Proceedings of the Nutrition Society

cambridge.org/pns

The Nutrition Society Scottish Section Conference 2024 was held at the University of Aberdeen on 26th–27th March 2024

Conference on 'Circadian rhythms in health and disease'

Symposium Three: Circadian systems in disease

Review Article

Cite this article: Flanagan A (2025). Is the timing of eating relevant for weight loss? *Proceedings of the Nutrition Society*, page 1 of 9. doi: 10.1017/S0029665124007547

Received: 29 May 2024
Revised: 5 September 2024
Accepted: 27 September 2024

Keywords:
Weight loss; Timing of eating; Meal timing; Metabolism; Chrono-nutrition

Corresponding author:
Alan Flanagan;
Email: alan.flanagan@surrey.ac.uk

Is the timing of eating relevant for weight loss?

Alan Flanagan[1,2,3]

[1]Department of Nutritional Sciences, Faculty of Health and Medical Science, University of Surrey, Guildford, Surrey GU2 7XH, UK; [2]Section of Chronobiology, Faculty of Health and Medical Science, University of Surrey, Guildford, Surrey GU2 7XH, UK and [3]NNEdPro Global Institute for Food, Nutrition & Health, Cambridge CB4 0WS, UK

Abstract

The potential influence of the timing of eating on body weight regulation in humans has attracted substantial research interest. This review aims to critically evaluate the evidence on timed eating for weight loss, considering energetic and behavioural components of the timing of eating in humans. It has been hypothesised that timed eating interventions may alter energy balance in favour of weight loss by enhancing energy expenditure, specifically the thermic effect of food. This energetic effect has been suggested to explain greater weight loss which has been observed with certain timed eating interventions, despite comparable self-reported energy intakes to control diets. However, timed eating interventions have little impact on total daily energy expenditure, and the apparent effect of time of day on the thermic effect of food largely represents an artefact of measurement methods that fail to account for underlying circadian variation in RMR. Differences in weight loss observed in free-living interventions are more likely explainable by real differences in energy intake, notwithstanding similar self-reported energy intakes. In addition, the energetic focus tends to overlook the role of behavioural factors influencing the timing of eating, such as appetite regulation chronotype-environment interactions, which may influence energy intake under free-living conditions. Overall, there is scant evidence that timed eating interventions are superior to general energy restriction for weight loss in humans. However, the role of behavioural factors in influencing energy intake may be relevant for adherence to energy-restricted diets, and this aspect remains understudied in human intervention trials.

In the 1970s Franz Halberg and his group at the University of Minnesota were the first to suggest an interaction in humans between the timing of eating, 'chrono-metabolism', and bodyweight regulation[1–3]. Their work compared the effects of a single daily meal comprising either a fixed 2000 kcal or *ad libitum* energy intake, consumed either 1 h or 12 h after waking, respectively. During both the fixed and *ad libitum* energy conditions, the morning meal resulted in greater weight loss compared to the later meal[2,3]. During the *ad libitum* condition, weight gain was observed in some participants when consuming a single daily meal 12 h after waking, for three consecutive weeks[2]. However, a 1986 paper by Sensi and Capani[4] that compared very low-energy diets (684 kcal/d) consumed either at 10.00 or 18.00, respectively, found no significant differences in weight loss between the respective timed eating conditions. Nevertheless, the hypothesis that timed eating may, to quote a 1989 Halberg review, '*have important implications regarding the ability to obtain "more for less" in a world of persistent hunger . . .* ' found favour based on the limited data at the time[1]. With the benefit of the current evidence base, is it possible to conclude that timed eating interventions provide 'more for less' for weight loss? This review aims to critically evaluate whether timed eating interventions offer an advantage for weight loss in humans, considering components of energy balance and behavioural mediators of the timing of energy intake.

Conceptual and methodological challenges in timing of eating research

Heterogenous definitions of 'meal timing' may be found in the literature[5–7]. This may reflect the fact that 'meal timing' encompasses two distinct but related concepts, i.e. the definition of 'meal' and the definition of 'timing'. The concept of a 'meal' remains primarily defined by pre-defined labels such as 'breakfast', 'lunch' and 'dinner', which are insufficient to capture the nutritional characteristics of those meals, including the time of day at which they may occur[7,8]. In addition, general definitions such as 'morning', 'afternoon' and 'evening', are insensitive to both the clock (i.e. external) time and circadian (i.e. internal) time (see Table 1 for definitions), including their interaction, at which eating within those periods may occur[6]. The definitions of 'timing' also vary substantially and may include the clock time at which eating occasions occur and related underlying circadian timing, the temporal distribution of total daily energy intake, the inter-day regularity of the timing of eating, the intra-day frequency of eating occasions and duration between eating occasions, and/or the total duration of the daily period of eating[5,6].

Table 1 Definitions of abbreviations and terminology

Abbreviation/Term	Definition
Clock time	The external time of day represented by time on the clock in the 24-hour day
Circadian time	The 'biological clock' or internal time representing an individual's endogenous circadian rhythms, which may vary between individuals according to their precise phase of alignment with external clock time
TDEI	Total daily energy intake
TDEE	Total daily energy expenditure
RMR	RMR
TEF	Thermic effect of food
PAT	Physical activity thermogenesis
CBT	Core body temperature
TRE	Time-restricted eating, generally defined as restricting the daily period of eating to < 12 h but with different possible temporal eating windows
eTRE	Early time-restricted eating, generally defined as an eating window between ~06.00–08.00 to ~14.00–16.00
mTRE	Midday time-restricted eating, generally defined as an eating window between ~12.00–13.00 to ~20.00–21.00
CRE	Continuous energy restriction, daily energy restriction with no limits on eating duration or intermittent fasting periods.

A comprehensive recent review by O'Connor *et al.*[5] summarised the heterogeneous definitions of the timing of eating applied in 136 nutritional epidemiological studies and 126 intervention trials. The timing of eating was most commonly defined in both epidemiology and intervention studies as the clock time of eating. Of note, intervention trials often considered multiple definitions of 'timing', with duration and timepoint, duration and distribution, or distribution and timepoint the most commonly utilised combinations. Given the overall evidence indicates that temporal eating patterns in humans exhibit within-person, between-person, within-population and between-population variation[6], the need for standardised operational definitions for meal/eating timing, and the development of dietary assessment instruments specifically validated to capture the timing of eating, is crucial to developing a rigorous and coherent evidence-base for the timing of eating and human health outcomes[5]. Where possible, the present review expresses the timing of eating as clock time if this was presented in the primary study.

Timing of eating and bodyweight in humans: energetic and behavioural hypotheses

Broadly, we may delineate two hypothesis-driven avenues of inquiry into the potential relevance of timed eating for weight loss and/or management. The first is the energetic hypothesis, i.e. that timed eating alters energy balance by influencing energy intake and/or expenditure. An important element of the energetic hypothesis has been the suggestion that greater weight loss may be observed with certain timed eating regimens independent of total daily energy intake (TDEI) (Table 1)[9,10]. In turn, to explain differences in weight loss which appear to be independent of TDEI, the core theory within the energetic hypothesis has related to energy expenditure, specifically that the thermic effect of food (TEF) may be enhanced by timed eating interventions that result in greater proportional energy intake early in the day compared to later[10–12]. Such a time-of-day effect of TEF, if indeed a real effect, would imply a role for the human circadian system[13], the endogenous biological timing system which regulates temporal physiological and metabolic processes in synchrony with the 24-hour external environment[6,14,15]. For example, several controlled trials have found a ~1·5–2·5-fold greater TEF response to meals consumed at breakfast (corresponding to the biological morning in circadian time) compared to dinner (the biological evening in circadian time)[12,13,16]. The evidence supporting the energetic hypothesis of timed eating for weight loss will be critically discussed by reference to available human intervention trials, below.

