure when allowed to eat freely]
Westerterp-Plantenga 2002 (32)	Netherlands Study date not provided	n=8 healthy adult women Mean age: 23 years (SE: 1.8 years) Mean BMI: 22.2 kg/m^2 (SD: 3.2 kg/m^2)	Randomised within-subject design: 1. Three 48-hour experiments in respiratory chamber, 2 at 27°C and one at 22°C 2. Standardised clothing, standardised daily activities 3. At 22°C and one 27°C experiment, participants were fed in energy balance for the first 24 hours then allowed to eat freely for the second 24 hours 4. In the additional 27°C experiment participants were fed in energy balance for the whole 48-hour duration Energy expenditure calculated from oxygen consumption and carbon dioxide production via the respiratory chamber.	Mean energy expenditure when participants fed in energy balance: • 27°C: 8.9 MJ per day (SD: 1.3 MJ per day) • 22°C: 9.9 MJ per day (SD: 1.5 MJ per day) • [9.9 – 8.9 = 1.0 MJ per day = 239 kcal per day more energy expenditure at 27°C versus 22°C when fed at energy balance] Mean energy expenditure when allowed to eat freely: • 27°C: 9.0 MJ per day (SD: 1.1 MJ per day) • 22°C: 9.9 MJ per day (SD: 1.2 MJ per day) • [9.9 – 9.0 = 0.9 MJ per day = 215 kcal per day more energy expenditure at 27°C versus 22°C when allowed to eat freely]
Wijers 2007 (33)	Netherlands Study dates not stated	n=13 Caucasian males Mean age= 22.7 years (SE: 1.72 years) Mean BMI= 22.96 kg/m^2 (SE: 0.90 kg/m^2)	1. 36 hour in respiration chamber (22°C) with energy balanced diet for baseline measurements 2. 36 hours in respiration chamber with high energy diet (22°C) 3. 84 hours cold exposure in respiration chamber with energy balanced diet (16°C)	Mean total daily energy expenditure (corrected for fat free mass): • baseline = 11.47 MJ per day (SE: 0.11 MJ per day) • high energy diet = 12.23 MJ per day (SE: 0.17 MJ per day) • cold exposure = 12.06 MJ per day (SE: 0.17 MJ per day) • cold exposure compared with baseline: 5.1% increase in energy expenditure (0.59 MJ per day), range: 0% to 14% (-0.19 to 1.58 MJ per day), $p<0.005$ • [12.06 – 11.47 = 0.59 MJ per day = 141 kcal per day more energy expenditure during cold exposure]
Wijers 2008 (34)	Netherlands Study dates not stated	n=11 lean males Mean age= 21.7 years (SE: 0.6 years) Mean BMI= 22.9 kg/m^2 (SE: 0.6 kg/m^2)	1. 34 hours in a thermoneutral environment in a respiration chamber (22°C) 2. 82 hours cold exposure (16°C)	Mean total daily energy expenditure, data extracted from figure: • 22°C = 11.48 MJ per day (SE: 0.23 MJ per day) • 16°C = 11.79 MJ per day (SE: 0.24 MJ per day), • percentage increase = 2.8%, $p<0.05$ • [11.79 – 11.48 = 0.31 MJ per day = 74 kcal per day more energy expenditure during cold exposure]
Wijers 2010 (35)	Netherlands Study dates not stated	n=20 (10 lean and 10 obese) Mean age = 26 years (SE: 1.8 years)	1. 36 hours in a respiration chamber for baseline measurements (22°C) 2. 48 hours cold exposure (16°C)	Total daily energy expenditure (mean): Whole group: • 22°C = 12.17 MJ per day (SE: 0.31 MJ per day) • 16°C = 12.32 MJ per day (SE: 0.28 MJ per day)

Reference	Study location, date	Population	Intervention procedure	Results
		Mean age (lean) = 23 years (SE: 0.8 years) Mean age (obese) = 29 years (SE: 3.2 years) Mean BMI = 28.1 kg/m² (SE: 1.4 kg/m²) Mean BMI (lean) = 22.6 kg/m² (SE: 0.4 kg/m²) Mean BMI (obese) = 33.5 kg/m² (SE: 1.3 kg/m²)		• [12.32 – 12.17 = 0.15 MJ per day = 36 kcal per day more energy expenditure during cold exposure] Lean: • 22°C = 11.35 MJ per day (SE: 0.32 MJ per day) • 16°C = 11.60 MJ per day (SE: 0.32 MJ per day) • p value for comparison <0.05 • [11.60 – 11.35 = 0.25 MJ per day = 60 kcal per day more energy expenditure during cold exposure] Obese: • 22°C = 12.92 MJ per day (SE: 0.40 MJ per day) • 16°C = 12.97 MJ per day (SE: 0.32 MJ per day) • [12.97 – 12.92 = 0.05 MJ per day = 12 kcal per day more energy expenditure during cold exposure] Mean daytime energy expenditure: Whole group: • 22°C = 13.92 MJ per day (SE: 0.35 MJ per day) • 16°C = 14.23 MJ per day (SE: 0.31 MJ per day) • p value for comparison <0.05 • [14.23 – 13.92 = 0.31 MJ per day = 74 kcal per day more energy expenditure during cold exposure] Lean: • 22°C = 13.03 MJ per day (SE: 0.35 MJ per day) • 16°C = 13.47 MJ per day (SE: 0.36 MJ per day) • p value for comparison <0.01 • [13.47 – 13.03 = 0.44 MJ per day = 105 kcal per day more energy expenditure during cold exposure] Obese: • 22°C = 14.73 MJ per day (SE: 0.47 MJ per day) • 16°C = 14.90 MJ per day (SE: 0.39 MJ per day) • [14.90 – 14.73 = 0.17 MJ per day = 41 kcal per day more energy expenditure during cold exposure]

