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Corresponding author:
Kristine Beaulieu;
Email: k.beaulieu@leeds.ac.uk

Chronotypical influence on eating behaviour and appetite control

Kristine Beaulieu[1,2], Graham Finlayson[1] and Jonas Salling Quist[1,2,3]

[1]School of Psychology, University of Leeds, Leeds, UK; [2]Copenhagen University Hospital - Steno Diabetes Center Copenhagen, Herlev, Denmark and [3]Department of Biomedical Sciences, University of Copenhagen, Copenhagen, Denmark

Abstract

A person's chronotype reflects individual variability in diurnal rhythms for preferred timing of sleep and daily activities such as exercise and food intake. The aim of this review is to provide an overview of the evidence around the influence of chronotype on eating behaviour and appetite control, as well as our perspectives and suggestions for future research. Increasing evidence demonstrates that late chronotype is associated with adverse health outcomes. A late chronotype may exacerbate the influence of greater evening energy intake on overweight/obesity risk and curtail weight management efforts. Furthermore, late chronotypes tend to have worse diet quality, with greater intake of fast foods, caffeine and alcohol and lower intake of fruits and vegetables. Late chronotype is also associated with eating behaviour traits that increase the susceptibility to overconsumption such as disinhibition, food cravings and binge eating. Whether an individual's chronotype influences appetite in response to food intake and exercise is an area of recent interest that has largely been overlooked. Preliminary evidence suggests additive rather than interactive effects of chronotype and meal timing on appetite and food reward, but that hunger may decrease to a greater extent in response to morning exercise in early chronotypes and in response to evening exercise in late chronotypes. More studies examining the interplay between an individual's chronotype, food intake/exercise timing and sleep are required as this could be of importance to inform personalised dietary and exercise prescriptions to promote better appetite control and weight management outcomes.

Definition and assessment

Chronotype reflects the circadian typology of an individual and their behavioural preference for morning or evening in terms of activities such as sleep, food intake and physical activity. As such, some individuals have preference for the morning (early chronotypes or 'larks') while others have preference for the evening (late chronotypes or 'owls'). The science of chronobiology has brought novel and important perspectives to understand metabolic homeostasis. Circadian rhythms contribute to diurnal variations in metabolism and physiology and are driven by molecular clocks in almost all organs and tissues in our body[1,2]. These rhythms support the temporal organisation of energy balance, cellular repair, resolution of inflammation and optimal mitochondrial function[1,3]. In modern societies, circadian rhythms are disrupted by sleep disruption[4] and erratic eating patterns[5,6]. Inappropriate timing of food intake[7] and physical activity[8] can also disrupt circadian rhythms.

Chronotype can be assessed via self-reported questionnaires such as the Horne-Ostberg Morningness-Eveningness Questionnaire (MEQ) which is representative of an individual's diurnal preference[9] or the Munich Chronotype Questionnaire which calculates the midpoint of sleep on work-free days without an alarm clock, correcting for oversleep[10], among other questionnaires. More objective measures of chronotype obtained from actigraphy data include the acrophase calculated from the cosinor method[11] or midpoint of sleep. Finally, chronotype can be determined via the dim-light melatonin onset (DLMO) biological sampling technique which provides circadian timing of the central clock but is quite resource-intensive[12]. A lengthy overview and discussion of the assessment of circadian typology is beyond the scope of this review and can be found elsewhere[13].

Chronotype, obesity and weight management

Increasing evidence suggests that late chronotype is associated with adverse health outcomes such as higher BMI, greater waist circumference, and a poorer cardiometabolic health profile[14–18]. This highlights the need to understand how chronotype influences energy balance behaviours and appetite control in order to design and improve current weight management interventions. In terms of energy balance and lifestyle behaviours, late chronotype is associated with lower physical activity and higher sedentary behaviour[19], poorer sleep quality[20,21] and other unhealthy behaviours such as smoking[22]. Most systematic reviews have found that chronotype may not affect total daily energy intake per se (although methodological limitations may preclude us from determining these differences)[14,16,17,23] but it does appear that chronotype influences temporal eating patterns, diet quality, appetite and eating behaviours[14,15,17,23,24] (discussed further below).

It is now widely acknowledged that temporal eating patterns have an important role in health and disease[25] and interestingly, the timing of food intake appears to interact with chronotype to influence weight outcomes. In middle-to-older age adults, greater energy intake in the morning (within 2 h after waking up) was associated with lower odds of having overweight/obesity but only in those considered as early chronotype, whereas greater energy intake in the evening (within 2 h before bedtime) was associated with greater odds of having overweight/obesity but only in those considered as late chronotype[26]. In this study, food intake timing was defined relative to wake/sleep time which is suggested to be more reflective of circadian timing than using clock time or meal classification i.e. breakfast, lunch and dinner. Chronotype was categorised as median split of the midpoint of time in bed obtained from self-report. The authors suggested that the early *v.* late timing of food intake in the two chronotypes could be in different circadian phases and influence metabolism differently[26]. The interaction between circadian food intake timing and chronotype on weight outcomes, metabolism and eating behaviour has up to now not been a large focus of attention and warrants further investigation.