The second may be characterised as the behavioural hypothesis, i.e. that behavioural factors mediate any relationship between timed eating and body weight regulation. It is important to note that the behavioural and energetic hypotheses are not mutually exclusive, but related, as insofar as behavioural factors mediate a relationship with timed eating and weight loss, it is likely through influencing reductions in TDEI. Behavioural factors may also relate to circadian biology, for example in the behavioural correlates related to an individual's 'chronotype'[17,18], and diurnal variation in hunger and appetite regulation[19–21]. Chronotype denotes an individual's behavioural expression of sleep-wake timing preferences, often colloquially referred to as 'morning larks' or 'night owls', related to the period of their internal biological time[22]. This latter characteristic indicates that chronotype is conceptualised as a biological construct, strongly influenced by genetic factors and reflecting endogenous circadian timing, rather than a psychological construct or trait[23]. In particular, associations between evening chronotypes and redistribution of energy and macronutrient intake to later in the wake cycle[18,24], suggest a potential behavioural influence of chronotype on time-of-day energy intake that may be relevant for weight management. The extent to which behavioural factors related to timed eating may influence weight loss is expanded in later sections.

Timing of eating and energy balance: energy expenditure

Total daily energy expenditure (TDEE) is comprised of three components; RMR, physical activity thermogenesis (PAT; including exercise and non-exercise activity thermogenesis), and the TEF[25]. RMR constitutes the largest component (~60–70 %), while TEF contributes the least at ~10 %, and PAT constitutes the most

https://doi.org/10.1017/S0029665124007547 Published online by Cambridge University Press

variable component at ~30–40 % depending on activity level[25]. All three components may be influenced by dietary energy intake; RMR exhibits decreases or increases as a function of energy balance relative to, respectively, loss or gains in body fat-free mass[25], while PAT may vary according to body size and composition, and energy balance, in particular restricted energy intake[25,26]. TEF, as the postprandial energy expenditure arising from the digestion, utilisation and storage of nutrients, represents the primary influence of diet on TDEE, and the absolute magnitude of TEF may be influenced by variation in diet composition[27].

In 1993, Romon *et al.*[16] demonstrated diurnal variation in the magnitude of postprandial TEF in response to a standardised test meal consumed at 09.00, 17.00, or 01.00, in which TEF as a proportion of the energy content of the meal was, respectively, 15·9 % (sd ± 1·6 %), 13·5 % (±1·8 %) and 10·9 % (±2·2 %). This generated a long-standing interest in the potential for time-of-day effects of TEF to provide a 'metabolic advantage' for influencing energy balance and body weight regulation. For example, in an randomised controlled trial (RCT) from Jakubowicz *et al.*[10] which showed 2·5–fold greater weight loss with high-energy intake at breakfast (700 kcal, 06.00–09.00) compared to a high-energy intake at dinner (700 kcal, 18.00–21.00), the authors suggested, citing Romon *et al.*[16], that greater TEF responses to the high-energy breakfast may have influenced body weight differences between the two conditions. This hypothesis was subsequently supported by repeated findings of significantly greater TEF responses to early compared to later energy intake. Morris *et al.*[13] demonstrated that 'early TEF', i.e. confined to measurements over ~114 min postprandial, was 44 % higher in the morning compared to the evening, indicating a circadian timing effect. Comparing identical standardised test meals consumed at either 08.00 or 20.00, Bo *et al.*[11] found that TEF responses were ~28 % lower following the evening meal. Richter *et al.*[12] compared TEF in response to both high-energy meals (69 % of TDEI) and low-energy meals (11 % of TDEI) consumed at 09.00 and 19.00, respectively, and found that the TEF response to the 09.00 breakfast was 2·5 times greater compared to the 19.00 dinner, irrespective of high or low-energy content. These lines of evidence collectively appeared to support the hypothesis that greater weight loss observed with high-energy intake in the morning reflected the apparent energetic advantage of TEF responses at that time of day.

However, this purported effect of TEF on weight loss related to high early/morning energy distribution does not appear to stand up to detailed scrutiny. The first point in this regard is that TEF comprises the smallest component of TDEE and while relative differences in TEF between a morning and evening meal may, particularly when expressed as a percentage, appear substantial, the absolute differences in TEF are minor, e.g. ~14 kcal (over 120 min postprandial measures) in Richter *et al.*[12], and ~12 kcal (over 114 min of postprandial measurements) in Morris *et al.*[13]. Bo *et al.*[11] expressed TEF as calories per kilogram of fat-free mass in their participants, with a morning-evening difference of 1·8 kcal/kg/fat-free mass (measured over 60 min). Even extrapolating these absolute differences to an entire postprandial period that may last for up to 6 h[28], or a full 24-hour day, these differences in TEF are insufficient to explain differences in weight loss associated with early energy intake in the magnitudes observed in free-living studies[9,10,29]. A controlled, in-patient metabolic ward intervention by Ravussin *et al.*[30] which compared isocaloric diets of three meals per day consumed either between a 6-hour (08.00–14.00) early time-restricted eating (eTRE) condition or a 12-hour (08.00–20.00) control condition, is illustrative of this point. While the proximity of energy intake in the condensed 6-hour eTRE condition did result in elevated postprandial TEF in response to the second and third meals, this effect was transient and ultimately amounted to a difference in 24-hour TDEE of just ~10 kcal[30]. The fact that there were no significant differences in TDEE provides evidence against the contention that minor and transient differences in TEF would be sufficient to manipulate energy balance in favour of weight loss in humans.

The second point against the potential role of diurnal variation in TEF in weight loss is, however, arguably more fundamental as it relates to the methods by which large diurnal differences in TEF have been demonstrated. Oscillating diurnal rhythms in resting respiratory metabolism were identified as early as 1973, with the implication that such variation, if unaccounted for, could confound measures of postprandial metabolism[31]. In 2018, Zitting *et al.*[32] demonstrated a robust circadian rhythm in RMR, with the nadir in RMR corresponding to the nadir of core body temperature (CBT) at ~05.00, and the peak corresponding to the peak in CBT at ~17.00. The nadir-to-peak difference of ~129 kcal is of such a magnitude that any RMR measure at a given clock time would be superimposed over meaningful time-of-day variance in underlying RMR. We have recently shown that the methods by which TEF is calculated and resulting values for postprandial energy expenditure are inextricably linked to underlying variation in RMR (Fig. 1(a) and (b))[33]. TEF is typically calculated as the incremental AUC in postprandial energy expenditure over and above a preceding measure of RMR. However, the timing of the RMR measurement which is used as the 'baseline' for the calculation, above which postprandial energy expenditure is calculated, has a crucial influence on the calculated TEF value. Uniformly, the research showing large diurnal variation in TEF has calculated TEF as the postprandial energy expenditure above an RMR measured immediately preceding a meal, irrespective of the timing of the meal[11–13]. This method, however, has the effect of resulting in a TEF calculation for a first meal which is above a fasted basal RMR measure, while the RMR measured preceding subsequent meals is inflated both from the energy intake at prior meal(s) and/or the underlying circadian RMR value at the specific clock time of the measurement[33]. Consequently, this method results in lower values for TEF calculated postprandial to lunch and dinner, reflecting the overinflated value of the RMR measure immediately preceding those respective meals. Another method is to calculate TEF responses to all meals, irrespective of the clock time at which they occur, as the postprandial energy expenditure above the first fasted RMR measure[16,30]. While this method abolishes the artefact in TEF values from calculations based on immediate pre-meal RMR measures for meals following breakfast, it introduces another source of error in assuming that the value for the fasted RMR represents a constant value across the day, when as stated RMR exhibits circadian variance[31,32].