Reference	Study location, date	Population	Intervention procedure	Results
Wijers 2011 (36)	Netherlands Study dates not stated	n=10 lean males Mean age= 23.0 years (SE: 0.8 years) Mean BMI= 22.6 kg/m^2 (SE: 0.4 kg/m^2), range: 20.8 to 24.8 kg/m^2	1. 36 hours in a respiration chamber for baseline measurements (22°C) 2. 48 hours cold exposure (16°C)	Total daily energy expenditure (mean): • 22°C = 131.5 W (SE: 1.1 W) • 16°C = 134.4 W (SE: 1.4 W) • [134.4 – 131.5 = 2.9 W = 60 kcal per day more energy expenditure during cold exposure] Mean daytime energy expenditure: • 22°C = 150.6 W (SE: 1.5 W) • 16°C = 155.7 W (SE: 1.8 W) • [155.7 – 150.6 = 5.1 W = 105 kcal per day more energy expenditure during cold exposure]
Yoneshiro 2011 (37)	Japan January 2009 and March 2009	n=13 males Mean age (BAT positive) = 22.7 years (SD: 3.0 years) Mean age (BAT negative) = 22.9 years (SD: 4.6 years) Mean BMI (BAT positive) = 20.0 kg/m^2 (SD: 2.0 kg/m^2) Mean BMI (BAT negative) = 21.4 kg/m^2 (SD: 1.7 kg/m^2)	1. Seated comfortably in a thermoneutral environment (27°C) 2. 2 hours of cold exposure (cold room) at 19°C with intermittent cooling of legs with ice block for 4 minutes after every 5 minutes 3. Energy expenditure was measured using respiratory gas analyser	Mean energy expenditure: BAT positive group: • 27°C = 1,446 kcal per day (SD: 97 kcal per day) • 19°C = 1,856 kcal per day (SD: 218 kcal per day) • [1,856 – 1,446 = 410 kcal per day more energy expenditure during cold exposure] BAT negative group: • 27°C = 1,434 kcal per day (SD: 246 kcal per day) • 19°C = 1,475 kcal per day (SD: 206 kcal per day) • [1,475 – 1,434 = 41 kcal per day more energy expenditure during cold exposure]
Yoneshiro 2013 (38)	Japan Study dates not stated	n=51 males Mean age = 24.4 years (SE: 0.5 years) Mean BMI = 22.0 kg/m^2 (SE: 0.4 kg/m^2)	1. Thermoneutral temperature at 27°C 2. Two hours cold exposure at 19°C with intermittent cooling of feet with ice block 3. Energy expenditure measured using respiratory gas analyser	Mean energy expenditure, data extracted from figure: BAT positive group: • 27°C = 1,427.7 kcal per day (SE: 21.5 kcal per day) • 19°C = 1,680 kcal per day (SE: 40 kcal per day) • $p<0.001$ • [1,680 – 1,427.7 = 252 kcal per day more energy expenditure during cold exposure] BAT negative group: • 27°C = 1,498.4 kcal per day (SE: 36.9 kcal per day) • 19°C = 1,575.3 kcal per day (SE: 43 kcal per day) • $p<0.05$

Reference	Study location, date	Population	Intervention procedure	Results
				• [1,575.3 – 1,498.4 = 77 kcal per day more energy expenditure during cold exposure]
Yoneshiro 2016 (39)	Japan July 2011 to September 2013	n=45 Mean age= 23.4 years (SE: 0.4 years) Mean BMI (summers) = 21.7 kg/m^2 (SE: 0.4 kg/m^2) Mean BMI (winters) = 21.9 kg/m^2 (SE: 0.4 kg/m^2)	1. Relaxed in an air conditioned room for more than 30 minutes (27°C) 2. 2 hours cold exposure (19°C) with an intermittent cooling of feet with an ice block for 4 minutes after every 5 minutes	Whole body energy expenditure (mean): Summers: • 27°C = 1,494 kcal per day (SE: 20 kcal per day) • 19°C = 1,499 kcal per day (SE: 26 kcal per day) • [1,499 – 1,494 = 5 kcal per day more energy expenditure during cold exposure] Winters: • 27°C = 1,471 kcal per day (SE: 24 kcal per day) • 19°C = 1,631 kcal per day (SE: 25 kcal per day) • $p<0.001$ • [1,631 – 1,471 = 160 kcal per day more energy expenditure during cold exposure]
Zakrzewski-Fruer 2021 (40)	UK January 2016 to January 2017	n=13 males Mean age = 21.5 years (SD: 1.4 years) Mean BMI = 24.7 kg/m^2 (SD: 2.2 kg/m^2)	Participants sat for 5.5 hours in a random order in 3 environmental chambers: 1. Thermoneutral (20°C) 2. Cold (10°C) 3. Hot (30°C)	Mean ad libitum energy intake, data extracted from figure: • thermoneutral environment = 4,634 kJ (SE: 1,320.9 kJ) • cold environment = 4,679 kJ (SE: 1,567.1 kJ) • hot environment = 3,447.7 kJ (SE: 828.3 kJ) • [cold versus thermoneutral: 4,679 – 4,634 = 45 kJ = 11 kcal increased energy intake during one 30-minute meal of pasta] • [cold versus hot: 4,679 – 3,447.7 = 1231 kJ = 294 kcal increased energy intake during one 30-minute meal of pasta]