In terms of weight loss/maintenance, in the classic Garaulet *et al.*[27] meal timing and weight loss study whereby those categorised as early eaters (grouped based on median split of timing of lunch) lost significantly more weight than those categorised as late eaters, early eaters also had greater MEQ scores (i.e. earlier chronotype) than late eaters. More recently, morning-types were found to lose more weight than evening-types (−9·0 % *v.* −5·7 %) during a 31-day very-low-calorie ketogenic diet[28]. Information on meal timing and dietary adherence would have helped in interpreting these results. In the context of weight loss maintenance, individuals from the National Weight Control Registry (NWCR; *n* 690, BMI = 26·4 ± 5·1 kg/m^2, with ≥13·6 kg weight loss for ≥1 year) had greater MEQ scores and were more categorised as morning-types, compared to individuals with overweight/obesity (*n* 75, BMI = 36·2 ± 4·7 kg/m^2) separately recruited from two behavioural weight loss programmes to act as a pre-weight loss/baseline comparison group[29]. Furthermore, NWCR participants also reported better overall sleep quality and sleep duration based on the Pittsburgh Sleep Quality Index[30]. These studies suggest chronotype plays a role in weight management success; however, there is a need to tease apart chronotype *v.* food intake timing (and other potential confounding) effects to further understand if and how they relate or interact with one another.

In an intervention whereby individuals were randomised to a standard hypocaloric diet or a hypocaloric diet adjusted to chronotype based on MEQ score (bigger breakfast/smaller dinner for morning types, and smaller breakfast/bigger dinner for evening types), the chronotype-adjusted diet led to a 1·4 % greater total percentage body weight loss over 3 months and 0·8 % greater after a 1-year follow-up[31]. Total percentage weight loss was similar between the two chronotype groups, suggesting a chronotype effect independent of meal timing. Therefore, aligning temporal eating patterns to an individual's circadian/activity patterns could lead to more successful (albeit modestly-so) weight management. However, in a feasibility study with a similar temporal eating pattern prescription according to chronotype, among other chronobiological recommendations such as eating the main meal before 15:00, eating dinner at least 2·5 h before sleep onset, avoiding night eating, and minimum 6 h of sleep with optimum sleep duration of 7–9 h across chronotype groups, both chronotype groups ended up increasing percentage energy intake in the morning and had similar weight loss over 12 weeks[32]. Changes in other chronobiological parameters of the intervention prescribed across the two chronotype groups may have contributed to the similar weight loss observed. Additionally, while only in evening chronotypes, after 12 weeks of a circadian timing intervention (including recommendations on wake/bed time, meal timing, caffeine intake, daytime sleep, exercise timing and light exposure delivered through a website) *v.* standard care as part of an obesity outpatient clinic, those in the intervention group lost 10·5 % body weight *v.* 4·3 % in the control group[33]. Compliance with the intervention recommendations was high. More research in this area is needed as this has potential to influence clinical practice by understanding whether to personalise dietary interventions to chronotype/circadian characteristics or provide more general chronobiological/sleep recommendations. In fact, another hypocaloric dietary intervention adjusted to chronotype of 4 months in duration with change in body weight as primary outcome measure is currently underway (clinicaltrials.gov NCT05941871)[34].

Chronotype, appetite and eating behaviour

The energy intake side of the energy balance equation is 100 % behavioural; it is the behaviour of eating that allows nutrition to exert its effect on physiology and body weight control. This is why it is important to understand how different dietary approaches and eating patterns influence appetite and eating behaviour to ultimately influence total daily energy intake and eating habits. In this context, eating patterns refer to the temporal elements of eating (defined below), appetite refers to the psychobiological system that influences the motivation to eat, eating behaviour to the expression of appetite and other factors (environmental, social, cultural, etc.) leading to food intake, and eating habits to longer-term dietary habits of an individual[35]. Additionally, eating behaviour traits – typically assessed with psychometric questionnaires – reflect food-related behaviours and the susceptibility to overconsumption through various constructs, and are predictive of energy intake and BMI[36].

As shown in Fig. 1, the components of energy intake traditionally studied consisted only of the macronutrient composition of the diet, but the field of chrono-nutrition has now highlighted an important role of temporal elements of eating such as the duration of the eating window, energy and macronutrient intake distribution, meal frequency and regularity[25,37,38]. This is addressed by Flanagan[39] in another review in this issue. Briefly, in the context of appetite, studies have shown that morning-loaded energy intake (bigger breakfast *v.* smaller dinner) results in lower daily hunger ratings[40,41] and shifting meals to later in the day (1h/5h10/9h20 after waking *v.* 5h10/9h20/13h30 after waking) doubled the odds of reporting a > 50 rating on the hunger visual analogue scale[42]. In terms of diurnal variations in appetite, Scheer *et al.*[43,44] have shown that in healthy participants without obesity, hunger, appetite and ghrelin follow endogenous circadian rhythms, peaking in the biological evening. This aligns with de Castro's[45] findings that as meal size increases over the course of a day, the time interval between meals actually decreases. This is reflected by a decrease in the satiating