Using data from Zitting *et al.*[32] to model underlying circadian changes in RMR across the day, we have demonstrated that any apparent differences in TEF are unlikely to reflect any true variation in postprandial energy expenditure, but represent an artefact of underlying circadian variance in RMR (Fig. 1(a) and (b))[33]. Our analysis, as part of the Big Breakfast Study[34], utilised energy expenditure measurements taken over a full 16-hour day, including 5 h of postprandial energy expenditure following three isocaloric meals (consumed 1-, 6- and 11 h after waking, respectively), to calculate TEF responses to each meal according to each aforementioned method; above the RMR immediately preceding each meal ('pre-meal RMR method');

https://doi.org/10.1017/S0029665124007547 Published online by Cambridge University Press

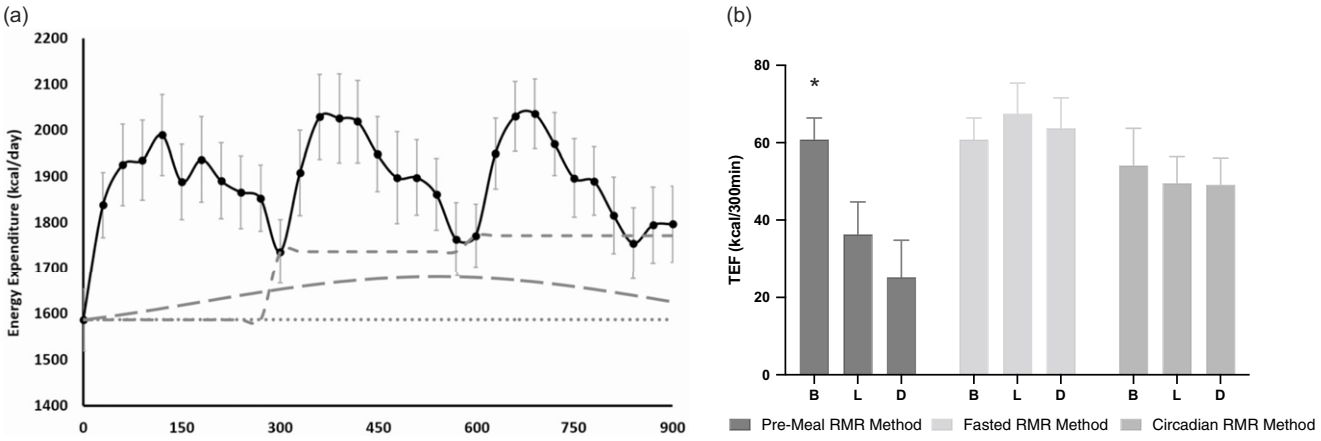

Figure 1. (a) Energy expenditure (solid black line) measured fasted for 30 min immediately after waking and over subsequent 15 h (900 min) following three isocaloric (33 % total daily energy intake) test meals: breakfast 1 h after waking (0 min); lunch 5 h after breakfast (300 min); dinner 5 h after lunch (600 min). Grey lines represent the underlying RMR for different calculation methods: dotted line represents the 'fasted RMR method', i.e. constant underlying RMR; short grey dashes represent the 'pre-meal RMR method', i.e. underlying RMR inflated from carryover energy of preceding meals and underlying circadian variance in RMR; long grey dashes represent the 'circadian RMR method', variation in underlying RMR across the day. (b) Thermic effect of food (TEF) responses to the same isocaloric test meals measured over 5 h (300 min) postprandial, calculated according to the pre-meal RMR method, the fasted RMR method and the circadian RMR method, respectively. All data are presented as means and se. Fig. 1(a) and data for Fig. 1(b) from Ruddick-Collins *et al.*[33], reproduced with permission.

above the fasted baseline RMR only ('fasted RMR method'); and as the postprandial energy expenditure above the modelled underlying circadian RMR value ('circadian RMR method')[33]. Calculating TEF according to the pre-meal RMR method replicated the findings of previous research using this method[11–13], showing a 2·4-fold greater TEF response following breakfast compared to dinner (Fig. 1(b)). The fasted RMR method abolished this apparent diurnal difference and significant between-meal effect of TEF but resulted in higher absolute values for TEF for each meal compared to the circadian RMR method. Finally, the circadian RMR method not only abolished the apparent diurnal variation in TEF but further attenuated the magnitude of the postprandial TEF estimates relative to the fasted RMR method (Fig. 1(b)). Thus, TEF is not a component of TDEE that may be manipulated by timed eating strategies to influence energy balance and is likely of little importance in the context of weight loss and weight management.

This lack of effect of timed eating on energy expenditure and weight loss has been further confirmed by the related findings from the Big Breakfast Study RCT[20] which accounted for all components of energy balance by controlling the energy intake of participants and measuring energy expenditure using the doubly labelled water technique, the gold standard for free-living energy expenditure measurements[35]. The intervention compared two temporal energy distributions, a sequence of 45 %, 35 % and 20 % energy at breakfast (~08.00), lunch (~13.00), and dinner (~18.30), respectively, compared to the inverse of 20 %, 35 % and 45 % energy, respectively, for four weeks. TDEE was unaffected by the distribution of energy intake and there was no difference in TDEE between the two conditions, and at matched, controlled, hypocaloric energy intakes, weight loss was practically identical at −3·33 kg and −3·38 kg (se diff., 0·51) in the high morning energy and high evening energy diets, respectively. The similar magnitude of weight loss between diets corresponded to a similar magnitude of decrease in RMR, as would be anticipated from energy restriction and weight loss[36–38], with RMR thus unaffected by the respective energy distributions. This extended the findings of Ravussin *et al.*[30] that showed no significant effect of eTRE on TDEE, thus it appears that temporal energy distribution patterns do not alter RMR in humans.

As the final component of TDEE, it should be noted that PAT was assessed in the Bath Breakfast Project[39,40], an RCT which compared the consumption of > 700 kcal before 11.00, with at least 50 % within 2 h of waking, to fasting until lunch, in both lean participants and participants with obesity. While PAT was elevated in the high-energy breakfast group compared to fasting until noon, the increase was proportional to the additional energy intake in the breakfast group, thus maintaining energy balance[39]. The increase in PAT was only observed concurrently with the additional morning energy intake compared to the fasted morning group, with no differences beyond 12.00 following the onset of eating in the morning fasting group, and no significant differences in whole-day PAT[40]. Thus, the short-term elevations in PAT were proportional to the greater energy intake in the breakfast group, maintaining energy balance and demonstrating a lack of overall difference in PAT between the respective timed eating regimens in the Bath Breakfast Project[39,40].

Cumulatively, there is little evidence that timed eating interventions exert any meaningful effect on individual components of energy expenditure or TDEE, in humans. However, the fact that several trials have reported greater weight loss despite similar self-reported energy intakes[10,29,41], warrants further scrutiny.