Table B.2. Experimental studies of the effect of different water filled clothing temperatures on energy expenditure

Reference	Study location, date	Population	Intervention procedure	Results
Acosta 2018 (43)	Spain March 2016 to April 2016	n=11 Caucasian male adults Mean age: 23 years (SD: 2 years) Mean BMI: 23.1 kg/m^2 (SD: 1.2 kg/m^2)	1. Reclined in warm room (22.7°C, SD: 0.2°C) for 40 minutes 2. Reclined in cool room (19.4°C, SD: 0.1°C) for 15 minutes 3. Wore water perfused cooling vest (initially 16.6°C, reduced by 1.4°C every 10 minutes) until shivering occurred Resting energy expenditure was estimated by indirect calorimetry (gas exchange)	Mean time: • 31% of cold exposure: 28 minutes (SD: 8 minutes) • 64% of cold exposure: 59 minutes (SD: 17 minutes) • to shivering: 88 minutes (SD: 26 minutes) Mean difference in resting energy expenditure, compared to the warm room: • 31% of cold exposure: 263 kcal per day (95% CI: 24 to 551 kcal per day) • 64% of cold exposure: 235 kcal per day (95% CI: 47 to 423 kcal per day) • to shivering: 500 kcal per day (95% CI: 64 to 936 kcal per day)
Acosta 2021 (44)	Spain December 2017 to February 2018	n=14 adults (n=5 women, n=9 men) Mean age: 26 years (SD: 3 years) Mean BMI: 23.6 kg/m^2 (SD: 2.8 kg/m^2)	First day: 1. Warm room (22 to 23°C) for 30 minutes 2. Supine in cool room (19.5 to 20°C) for 15 minutes 3. Wore water perfused cooling vest (initially 16.6°C, reduced by 1.4°C every 10 minutes) until shivering occurred Second and third days (randomised to be in the morning or evening): 1. Ate standardised meal 10 hours previously 2. Supine in warm room (22 to 23°C) for 50 minutes 3. Supine in cool room (19.5 to 20°C), and wore water perfused cooling vest (set at 4°C above individual shivering temperature) for one hour 4. Cooling vest was increased by 1°C if shivering occurred, until shivering ceased Resting energy expenditure was estimated by indirect calorimetry (gas exchange)	Resting energy expenditure: Morning: • warm room: 1 kcal per minute (SD: 0.19 kcal per minute) • by end of cold exposure: 1.24 kcal per minute (SD: 0.3 kcal per minute) • $p < 0.001$ • [1.24 – 1 = 0.24 kcal per minute more in cold exposure = 345.6 kcal per day] Evening: • warm room: 1.03 kcal per minute (SD: 0.16 kcal per minute) • by end of cold exposure: 1.23 kcal per minute (SD: 0.3 kcal per minute) • $p=0.005$ • [1.23 – 1.03 = 0.20 kcal per minute more in cold exposure = 288 kcal per day]
Blondin 2015 (45)	Canada Study date not provided	n=25 men (n=6 adults with well-controlled type 2 diabetes [A], n=7 age-matched controls with similar weight and BMI [B], n=12 healthy young men from a previous study [C], original data presented for 13 out of the 25 participants)	19 of the participants underwent 2 experimental conditions in a random order separated by an average of 20 days. 6 participants underwent a single experimental condition only. 1. 12-hour fast 2. Wearing shorts only	Mean energy expenditure: Group with type 2 diabetes: • at room temperature: 1.2 kcal per minute (95% CI: 1.0 to 1.4 kcal per minute) • during cold exposure: 2.2 kcal per minute (95% CI: 1.9 to 2.5 kcal per minute)