Timing of eating and energy balance: energy intake

Energy balance in humans is a function of exogenous dietary energy intake and endogenous energy expenditure requirements for physiological functions and activity, and the relationship between intake, expenditure and energy storage[42]. Thus, the stability, net gain, or net loss, of body mass is relative to whether energy intake is, respectively, equivalent to, surplus to, or in deficit to, the energy level required for expenditure[42]. While this energy balance principle is fundamental to human nutrition, a multiplicity of factors may influence the ultimate state of energy balance,

https://doi.org/10.1017/S0029665124007547 Published online by Cambridge University Press

including biological, behavioural, social, economic and environmental factors[42–49]. Nevertheless, it is important to emphasise in the context of weight loss that the essential principle, established for up to 60 years, holds that at a constancy of energy intake and relatively constant physical activity, the rate of weight loss is relatively unaffected by dietary modifications[50]. This is important to reiterate as a guiding interpretative principle for considering the potential effect of timed eating interventions on weight loss, i.e. whether there is a biologically plausible explanation for differences in weight loss observed between timed eating interventions and a comparative/control group, but with similar self-reported energy intakes[9,10,51]. Given the well-established systematic bias and underestimation of energy intake in self-reported dietary assessment methods[52,53] and the fact that nutrition intervention trials seldom adjust for energy misreporting, differences in weight loss should be considered an indication of differences in self-reported energy intake[54,55].

Two papers published in the same year, 2013, showed that participants consuming a greater proportion of energy intake earlier had significantly greater weight loss compared to those consuming energy later in the day[9,10]. The first was an observational analysis of female participants consuming their largest energy meal of the day at lunch (~40 % TDEI), which categorised participants as 'early eaters' or 'late eaters' depending on whether they consumed that meal before or after, respectively, the median reported time of 15.00[9]. Despite similar self-reported energy intake, the early eaters lost ~2·2 kg more total weight over 20 weeks compared to the late eaters. The findings, however, were primarily hypothesis-generating given the observational nature of the design. However, the second study by Jakubowicz *et al.*[10] cited previously showed in an RCT that women with overweight/obesity in the high-energy breakfast group lost −8·7 kg (± 1·4 kg) compared to −3·6 kg (± 1·5 kg) in the high-energy dinner group, despite similar self-reported energy intakes.

The fact that the latter trial was an RCT invites the assumption that the difference in weight loss between diet groups was the downstream effect of the intervention, i.e. was independent of other potential causes of the outcome[56,57]. However, this assumes that no post-randomisation differences *but for* the addition of the intervention are introduced between groups, which may be an untenable assumption for many free-living diet RCTs given that changes in dietary intake and behaviours may occur in both intervention and control groups[58]. In particular, modelled differences in free-living energy intake, based on the energy balance principle of estimated energy intakes as a function of dynamic changes in weight[54], may be present post-randomisation even with no significant differences in self-reported energy intakes between comparative diet groups[59]. The energy balance principle, i.e. that changes in body mass reflect the balance between energy intake from food and daily energy expenditure, remains fundamental to human nutrition[42,55]. Thus, in the absence of control of energy intake, mathematically modelled changes in energy intake may provide more representative assessments of changes in energy intake during an intervention and correlate strongly with observed changes in bodyweight[55,59].

This principle holds important implications for timed eating research as it indicates that the most parsimonious explanation for differential weight loss in a free-living context is differences in energy intake, similar self-reported energy intake notwithstanding. As a case study in point, Jamshed *et al.*[51] randomised participants with obesity to an 8-hour eTRE intervention or a ≥ 12-hour eating duration control, with both groups counselled to achieve the same energy restriction of 500 kcal/d. Over 14 weeks the eTRE group lost 2·3 kg (95 % CI, −3·7, −0·9 kg), despite a self-reported difference of 1 kcal/d. However, applying energy intake-balance modelling[55] to participants with repeated bodyweight measurements showed an average decrease in energy intake in the eTRE group of ~214 kcal/d greater than the control group. This additional energy deficit would be sufficient to explain the differential weight loss observed between groups[51]. Similarly, the TREAT trial randomised participants with overweight/obesity to either time-restricted eating (TRE; 12.00–20.00) or a conventional meal timing (CMT; 3 main meals between 06.00–10.00; 11.00–15.00; 17.00–22.00, respectively), with no limitations on energy intake or dietary prescriptions provided[60]. The intervention was delivered through a mobile app, and participants were provided with a Bluetooth weight scale to weigh weekly, which the app would record. Over 12 weeks there was no significant difference in weight loss between groups, with weight loss of 0·94 kg (95 % CI, −1·68, −0·20 kg) and 0·68 kg (95 % CI, −1·41, 0·05 kg) in the TRE and CMT groups, respectively. Using the same energy intake-balance modelling approach[54,59] based on the at-home scale weight measurements, there were no significant differences in estimated energy intake between the TRE and CMT groups[60].

Other TRE research is indicative of the issue of the validity of energy intake assessments related to weight loss in human RCTs. A 5-week trial by Xie *et al.*[61] compared an eTRE (06.00–15.00) and midday TRE (mTRE; 12.00–20.00) against a control group with a habitual daily eating window of > 8 h. Compared to the control group, the eTRE group lost 1·6 kg (± 1·4 kg) while the mTRE group lost 0·2 kg (± 2·2 kg), despite relatively estimated decreases in energy intake (−240 kcal/d and −159 kcal/d for eTRE and mTRE, respectively). However, energy intake was estimated from food photographs using an unvalidated methodology, with the potential for misestimations of energy intake and no adjustments for the potential measurement error. The differential in weight loss likely reflects differences in energy intake, with greater reductions in energy intake in the eTRE group[61]. Conversely, Liu *et al.*[62] compared prescribed 25 % energy restriction with additional eTRE (08.00–16.00) to 25 % continuous energy restriction (CER, i.e. daily energy restriction with no limits on eating duration) alone over 1 year of intervention; achieved weight loss was similar between groups at ~7–8 % initial body weight while self-reported energy intake was also similar. A recent meta-analysis by Schroor *et al.*[63] provided an instructive synthesis of the relationship between TRE, weight loss and reported energy intakes. Based on six included trials, the summary estimate was −0·93 kg (95 % CI, −1·69, −0·17 kg) greater weight loss in the TRE group compared to CER. However, the included primary trials reported either no differences in weight loss and no differences in energy intake[64,65], or no differences in energy intake but greater weight loss in the TRE groups[51,66,67], one of which was the Jamshed *et al.*[51] trial where the lack of differences in energy intake was no longer evident after correction for weight loss modelling. Such discrepancies between the included trials preclude any inference that the magnitude of the effect between TRE and CER was independent of energy intake[63]. Further, the point estimate of < 1 kg of weight loss and confidence intervals < 2 kg places the entire range of the effect estimate far short of clinically meaningful thresholds (i.e. a minimum of 5 %) for weight loss[68,69], and thus of questionable validity for clinical practice. Taken together, TRE interventions appear to influence weight loss through influencing reductions in energy intake, but there is little to no additional weight loss

https://doi.org/10.1017/S0029665124007547 Published online by Cambridge University Press

advantage to TRE compared to CER at the same magnitude of energy restriction[51,60,62,63].

The evidence for other timed eating interventions exhibits similar characteristics. A 1997 review of human eating frequency research found that, among seven experimental interventions, six showed no significant difference in weight loss across a range from 1–9 meals per day[70]. In particular, as no differences in energy expenditure were observed between eating frequencies, the authors emphasised that any effect of meal frequency on weight loss was explained by energy restriction, and the frequency of eating had no significant impact on the rate of weight loss under hypocaloric conditions. A 2020 network meta-analysis of the effect of eating frequency included 22 RCTs, of which 13 had prescribed energy-restricted diets[71]. Compared to ≥ 8/d 'meals', there were no significant effects of 1/d, 3/d, 4/d, or 6/d meals. 2/d meals, however, showed a decrease in weight of −1·32 kg (95 % CI, −2·19, −0·45 kg) when compared to ≥ 8/d meals, −1·29 kg (95 % CI, −1·74, −0·84 kg) compared to 6/d meals, and −1·02 kg (95 % CI, −1·70, −0·35 kg) compared, 3/d meals. However, this effect of the 2/d meal frequency appeared to be mediated by energy restriction, with a sensitivity analysis confined to hypocaloric studies indicating that decreases in weight evident for the 2/d meals condition were explained by energy restriction. More particularly, the entire range of the effect estimates for the 2/d eating frequency were of an insufficient magnitude to be considered clinically relevant for weight loss[68,69]. A more recent 2023 systematic review and meta-analysis of eating frequency from Blazey *et al.*[72] included 16 RCTs that compared either 'low' (≤ 3/d) or 'high' (≥ 4/d) meal frequencies. Based on eight trials that met the criteria for meta-analysis, there was no significant difference in weight loss observed, with a mean difference of −0·62 kg (95 % CI, −2·75, 1·52 kg). The trials included in the meta-analysis included three with prescribed energy deficits, four trials with prescribed energy balance, and one with an unclear energy prescription. Overall, there is little to no evidence that eating frequency modifies weight loss independent of restricted energy intake.

However, arguably the form of timed eating intervention, other than TRE, that has received the most attention is the temporal distribution of energy, in particular high morning/breakfast energy intake[10,29,41]. Lombardo *et al.*[29] reported that distribution of ~35 %, 35 % and 30 % energy intake at breakfast, lunch and dinner, respectively (no data provided on clock time), resulted in an 8·2 kg (± 3·0 kg) weight loss compared to weight loss of 6·5 kg (± 3·4 kg) on a 20 %, 35 % and 45 % energy distribution, respectively. Similar to the Jakubowicz *et al.*[10] trial, the difference showed by Lombardo *et al.*[29] was also observed in the context of similar self-reported energy intakes. Conversely, in the Bath Breakfast Project, while the breakfast group consumed more TDEI compared to the extended fasting group, this was reflected in a proportional increase in TDEE, such that energy balance was maintained and there was no difference in weight after 6 weeks in either lean or participants with obesity[39,40]. However, methodologically the Big Breakfast Study supersedes prior evidence given that energy intake was controlled with full provision of meals to participants tailored to individual energy-restriction requirements[20]. As highlighted in the previous section, weight loss was practically identical at ~3·3 kg over four weeks between the morning-loaded and evening-loaded diets, matched for energy intakes. Thus, with control over energy intake, any apparent differences in weight loss from timed eating interventions are no longer evident.

Behavioural mediators of time-of-day energy intakes

While timed eating interventions may not lead to greater weight loss under conditions of controlled energy intake, in the free-living context in which individuals are required to achieve weight loss, behavioural factors which influence energy intake may act as important mediators of weight loss and management. In particular, appetite regulation appears to exhibit time-of-day variation which may be influenced by the timing of energy intake. In the Big Breakfast Study[20], the high morning energy condition exhibited significantly reduced subjective appetite ratings, both acutely in response to an in-laboratory test breakfast comparing 45 % to 20 % meal energy, and over three days of hourly subjective appetite ratings during the high morning energy and high evening energy diets, respectively. This corresponded with greater suppression of ghrelin and elevations in gastrointestinal incretin hormones related to satiety, such as glucagon-like peptide 1 (GLP-1) and gastric inhibitory polypeptide (GIP)[20]. Suppression of ghrelin, lower subjective appetite and greater subjective satiety associated with higher energy intake in the morning have previously been shown in the context of hypocaloric weight loss interventions[10,41], and also with an eTRE (08.00–14.00) intervention conducted in energy balance[30]. It is interesting to note that GLP-1 and GIP have previously been shown to exhibit diurnal variation, with greater responsiveness to a test meal consumed at 08.00 compared to the same isocaloric meal consumed at 17.00[73].

The potential for enhanced appetite regulation associated with earlier temporal energy distribution may reflect diurnal variation in appetite[21], and a tendency for greater proportions of energy consumed in the evening to be positively associated with TDEI[74,75]. Scheer *et al.*[21] demonstrated a circadian rhythm in subjective hunger and appetite, increasing over the day with a peak at a clock time of ~20.00. Such rhythms in subjective appetite may explain why satiety appears to decrease over the course of the day[76]. Using a metric known as the satiety ratio, reflecting the duration between meals relative to the energy content of the preceding meal, de Castro showed that the satiety ratio was highest in the morning and declined steadily over the remainder of the day[76]. This could explain why greater earlier temporal distribution of energy appears to exert an influence on appetite over the rest of the day[10,20,41], i.e. mitigating against a pattern of increasing meal size over the day, and a shorter duration between meals as the day progresses, combining with higher evening subjective appetite to promote overeating. In a rigorous recent in-patient laboratory study using a crossover design, Vujović *et al.*[19] compared two meal schedules, one with isocaloric meals consumed 1-, 5- and 9-hours, respectively, after wake time and the other a delayed schedule with meals consumed 5-, 9- and 13-hours, respectively, after wake time. Despite the isocaloric energy content of the diets, the later meal schedule resulted in significantly elevated subjective hunger and appetite scores, decreased 24-hour leptin levels and a 34 % increase in the ratio of leptin to ghrelin during waking hours, all indicative of dysregulated appetite regulation associated with later temporal meal timing[19].

Such time-of-day associations may provide a more plausible explanation for the difference in weight loss observed with high-energy intake at breakfast compared to dinner in previous trials[10,29,41]. However, some caution is required against the temptation to fill in evidential gaps. In the wider literature on the relationship between appetite regulation and weight loss, it remains unclear whether interventions targeting appetite enhancement improve weight loss outcomes[77,78]. Differences in subjective

https://doi.org/10.1017/S0029665124007547 Published online by Cambridge University Press

appetite ratings may be present independent of significant differences in weight loss between intervention and control groups[77]. In the SATIN study, which was not a specific timed eating intervention but aimed to assess the effects of a satiety-enhancing diet on weight loss, there were weak inverse correlations ($r = -0{\cdot}33$) between appetite suppression scores and weight loss and maintenance[78]. Further, elevated subjective appetite and hunger hormones do not appear to correlate with weight regain[79,80]. These evidential gaps highlight some potential disconnects in the hypothesised chain of causation, which is that reduced appetite leads to reduced energy intake, which leads to improved body weight regulation. In the context of timed eating interventions, it should be noted that the potential for such interventions to influence weight loss through enhanced appetite regulation remains to be directly tested as an *a priori* hypothesis. In the Big Breakfast Study[20], the controlled and isocaloric diets meant that any effect of appetite on enhancing weight loss could not be demonstrated. Thus, to what extent any diurnal variation in appetite regulatory hormones, and subjective appetite and satiety, may influence energy intake and weight loss, remains to be directly tested in human intervention trials.

Other novel research opportunities exist, particularly with regard to the relationship between circadian typology and behavioural factors. As a behavioural phenotype, chronotype has attracted interest in potential relationships with personality traits[81]. In particular, chronotype exhibits associations with Big Five Factor Inventory (BFI) personality traits, with early chronotypes ('morning larks') tending to correlate with traits like conscientiousness and agreeableness, while late chronotypes ('night owls') show stronger correlations with traits such as neuroticism and extraversion[81,82]. A late chronotype has been associated with several negative health-related behaviours, including low diet quality, higher prevalence of smoking, and less physical activity[17,18]. In addition, BFI personality traits such as conscientiousness have been associated with breakfast consumption, and chronotype has been shown to mediate the relationship between attitudes toward breakfast consumption and personality traits[83]. Breakfast consumption also correlates strongly with wider health-promoting behaviours[84], therefore the potential for chronotype to mediate relationships between behaviours and time-of-day energy intake preferences may have important implications for health outcomes[83,84]. Specifically, chronotype may influence time-of-day energy intake, given associations between evening chronotypes and a tendency to redistribute energy and macronutrient intake later in the wake cycle[18,24]. This may be relevant given that several cross-sectional studies have demonstrated an association between energy intake close to dim-light melatonin onset, a marker of endogenous circadian timing used to determine chronotype, and higher adiposity[85–87]. However, the relevance of any potential interaction in the context of weight loss has yet to be tested in a human intervention.