Reference	Study location, date	Population	Intervention procedure	Results
		Mean age group A: 60 years (95% CI: 56 to 64 years) Mean age group B: 59 years (95% CI: 56 to 62 years) Mean age group C: 24 years (95% CI: 22 to 26 years) Mean BMI group A: 28.6 kg/m^2 (95% CI: 21.5 to 35.8 kg/m^2) Mean BMI group B: 26.3 kg/m^2 (95% CI: 24.7 to 28.9 kg/m^2) Mean BMI group C: 25.4 kg/m^2 (95% CI: 23.6 to 27.3 kg/m^2)	3. Liquid conditioned tube suit perfused using a temperature and flow-controlled circulation bath to minimise overt shivering 4. 120 minutes at ambient temperate (23 to 25°C) 5. 18°C for 5 hours 6. Shivering intensity and metabolic outcomes measured, amongst others 7. Data from final 30 minutes of ambient temperature and final 120 minutes of cold exposure reported Energy expenditure measured using indirect respiratory calorimetry.	• [3,168 – 1,728 = 1,440 kcal per day more energy expenditure during cold exposure] Age-matched controls: • at room temperature: 1.2 kcal per minute (95% CI: 1.1 to 1.3 kcal per minute) • during cold exposure: 2.0 kcal per minute (95% CI: 1.6 to 2.4 kcal per minute) • [2,880 – 1,728 = 1,152 kcal per day more energy expenditure during cold exposure] Healthy young men: • at room temperature: 1.6 kcal per minute (95% CI: 1.4 to 1.8 kcal per minute) • during cold exposure: 2.9 kcal per minute (95% CI: 2.5 to 3.4 kcal per minute) • [4,176 – 2,304 = 1,872 kcal per day more energy expenditure during cold exposure]
Chondronikola 2015 (46)	US Study date not stated	N=12 adult males BAT+ (those with detectable brown adipose tissue) (n=7): • Mean age: 41.2 years (SE: 5.3 years) • Mean BMI: 28.2 kg/m^2 (SE: 1.5 kg/m^2) BAT- (those without detectable brown adipose tissue) (n=5): • Mean age: 49.8 years (SD: 7.3 years) • Mean BMI: 30.0 kg/m^2 (SE: 2.8 kg/m^2)	Resting energy expenditure was measured using indirect calorimetry under 2 conditions: 1. Under thermoneutral (19°C) conditions 2. During cold exposure, 1°C above shivering, using garments cooled by liquid circulation	Resting energy expenditure BAT-, data extracted from figure: • thermoneutral: 1,683 kcal per day • cold exposure: 1,751 kcal per day • [1,751 – 1,683 = 68 kcal per day more energy expenditure during cold exposure] Resting energy expenditure BAT+, data extracted from figure: • thermoneutral: 1,760 kcal per day • cold exposure: 1,981 kcal per day (15% increase, $p < 0.05$) • [1,981 – 1,760 = 221 kcal per day more energy expenditure during cold exposure]
Din 2016 (47)	Finland Study date not provided	n=7 healthy adults (n=2 women, n=5 men) Mean age: 36 years (SD: 11 years)	Two experimental conditions: 1. Room temperature (approximately 22°C) 2. Cold exposure using cooling blankets (initially set to 6°C but temperature gradually raised once shivering occurred)	Mean whole body energy expenditure: • room temperature: 1,702 kcal per day (SD: 282 kcal per day) • cold temperature: 2,052 kcal per day (SD: 574 kcal per day) • [2,052 – 1,702 = 350 kcal per day more energy expenditure in cold exposure]

Reference	Study location, date	Population	Intervention procedure	Results
		Mean BMI: 25.5 kg/m^2 (SD: 3.3 kg/m^2)	Whole body energy expenditure measured using indirect calorimetry.	
Gashi 2019 (48)	Switzerland February 2016 to February 2018	N=18 adults (n=8 women, n=10 men) Mean age: 26 years (SD: 7.5 years) Mean BMI: 23 kg/m^2 (SD: 2.8 kg/m^2)	Energy expenditure was measured while the participant was in a supine position under 2 experimental conditions: 1. In an ambient temperature (24°C) for 30 minutes 2. During the last 30 minutes of 120 minutes of cold exposure using a cooling jacket with a water-circulated cooling system. Temperature was a minimum of 10°C, or 2°C above shivering Energy expenditure measured using indirect calorimetry (COSMED Quark RMR)	Mean energy expenditure: • 24°C: 1,648 kcal per day (SD: 354 kcal per day) • after cold exposure: 1,795 kcal per day (SD: 396 kcal per day) • increase in energy expenditure of 8.9% after cold exposure (P=0.0002) • [1,795 – 1,648 = 147 kcal per day more energy expenditure in cold exposure]
Haman 2002 (49)	Canada Study date not stated	n=6 healthy, physically trained men Mean age: 25 years (SE: 1.5 years) Mean BMI: not provided	1. Standardised evening meal 2. Sat quietly for 2 hours (28°C) 3. Transferred to environmental chamber (11°C) wearing a liquid conditioned suit (10°C) for 2 hours Heat production estimated using heat flux transducers.	Shivering activity appeared minimal for the first 60 minutes of cold exposure then increased progressively over the latter 60 minutes. Mean heat production in warm (28°C) versus cold (10°C) conditions: • 28°C: 95.3 W (SE: 2.2 W) • 10°C: 243.8 W (SE: 4.2 W) • [5,035 – 1,968 = 3,067 kcal per day more heat production in cold exposure]
Haman 2005 (50)	Canada Study date not stated	n=8 healthy men Mean age low intensity shivering group: 25 years (SE: 1.5 years) Mean age high intensity shivering group: 23 years (SE: 0.4 years) Mean BMI: not provided	1. Standardised evening meal 2. Seated in ambient conditions (25.5°C, 45% relative humidity) 3. Transferred to environmental chamber (5.7°C) wearing a liquid conditioned suit (5°C) for 90 minutes 4. Shivering intensity and metabolic outcomes measured Heat production estimated using indirect respiratory calorimetry corrected for protein oxidation.	Mean heat production in warm (25.5°C) versus cold (5°C) conditions: • 25.5°C: 89.5 W (SE: 3.5 W) • 5°C: 292.1 W (SE: 18.2 W) • [6,031 – 1,848 = 4,183 kcal per day more heat production in cold exposure]
Kovanicova 2020 (51)	Austria (Cohort 2 only) Study date not provided	n=6 (n=1 woman, n=5 men, all cold-water swimmers) Mean age 37 years (SD: 4 years) Mean BMI 25.1 kg/m^2 (SD: 5.0 kg/m^2)	1. More than 10 hour overnight fast 2. Resting energy expenditure measured at room temperature (warm: 24°C) and after a personalised cooling protocol for 150 minutes (energy expenditure measured after 90 minutes cold exposure) using a water-perfused cooling vest kept slightly above shivering temperature (mean: 6.5°C, SD: 3.4°C) Energy expenditure measured using a computerised open-circuit indirect calorimeter.	Mean resting metabolic rate: • warm condition: 1,720 kcal per day (SD: 300 kcal per day) • cold condition: 1,830 kcal per day (SD: 294 kcal per day) • [1,830 – 1,720 = 110 kcal per day more energy expenditure in cold condition]

Reference	Study location, date	Population	Intervention procedure	Results
Loeliger 2021 (52)	Switzerland June 2017 to February 2018	n=17 healthy male volunteers Mean age: 23 years (SD: 3 years) Mean BMI: 23.2 kg/m^2 (SD: 1.7 kg/m^2)	Data prospectively collected as part of an interventional trial. 1. 30 minutes of resting, dressed in T-shirt and shorts in an air-conditioned room (24°C) 2. Participants covered with a fleece blanket during measurement of energy expenditure to ensure brown adipose tissue not activated 3. Water circulated cooling system placed around midsection, lowering temperature in 1°C per minute increments from 25 to 10°C 4. If shivering occurred, temperature was increased by 2°C and not decreased further 5 After 90 minutes of cooling, energy expenditure measured again (lasting 30 minutes) Cold-induced thermogenesis measured by indirect calorimetry (difference between energy expenditure in the warm and cold conditions).	Mean energy expenditure: • warm conditions (24°C): 1,908 kcal per day (SD 181 kcal per day) • cold conditions (10°C if tolerated, otherwise cooled to just above shivering threshold): 2,128 kcal per day (SD: 277 kcal per day) • energy expenditure rose by 11.5% in cold condition versus warm • [2,128 – 1,908 = 220 kcal per day more energy expenditure in the colder condition]
Mengel 2020 (53)	Germany October 2016 to May 2018	N=117 adults (n=59 women, n=58 men) Mean age: 25.1 years (SD: 3.6 years) Mean BMI: 22.3 kg/m^2 (SD: 1.7 kg/m^2)	Resting energy expenditure (30 minutes) was measured under 2 conditions: 1. Bedded between 2 water perfused blankets set to thermoneutral temperature (32°C) 2. After 2 hours bedded between 2 water perfused mattresses set at 2°C above shivering Resting energy expenditure was estimated using indirect calorimetry using a hood system (COSMED Quark RMR)	Median resting energy expenditure (all): • thermoneutral (32°C): 1,568 kcal per day (IQR: 1,388 to 1,742 kcal per day) • after 2 hours cold exposure: 1,687 kcal per day (IQR: 1,476 to 1,938 kcal per day) • change in resting energy expenditure between conditions: 103 kcal per day (IQR: -6 to 274 kcal per day), 6.5% (-0.4 to 19.4%) • $p < 0.001$ Median resting energy expenditure (women): • thermoneutral (32°C): 1,408 kcal per day (IQR: 1,260 to 1,531 kcal per day) • after 2 hours cold exposure: 1,500 kcal per day (IQR: 1,369 to 1,688 kcal per day) • change in resting energy expenditure between conditions: 114 kcal per day (IQR: -7 to 283 kcal per day), 7.4% (-0.5 to 20.5%) • $p < 0.001$ Median resting energy expenditure (men): • thermoneutral (32°C): 1,742 kcal per day (IQR: 1,626 to 1,871 kcal per day)