Thus, the extent to which chronotype may mediate relationships between chronotype, timing of eating, weight loss and management, remains unclear. Xiao *et al.*[88] investigated the associations between chronotype, meal timing and obesity in a U.S. cohort, and found that increasing levels of energy consumed within 2 h of waking were only associated with lower odds of obesity in early chronotypes, while neither higher nor lower energy intake within 2 h of waking was protective in late chronotypes. Late chronotypes also exhibited a ~5-fold (OR 4·94; 95 % CI, 1·61, 15·14) higher odds of overweight and obesity associated with the highest quintile of energy intake within 2 h of bedtime[88]. This suggests that chronotype may mediate associations between time-of-day energy intake and health outcomes. The lower odds for overweight/obesity associated with high morning energy intake in early chronotypes observed by Xiao *et al.*[88] may reflect a correlation between chronotype and meal timing with a genetic heritability component. Lopez-Minguez *et al.*[89] investigated the heritability of food timing among 56 pairs of monozygotic and dizygotic female twins, which showed 56 % and 38 % heritability for breakfast and lunch timing, respectively, but no such heritability was found for dinner timing. This suggests that, while earlier temporal energy intake may have a strong genetic component, evening energy intake may be influenced by behavioural factors and preferences[89]. However, to date, there is a dearth of interventions specifically testing the potential interaction between chronotype, the timing of eating and weight loss. In one such RCT published in 2020 by Galindo Muñoz *et al.*[90], a control diet of CER was compared against the same prescription of energy restriction, but with the distribution of energy-adjusted according to individual chronotype. Thus, early chronotypes consumed 40 %, 40 % and 20 % energy between breakfast, lunch and dinner, respectively, while late chronotypes consumed 30 %, 45 %, and 25 % energy between breakfast, lunch and dinner, respectively[90]. Both the CER and chronotype-adjusted diet groups achieved a significant weight loss of 7–8 kg, with a between-group difference of –1 kg (95 % CI, –1·4, –0·06 kg) in favour of the chronotype-adjusted diet. Thus, the magnitude of the difference is unconvincing. A further protocol for a similar chronotype-adjusted diet RCT was published this year, for which we await the results[91]. At this juncture, however, the evidence in relation to behavioural mediation of chronotype remains suggestive but lacks the probity to come to any confident conclusions.

Conclusions

Insofar as timed eating interventions may be effective for weight loss, this effect is proportional to the magnitude of energy restriction and is not superior to CER when matched for hypocaloric energy intakes. Manipulations of eating duration or distribution of energy confer no additional energetic advantage in the form of enhanced TEF, PAT or TDEE. The apparent diurnal difference in TEF between morning and evening meals represents an artefact of the method of calculating TEF, when in fact underlying circadian rhythms in RMR better explain such apparent time-of-day differences in TEF. Consequently, evidence is lacking for time-of-day variation in TEF that would be of any relevance, as a component of TDEE, for weight loss and management. In relation to behavioural mediators of time-of-day energy intake, however, the existing evidence offers potential for timed eating interventions directed toward specific behavioural mediators, such as appetite regulation or behavioural correlates of chronotype, to be further investigated and directly tested as *a priori* hypotheses.

Acknowledgements. A.F. would like to thank the organisers of the Scottish Section Conference 2024 for the speaker invitation. With thanks to Prof Alexandra M. Johnstone, Prof Jonathan D. Johnston, Dr Leonie Ruddick-Collins, Prof Peter J. Morgan, Dr Barbara Fielding and the Big Breakfast Study academic and clinical research teams.

Authorship. A.F. wrote the manuscript and related editing and is responsible for the final contents.

https://doi.org/10.1017/S0029665124007547 Published online by Cambridge University Press

Financial support. This review received no specific grant from any funding agency, commercial or not-for-profit sectors. The Big Breakfast Study was funded by a Medical Research Council grant (MR/P012205/1).

Competing interests. There are no competing interests to declare.