Reference	Study location, date	Population	Intervention procedure	Results
				• after 2 hours cold exposure: 1,880 kcal per day (IQR: 1,693 to 2,024 kcal per day) • change in resting energy expenditure between conditions: 88 kcal per day (IQR: 18 to 262 kcal per day), 5.1% (1.1 to 14.6%) • p < 0.001 No significant difference between men and women (p=0.908)
Mengel 2022 (54)	Germany October 2016 to April 2019	N=170 adults (n=87 women, n=83 men) Median age: 26 years (IQR: 23 to 28 years) Median BMI: 23.6 kg/m^2 (IQR: 21.9 to 26.6 kg/m^2) Stratified by BMI category: Normal weight (n=117 adults. n=59 women, n=58 men): Median age: 25 years (IQR: 23 to 27 years) Median BMI: 22.6 kg/m^2 (IQR: 21.3 to 23.7 kg/m^2) Overweight (n=27. n=13 women, n=14 men): Median age: 27 years (IQR: 25 to 28.5 years) Median BMI: 26.8 kg/m^2 (IQR: 26.2 to 27.8 kg/m^2) Obese (n=26. n=15 women, n=11 men): Median age: 28 years (IQR: 26 to 31.8 years) Median BMI: 34.1 kg/m^2 (31.7 to 36.3 kg/m^2)	Resting energy expenditure (REE) (30 minutes) was measured under 2 conditions: 1. Bedded between 2 water perfused blankets set to thermoneutral temperature (32°C, although this was lowered if temperature was sensed as too warm) 2. After 2 hours bedded between 2 water perfused mattresses set at 2°C above shivering REE was estimated using indirect calorimetry using a hood system (COSMED Quark RMR)	Median resting energy expenditure (all): • thermoneutral (32°C): 1,619 kcal per day (IQR: 1,438 to 1,818 kcal per day) • after 2 hours cold exposure: 1,700 kcal per day (IQR: 1,503 to 1,934 kcal per day) • p <0.001 • high inter-individual variability • [1,700 – 1,619 kcal per day = 81 kcal per day] Stratified by BMI category: • normal weight: increase in REE of 6.5% following cold exposure compared to thermoneutral (p < 0.001) • overweight: little change in REE following cold exposure compared to thermoneutral (1.6%, p=0.468) • obese: little change in REE following cold exposure compared to thermoneutral (-1.7%, p=0.917) • p value for differences between group < 0.001

Reference	Study location, date	Population	Intervention procedure	Results
Niclou 2022 (55)	US During May to October (2018) and February to April 2019 (Winter)	N=58 adults Summer (n=37 women, n=21 men): Mean age: Women 26.8 years (SD: 7.1 years); Men 31.2 years (SD: 7.0 years) Mean BMI: Women 26.9 kg/m^2 (SD: 5.4 kg/m^2); Men 28.4 kg/m^2 (SD: 4.1 kg/m^2) Winter (n=27 women, n=15 men): Mean age: Women 27.7 years (SD: 8.3 years); Men 30.1 years (SD: 8.8 years) Mean BMI: Women 27.0 kg/m^2 (SD: 5.3 kg/m^2); Men 28.6 kg/m^2 (SD: 3.8 kg/m^2)	Participants were measured during the summer months (where outdoor temperatures were consistently more than 15°C), and in the winter months (where outdoor temperatures were consistently below 10°C). Resting energy expenditure was measured under 2 conditions in both summer and winter: 1. Thermoneutral (20 to 27°C) for 30 minutes 2. Cold exposure (15 to 18°C) from wearing cooling suits pumped with cold water for 30 minutes. If participants started to shiver, then warm water was added until shivering stopped	Mean resting energy expenditure in summer in women: • cold exposure: 1,793 kcal per day (SD: 457 kcal per day) • thermoneutral (1,534 kcal per day (SD: 391 kcal per day) • $p < 0.001$ • [1,793 – 1,534 = 259 kcal per day more energy expenditure in cold condition] Mean resting energy expenditure in summer in men: • cold exposure: 1,997 kcal per day (SD: 506 kcal per day) • thermoneutral: 1,905 kcal per day (SD: 474 kcal per day) • $p=0.587$ • [1,997 – 1,905 = 92 kcal per day more energy expenditure in cold condition] Mean resting energy expenditure in winter in women: • cold exposure: 1,857 kcal per day (SD: 475 kcal per day) • thermoneutral: 1,629 kcal per day (SD: 374 kcal per day) • $p <0.001$ • [1,857 – 1,629 = 228 kcal per day more energy expenditure in cold condition] Mean resting energy expenditure in winter in men: • cold exposure: 2,080 kcal per day (SD: 645 kcal per day) • thermoneutral: 1,919 kcal per day (SD: 615 kcal per day) • $p=0.264$ • [2,080 – 1,919 = 161 kcal per day more energy expenditure in cold condition] Resting energy expenditure did not significantly differ between seasons for males and females nor for the sample overall ($p=0.766$ at thermoneutrality, $p=0.862$ at mild cold exposure)
Ouellet 2012 (56)	Canada Study date not stated	N=6 adult men Age range: 23 to 42 years BMI range: 23.7 to 31.0 kg/m^2	Total energy expenditure was calculated using indirect calorimetry under 2 conditions: 1. Room temperature (approximately 25°C) for 120 minutes 2. While wearing a liquid-conditioned tube suit with water perfused at 18°C for 150 minutes	• mean total energy expenditure at 25°C was 1.80 kcals per minute (SE: 0.08 kcals per minute) [2,592 kcals per day, SE: 115 kcal per day] • mean total energy expenditure during cold exposure was 3.19 kcal per minute (SE: 0.31 kcals per minute) [4,597 kcal per day, SE: 446 kcal per day]

Reference	Study location, date	Population	Intervention procedure	Results
				• [4,597 – 2,592 = 2,005 kcal per day more energy expenditure in cold condition]
Salem 2016 (57)	UK Study date not stated	N=11 adult men Mean age: 26.1 years Mean BMI: 22.5 kg/m^2	Resting energy expenditure was measured under the following conditions: 1. At room temperature (22 to 25°C) 2. While wearing a cooling vest, cooled with water at 8°C	Compared to baseline cold exposure increased resting energy expenditure by approximately 14% (193.0 kcal per day, SD: 27.2 kcal per day)
Scott 1988 (58)	UK Study date not stated	n=12 patients with diabetic autonomic neuropathy n=12 non-diabetic subjects n=11 patients without diabetic autonomic neuropathy Mean age: 43 years (range: 28 to 55 years) for patients with diabetic autonomic neuropathy, 35 years (range: 23 to 54 years) for non-diabetic subjects and 34 years (range: 17 to 46 years) for patients without diabetic neuropathy BMI range: 22.1 to 28.7 kg/m^2 of patients with diabetic neuropathy, 19.5 to 29.4 kg/m^2 of non-diabetic subjects, 20.4 to 31.7 kg/m^2 of patients without diabetic neuropathy	1. Temperature controlled laboratory (25 to 26°C) for one hour 2. Subjects placed supine in water perfused coverall at room temperature for baseline measurements for more than 30 minutes 3. Suit was perfused with cold water (16°C) at 1.5L per minute for 45 minutes Metabolic rate was measured by indirect calorimetry	Mean baseline metabolic rate: • patients with diabetic autonomic neuropathy who shivered: 6.1 kJ per minute (SD: 0.6 kJ per minute) [2,099 kcal per day, SD: 207 kcal per day] • patients with diabetic autonomic neuropathy who did not shiver: 4.90 kJ per minute (SD: 0.6 kJ per minute) [1,686 kcal per day, SD: 207 kcal per day] • diabetic patients without neuropathy = 5.2 kJ per minute (SD: 0.2 kJ per minute) [1,790 kcal per day, SD: 69 kcal per day] • non-diabetic subjects = 5.2 kJ per minute (SD: 0.2 kJ per minute) [1,790 kcal per day, SD: 69 kcal per day] Percentage increase in metabolic rate on cooling (at 30 minutes): • patients with diabetic autonomic neuropathy who shivered = 30% • patients with diabetic autonomic neuropathy who did not shiver = 10% ($p < 0.02$) • diabetic patients without neuropathy = 13% ($p<0.02$) • non-diabetic subjects = 9% ($p<0.02$)
Sellers 2021 (59)	Netherlands January 2019 to November 2019	n=17 White European male Mean age: 26 years (SD: 5 years) Mean BMI: 23.9 kg/m^{-2} (SD: 2.5 kg/m^{-2})	1. Baseline: 1 hour at 32°C 2. Experiment 1: cold exposure (10°C) via water-perfused with individual variations to achieve shivering for 1 hour 3. Experiment 2: rest at thermoneutral environment (32°C) in the water perfused suit, time-matched to cold exposure condition Mean duration of cold exposure: 76 minutes (SD: 2 minutes), range 70 to 95 minutes	Mean energy expenditure: • cold exposure including time until shivering until 1 hour of shivering: 717kJ (SD: 31 kJ), range: 539 to 948 kJ • equivalent duration thermoneutral exposure: 392 kJ (SD: 17 kJ), range 305 to 537 kJ • [717 – 392 = 325 kJ = 78 kcal over a mean of 76 minutes = approximately 1,440 kcal per day more energy expenditure across entirety of cold condition] • one hour of shivering only: 619 kJ (SD: 23 kJ), range 451 to 735 kJ ($p < 0.001$)