References

1. Halberg F (1989) Some aspects of the chronobiology of nutrition: more work is needed on 'When to Eat'. *J Nutr* **119**, 333–343.
2. Jacobs H, Thompson M, Halberg E, *et al.* (1975) Relative body weight loss on limited free-choice meal consumed as breakfast rather than dinner. *Chronobiologia* **2**, 33.
3. Hirsch E, Halberg F, Goetz FC, *et al.* (1975) Body weight change during 1 week on a single daily 2000-calorie meal consumed as breakfast (B) or dinner (D). *Chronobiologia* **2**, 31–32.
4. Sensi S & Capani F (1987) Chronobiological aspects of weight loss in obesity: effects of different meal timing regimens. *Chronobiol Int* **4**, 251–261.
5. O'Connor SG, O'Connor LE, Higgins KA, *et al.* (2024) Conceptualization and assessment of 24-h timing of eating and energy intake: a methodological systematic review of the chronic disease literature. *Adv Nutr* **15**, 100178.
6. Flanagan A, Bechtold DA, Pot GK, *et al.* (2021) Chrono-nutrition: from molecular and neuronal mechanisms to human epidemiology and timed feeding patterns. *J Neurochem* **157**, 53–72.
7. Leech RM, Worsley A, Timperio A, *et al.* (2015) Understanding meal patterns: definitions, methodology and impact on nutrient intake and diet quality. *Nutr Res Rev* **28**, 1–21.
8. Mäkelä J, Kjærnes U, Ekström MP, *et al.* (1999) Nordic meals: methodological notes on a comparative survey. *Appetite* **32**, 73–79.
9. Garaulet M, Gómez-Abellán P, Alburquerque-Béjar JJ, *et al.* (2013) Timing of food intake predicts weight loss effectiveness. *Int J Obes* **37**, 604–611.
10. Jakubowicz D, Barnea M, Wainstein J, *et al.* (2013) High caloric intake at breakfast *v.* dinner differentially influences weight loss of overweight and obese women. *Obesity* **21**, 2504–2512.
11. Bo S, Fadda M, Castiglione A, *et al.* (2015) Is the timing of caloric intake associated with variation in diet-induced thermogenesis and in the metabolic pattern? A randomized cross-over study. *Int J Obes* **39**, 1689–1695.
12. Richter J, Herzog N, Janka S, *et al.* (2020) Twice as high diet-induced thermogenesis after breakfast *v.* dinner on high-calorie as well as low-calorie meals. *J Clin Endocrinol Metab* **105**, dgz311.
13. Morris CJ, Garcia JI, Myers S, *et al.* (2015) The human circadian system has a dominating role in causing the morning/evening difference in early diet-induced thermogenesis. *Obesity (Silver Spring)* **23**, 2053–2058.
14. Ruddick-Collins LC, Morgan PJ & Johnstone AM (2020) Mealtime: a circadian disruptor and determinant of energy balance? *J Neuroendocrinol* **32**, 1–18.
15. Johnston JD, Ordovas JM, Scheer FAJL, *et al.* (2016) Circadian rhythms, metabolism, and chrononutrition in rodents and humans. *Adv Nutr* **7**, 399–406.
16. Romon M, Boulenguez C & Frimat P (1993) Circadian variation of diet-induced thermogenesis. *Am J Clin Nutr* **57**, 476–480.
17. Maukonen M, Kanerva N, Partonen T, *et al.* (2016) The associations between chronotype, a healthy diet and obesity. *Chronobiol Int* **33**, 972–981.
18. Kanerva N, Kronholm E, Partonen T, *et al.* (2012) Tendency toward eveningness is associated with unhealthy dietary habits. *Chronobiol Int* **29**, 920–927.
19. Vujović N, Piron MJ, Qian J, *et al.* (2022) Late isocaloric eating increases hunger, decreases energy expenditure, and modifies metabolic pathways in adults with overweight and obesity. *Cell Metab* **34**, 1486–1498.e7.
20. Ruddick-Collins LC, Morgan PJ, Fyfe CL, *et al.* (2022) Timing of daily calorie loading affects appetite and hunger responses without changes in energy metabolism in healthy subjects with obesity. *Cell Metab* **34**, 1472–1485.e6.
21. Scheer FAJL, Morris CJ & Shea SA (2013) The internal circadian clock increases hunger and appetite in the evening independent of food intake and other behaviors. *Obesity* **21**, 421–423.
22. Roenneberg T, Wirz-Justice A & Merrow M (2003) Life between clocks: daily temporal patterns of human chronotypes. *J Biol Rhythms* **18**, 80–90.
23. Roenneberg T, Pilz LK, Zerbini G, *et al.* (2019) Chronotype and social jetlag: a (self-) critical review. *Biology (Basel)* **8**, 54.
24. Maukonen M, Kanerva N, Partonen T, *et al.* (2019) Chronotype and energy intake timing in relation to changes in anthropometrics: a 7-year follow-up study in adults. *Chronobiol Int* **36**, 27–41.
25. Westerterp KR (2017) Control of energy expenditure in humans. *Eur J Clin Nutr* **71**, 340–344.
26. Taylor HL & Keys A (1950) Adaptation to caloric restriction. *Science (1979)* **112**, 215–218.
27. Westerterp-Plantenga MS, Rolland V, Wilson SA, *et al.* (1999) Satiety related to 24 h diet-induced thermogenesis during high protein/carbohydrate *v.* high fat diets measured in a respiration chamber. *Eur J Clin Nutr* **53**, 495.
28. Reed GW & Hill JO (1996) Measuring the thermic effect of food. *Am J Clin Nutr* **63**, 164–169.
29. Lombardo M, Bellia A, Padua E, *et al.* (2014) Morning meal more efficient for fat loss in a 3- month lifestyle intervention. *J Am Coll Nutr* **33**, 198–205.
30. Ravussin E, Beyl RA, Poggiogalle E, *et al.* (2019) Early time-restricted feeding reduces appetite and increases fat oxidation but does not affect energy expenditure in humans. *Obesity* **27**, 1244–1254.
31. Bailey D, Harry D, Johnson RE, *et al.* (1973) Oscillations in oxygen consumption of man at rest. *J Appl Physiol* **34**, 467–470.
32. Zitting KM, Vujovic N, Yuan RK, *et al.* (2018) Human resting energy expenditure varies with circadian phase. *Curr Biol* **28**, 3685–3690.e3.
33. Ruddick-Collins LC, Flanagan A, Johnston JD, *et al.* (2022) Circadian rhythms in resting metabolic rate account for apparent daily rhythms in the thermic effect of food. *J Clin Endocrinol Metab* **107**, e708–15.
34. Ruddick-Collins LC, Johnston JD, Morgan PJ, *et al.* (2018) The Big Breakfast Study: chrono-nutrition influence on energy expenditure and bodyweight. *Nutr Bull* **43**, 174–183.
35. Westerterp KR (2017) Doubly labelled water assessment of energy expenditure: principle, practice, and promise. *Eur J Appl Physiol* **117**, 1277–1285.
36. Rosenbaum M, Hirsch J, Gallagher DA, *et al.* (2008) Long-term persistence of adaptive thermogenesis in subjects who have maintained a reduced body weight. *Am J Clin Nutr* **88**, 906–912.
37. Amatruda JM, Statt MC & Welle SL (1993) Total and resting energy expenditure in obese women reduced to ideal body weight. *J Clin Invest* **92**, 1236–1242.
38. Martins C, Gower BA, Hill JO, *et al.* (2020) Metabolic adaptation is not a major barrier to weight-loss maintenance. *Am J Clin Nutr* **112**, 558–565.
39. Betts JA, Richardson JD, Chowdhury EA, *et al.* (2014) The causal role of breakfast in energy balance and health: a randomized controlled trial in lean adults. *Am J Clin Nutr* **100**, 539–547.
40. Chowdhury EA, Richardson JD, Holman GD, *et al.* (2016) The causal role of breakfast in energy balance and health: a randomised controlled trial in obese adults. *Am J Clin Nutr* **103**, 747–756.
41. Jakubowicz D, Froy O, Wainstein J, *et al.* (2012) Meal timing and composition influence ghrelin levels, appetite scores and weight loss maintenance in overweight and obese adults. *Steroids* **77**, 323–331.
42. Hill JO (2006) Understanding and addressing the epidemic of obesity: an energy balance perspective. *Endocr Rev* **27**, 750–761.
43. Schoeller DA & Buchholz AC (2005) Energetics of obesity and weight control: does diet composition matter? *J Am Diet Assoc* **105**, 24–28.
44. Rogers PJ & Brunstrom JM (2016) Appetite and energy balancing. *Physiol Behav* **164**, 465–471.
45. Speakman JR, Levitsky DA, Allison DB, *et al.* (2011) Set points, settling points and some alternative models: theoretical options to understand how genes and environments combine to regulate body adiposity. *Dis Model Mech* **4**, 733–745.
46. Hall KD (2018) Did the food environment cause the obesity epidemic? *Obesity* **26**, 11–13.

https://doi.org/10.1017/S0029665124007547 Published online by Cambridge University Press

47. Blundell JE, Gibbons C, Caudwell P, *et al.* (2015) Appetite control and energy balance: impact of exercise. *Obes Rev* **16**, 67–76.
48. Hopkins M, Finlayson G, Duarte C, *et al.* (2016) Modelling the associations between fat-free mass, resting metabolic rate and energy intake in the context of total energy balance. *Int J Obes* **40**, 312–318.
49. Fazzino TL, Courville AB, Guo J, *et al.* (2023) Ad libitum meal energy intake is positively influenced by energy density, eating rate and hyper-palatable food across four dietary patterns. *Nat Food* **4**, 144–147.
50. Kinsell LW, Gunning B, Michaels GD, *et al.* (1964) Calories do count. *Metabolism* **13**, 195–204.
51. Jamshed H, Steger FL, Bryan DR, *et al.* (2022) Effectiveness of early time-restricted eating for weight loss, fat loss, and cardiometabolic health in adults with obesity. *JAMA Intern Med* **182**, 953.
52. Black AE, Goldberg GR, Jebb SA, *et al.* (1991) Critical evaluation of energy intake data using fundamental principles of energy physiology: 2. Evaluating the results of published surveys. *Eur J Clin Nutr* **45**, 583–599.
53. Johansson L, Solvoll K, Bjorneboe GEA, *et al.* (1998) Under- and overreporting of energy intake related to weight status and lifestyle in a nationwide sample. *Am J Clin Nutr* **68**, 266–274.
54. Sanghvi A, Redman LM, Martin CK, *et al.* (2015) Validation of an inexpensive and accurate mathematical method to measure long-term changes in free-living energy intake. *Am J Clin Nutr* **102**, 353–358.
55. Hall KD, Sacks G, Chandramohan D, *et al.* (2011) Quantification of the effect of energy imbalance on bodyweight. *Lancet* **378**, 826–837.
56. Deaton A & Cartwright N (2018) Understanding and misunderstanding randomized controlled trials. *Soc Sci Med* **210**, 2–21.
57. Cook TD (2018) Twenty-six assumptions that have to be met if single random assignment experiments are to warrant 'gold standard' status: a commentary on Deaton and Cartwright. *Soc Sci Med* **210**, 37–40.
58. Flanagan A, Bradfield J, Kohlmeier M, *et al.* (2023) Need for a nutrition-specific scientific paradigm for research quality improvement. *BMJ Nutr Prev Health* **6**, 383–391.
59. Guo J, Robinson JL, Gardner CD, *et al.* (2019) Objective *v.* self-reported energy intake changes during low-carbohydrate and low-fat diets. *Obesity* **27**, 420–426.
60. Lowe DA, Wu N, Rohdin-bibby L, *et al.* (2020) Effects of time-restricted eating on weight loss and other metabolic parameters in women and men with overweight and obesity the TREAT randomized clinical trial. *JAMA Intern Med* **180**, 1491–1499.
61. Xie Z, Sun Y, Ye Y, *et al.* (2022) Randomized controlled trial for time-restricted eating in healthy volunteers without obesity. *Nat Commun* **13**, 1003.
62. Liu D, Huang Y, Huang C, *et al.* (2022) Calorie restriction with or without time-restricted eating in weight loss. *N Engl J Med* **386**, 1495–1504.
63. Schroor MM, Joris PJ, Plat J, *et al.* (2024) Effects of intermittent energy restriction compared with those of continuous energy restriction on body composition and cardiometabolic risk markers – a systematic review and meta-analysis of randomized controlled trials in adults. *Adv Nutr* **15**, 100130.
64. de Oliveira Maranhão Pureza IR, da Silva Junior AE, Praxedes DR, *et al.* (2021) Effects of time-restricted feeding on body weight, body composition and vital signs in low-income women with obesity: a 12-month randomized clinical trial. *Clin Nutr* **40**, 759–766.
65. Isenmann E, Dissemond J & Geisler S (2021) The effects of a macronutrient-based diet and time-restricted feeding (16: 8) on body composition in physically active individuals—a 14-week randomised controlled trial. *Nutrients* **13**, 3122.
66. Thomas EA, Zaman A, Sloggett KJ, *et al.* (2022) Early time-restricted eating compared with daily caloric restriction: a randomized trial in adults with obesity. *Obesity (Silver Spring)* **30**, 1027–1038.
67. Lin YJ, Wang YT, Chan LC, *et al.* (2022) Effect of time-restricted feeding on body composition and cardio-metabolic risk in middle-aged women in Taiwan. *Nutrition* **93**, 111504.
68. Douketis JD, Macie C, Thabane L, *et al.* (2005) Systematic review of long-term weight loss studies in obese adults: clinical significance and applicability to clinical practice. *Int J Obes* **29**, 1153–1167.
69. Blackburn G (1995) Effect of degree of weight loss on health benefits. *Obes Res* **3**, 211s–216s.
70. Bellisle F, McDevitt R & Prentice AM (1997) Meal frequency and energy balance. *Br J Nutr* **77**, S57–70.
71. Schwingshackl L, Nitschke K, Zähringer J, *et al.* (2020) Impact of meal frequency on anthropometric outcomes: a systematic review and network meta-analysis of randomized controlled trials. *Adv Nutr* **11**, 1108–1122.
72. Blazey P, Habibi A, Hassen N, *et al.* (2023) The effects of eating frequency on changes in body composition and cardiometabolic health in adults: a systematic review with meta-analysis of randomized trials. *Int J Behav Nutr Phys Act* **20**, 133.
73. Lindgren O, Mari A, Deacon CF, *et al.* (2009) Differential islet and incretin hormone responses in morning *v.* afternoon after standardized meal in healthy men. *J Clin Endocrinol Metab* **94**, 2887–2892.
74. Reid KJ, Baron KG & Zee PC (2014) Meal timing influences daily caloric intake in healthy adults. *Nutr Res* **34**, 930–935.
75. Dattilo M, Crispim CA, Zimberg IZ, *et al.* (2011) Meal distribution across the day and its relationship with body composition. *Biol Rhythm Res* **42**, 119–129.
76. de Castro JM (2004) The time of day of food intake influences overall intake in humans. *J Nutr* **134**, 104–111.
77. Hansen TT, Andersen SV, Astrup A, *et al.* (2019) Is reducing appetite beneficial for body weight management in the context of overweight and obesity? A systematic review and meta-analysis from clinical trials assessing body weight management after exposure to satiety enhancing and/or hunger reducing products. *Obes Rev* **20**, 983–997.
78. Hansen TT, Mead BR, García-Gavilán JF, *et al.* (2019) Is reduction in appetite beneficial for body weight management in the context of overweight and obesity? Yes, according to the SATIN (Satiety Innovation) study. *J Nutr Sci* **8**, e39.
79. Sumithran P, Prendergast LA, Delbridge E, *et al.* (2011) Long-term persistence of hormonal adaptations to weight loss. NEJM 365, 1597–1604.
80. Nymo S, Coutinho SR, Rehfeld JF, *et al.* (2019) Physiological predictors of weight regain at 1-year follow-up in weight-reduced adults with obesity. *Obesity* **27**, 925–931.
81. Tsaousis I (2010) Circadian preferences and personality traits: a meta-analysis. *Eur J Pers* **24**, 356–373.
82. Lenneis A, Vainik U, Teder-Laving M, *et al.* (2021) Personality traits relate to chronotype at both the phenotypic and genetic level. *J Pers* **89**, 1206–1222.
83. Walker RJ & Christopher AN (2016) Time-of-day preference mediates the relationship between personality and breakfast attitudes. *Pers Individ Diff* **91**, 138–143.
84. Reeves S, Halsey LG, McMeel Y, *et al.* (2013) Breakfast habits, beliefs and measures of health and wellbeing in a nationally representative UK sample. *Appetite* **60**, 51–57.
85. Baron KG, Reid KJ, Wolfe LF, *et al.* (2018) Phase relationship between DLMO and sleep onset and the risk of metabolic disease among normal weight and overweight/obese adults. *J Biol Rhythms* **33**, 76–83.
86. McHill AW, Czeisler CA, Phillips AJK, *et al.* (2019) Caloric and macronutrient intake differ with circadian phase and between lean and overweight young adults. *Nutrients* **11**, 587.
87. McHill AW, Phillips AJK, Czeisler CA, *et al.* (2017) Later circadian timing of food intake is associated with increased body fat. *Am J Clin Nutr* **106**, 1213–1219.
88. Xiao Q, Garaulet M & Scheer FAJL (2019) Meal timing and obesity; interactions with macronutrient intake and chronotype. *Int J Obes (Lond)* **344**, 1173–1178.
89. Lopez-minguez J, Dashti HS, Madrid-valero JJ, *et al.* (2019) Heritability of the timing of food intake. *Clin Nutr* **38**, 767–773.
90. Galindo Muñoz JS, Gómez Gallego M, Díaz Soler I, *et al.* (2020) Effect of a chronotype-adjusted diet on weight loss effectiveness: a randomized clinical trial. *Clin Nutr* **39**, 1041–1048.
91. Dinu M, Lotti S, Pagliai G, *et al.* (2024) Effects of a chronotype-adapted diet on weight loss, cardiometabolic health, and gut microbiota: study protocol for a randomized controlled trial. *Trials* **25**, 152.

https://doi.org/10.1017/S0029665124007547 Published online by Cambridge University Press