Reference	Study location, date	Population	Intervention procedure	Results
				• one hour thermoneutral exposure = 309 kJ (SD: 7 kJ), range 266 to 360 kJ • [619 – 309 = 301 kJ per hour = 1,727 kcal per day more energy expenditure when shivering]
Senn 2018 (60)	Switzerland April 2016 to January 2018	n= 56 (11 female and 44 male) Mean age: 25.91 years (SD: 5.75 years), range 18 to 47 years Mean BMI: 22.99 kg/m^2 (SD: 2.15 kg/m^2)	1. Participants were covered with a fleece blanket in supine position at 24°C 2. Cold exposure via water circulated cooling system around patient's midsection (10°C) for 90 to 120 minutes	• mean energy expenditure during cold exposure = 1,888 kcal per day (SD: 350.1 kcal per day) • mean energy expenditure during warm environment = 1,768 kcal per day (SD: 278.2: kcal per day) • [1,888 - 1,768 = 120 kcal per day more energy expenditure in cold condition]
Straat 2022 (61)	Netherlands December 2019 to December 2020	n=24 (12 male and 12 female) Male age range: 18 to 31 years Female age range: 18 to 29 years Male BMI range: 18 to 26 kg/m^2 Female BMI range: 18 to 26 kg/m^2	1. 45 minutes in thermoneutral environment (32°C) 2. 90 minutes cold exposure via lying between 2 mattresses filled with water (reduced by 5°C every 10 minutes until shivering or minimum temperature of 9°C) Energy expenditure was assessed by indirect calorimetry	All data extracted from figure. Mean energy expenditure in morning (males): • thermoneutral = 1,810 kcal per day (SE: 103 kcal per day) • cooling down = 2,174 kcal per day (SE: 98 kcal per day) • plus 60 minutes = 2,489 kcal per day (SE: 182 kcal per day) • end cooling = 2,734 kcal per day (SE: 157 kcal per day) • [2,734 - 1,810 = 924 kcal per day more energy expenditure in end cooling compared with thermoneutral] Mean energy expenditure in morning (females): • thermoneutral = 1,636 kcal per day (SE: not presented) • cooling down = 2,081 kcal per day (SE: 103 kcal per day) • plus 60 minutes = 2,206 kcal per day (SE: 141 kcal per day) • end cooling = 2,234 kcal per day (SE: 147 kcal per day) • [2,234 - 1,636 = 598 kcal per day more energy expenditure in end cooling compared with thermoneutral] Mean energy expenditure in evening (males): • thermoneutral = 1,854 kcal per day (SE: 84 kcal per day) • cooling down = 2,169 kcal per day (SE: 103 kcal per day) • plus 60 minutes = 2,385 kcal per day (SE: 157 kcal per day) • end cooling = 2,410 kcal per day (SE: 162 kcal per day) • [2,410 - 1,854 = 556 kcal per day more energy expenditure in end cooling compared with thermoneutral]

Reference	Study location, date	Population	Intervention procedure	Results
				Mean energy expenditure in evening (females): • thermoneutral = 1,630 kcal per day (SE: not presented) • cooling down = 2,196 kcal per day (SE: 141 kcal per day) • plus 60 minutes = 2,130 kcal per day (SE: 141 kcal per day) • end cooling = 2,109 kcal per day (SE: 147 kcal per day) • [2,109 - 1,630 = 479 kcal per day more energy expenditure in end cooling compared with thermoneutral] Increase in cold induced energy expenditure in males (mean): • morning = 54% (SE: 10%) • evening = 30% (SE: 7%), p=0.05 Increase in cold induced energy expenditure in females (mean): • morning = 37% (SE: 9%) • evening = 30% (SE: 10%), p=0.42
Vijgen 2011 (62)	Netherlands Study dates not stated	n=15 (2 males and 13 females) Mean age: 39.2 years (SD: 8.1 years), range 24 to 51 years Mean BMI: 42.1 kg/m^2 (SD: 3.8 kg/m^2), range 34.8 to 48.3 kg/m^2	1. One hour in mean room temperature (22.3°C) 2. One hour cold exposure via cooling mattress until shivering (Mean temperature 14.7°C, lowest possible temperature 12°C)	Mean energy expenditure: • thermoneutral environment = 41.9 J/s (SD: 3.3 J/s) • cold exposure = 43.7 J/s (SD: 4.8 J/s) • p=0.100 • [43.7 – 41.9 = 1.8 J/s = 37 kcal per day more energy expenditure in cold condition]

Table B.3. Modelling studies of the difference in energy expenditure in different temperatures

Reference	Study location, date	Population	Methods	Results
Nahon 2017 (63)	Netherlands Study date not stated	N=40 adult men (n=20 lean, n=20 overweight or obese) Age range: 18 to 55 years BMI range: 17.2 to 31.5 kg/m^2	Resting energy expenditure was measured under the following conditions: 1. Lying between 2 water-perfused mattresses at thermoneutral temperature (27 to 32°C) 2. Lying between 2 water-perfused mattresses for cold exposure (9°C or 3 to 4°C above shivering) Model: The model used to compare heat loss rates in cold in relation to basal metabolic rate was the Scholander-Irving model (64). Based on the above measures of energy expenditure at thermoneutrality and cold exposure.	• the estimated cold induced thermogenesis at 15°C was lower in overweight or obese individuals (449 kcals per degree C per day, SE: 58 kcals per degree C per day) than in lean participants (724 kcals per degree C per day, SE: 77 kcal per degree C per day, p=0.0042) • for each degree of cold exposure, lean individuals increased their metabolic rates by 7.0% (SE: 0.3%), while overweight did so by 5.9% (SE: 0.2%) (p=0.0016) • consistently, when temperature was modelled to 15°C, the lean group was estimated to increase heat production by 32.2% (SE: 2.7%), in comparison to only 20.5% (SE: 2.3%) in overweight (p=0.0011)

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