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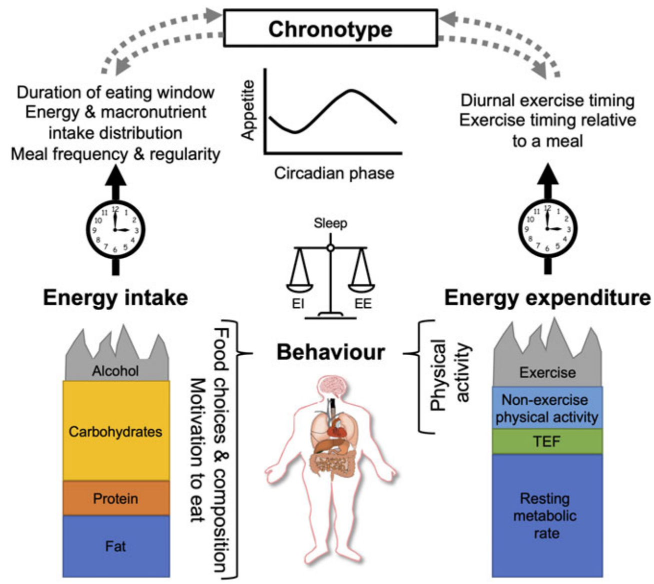

Figure 1. Chronobiological considerations for energy balance behaviours. Beyond the traditional energy balance components, on the energy intake side, duration of eating window, energy and macronutrient intake distribution, and meal frequency and regularity should be considered, while on the energy expenditure side, diurnal exercise timing and exercise timing relative to a meal. Sleep should be considered alongside energy intake and energy expenditure as it influences energy balance. Diurnal and circadian variations in appetite and appetite-related hormones also need to be considered. Finally, individual variations in circadian characteristics and activity patterns are important as they may interact with food intake and exercise timing, or impact weight outcomes. Chronotype as a cause or consequence of diurnal food intake and exercise patterns remains to be fully understood. Abbreviations: EI, energy intake; EE, energy expenditure; TEF, thermic effect of food.

capacity of foods (satiety ratio) over the course of a day[45]. On the energy expenditure side, the timing of exercise is also important to consider for appetite control and energy balance in terms of when exercise is performed during the day and in relation to a meal, as exercise, in general, has been shown to influence appetite control. For reviews see elsewhere[46–50]. Finally, sleep - while not an energy balance behaviour per se - is another important element that should be considered for its influence on energy balance and overweight/obesity[51,52]. This is conceptualised in Fig. 1, with the role of chronotype still to be fully understood.

While the influence of chronotype on total daily energy intake remains to be fully understood, a number of systematic reviews have shown that late chronotype is associated with less favourable temporal eating patterns and poorer diet quality[14,15,17,23,24]. These reviews have demonstrated that late chronotypes have their food intake shifted later in the day and have higher prevalence of night eating, tend to skip breakfast more frequently, and have more irregular eating patterns[14,15,17,23,24]. Late chronotypes also have a lower intake of fruits and vegetables, and greater intake of fast food, caffeine and alcohol[14,15,17,23,24].

In terms of eating behaviour traits, late chronotype is associated with greater susceptibility to overconsumption. Studies using the Three-Factor Eating Questionnaire have shown greater uncontrolled eating/disinhibition and lower restrained eating in late chronotype[53–55]. For example, in 335 university students (59 % female), early chronotype (assessed by the Composite Scale of Morningness[56]) was positively associated with cognitive restraint, and inversely associated with disinhibition and susceptibility to hunger[53]. More recently, Garaulet *et al.*[57] have shown that late chronotype, assessed by both MEQ and DLMO, was associated with greater emotional eating scores from the Emotional Eater Questionnaire (subscales of disinhibition, food craving and sense of guilt)[58]. More specifically, in their study, they analysed four international cohorts from Spain, the US and Mexico, totalling just under 4000 participants[57]. An important strength of this study was the subjective and objective assessment of chronotype via MEQ (as per original classification guidelines) and DLMO in a subsample (by tertile split), respectively. In three of the four MEQ cohorts and in the DLMO subsample, total emotional eating scores were greater in those classified as evening types. Interestingly, mediation analyses suggested that in some cohorts, emotional eating mediated the association between chronotype and BMI. To add to these findings, a systematic scoping review highlighted that binge eating behaviour occurs more frequently later in the day, has a large overlap with night eating behaviour and may be associated with an evening chronotype[59]. One study suggested a sex-by-chronotype interaction on binge eating, with binge eating scores being greater in males with late chronotype, similar to women across all chronotypes, and lower in males with earlier chronotype[60]. However, only 30 % of participants were males and 9 % of males and females were evening types, so results should be confirmed in other studies. While not directly related to chronotype but along these lines, Jacob and colleagues[61] found sex-by-food intake timing interactions showing that percentage of total energy intake (%TEI) after 17:00 was positively associated with disinhibition in women and negatively associated with susceptibility to hunger in men. Interestingly, in women, disinhibition mediated the association between %TEI after 17:00 and TEI, and in men and women, susceptibility to hunger mediated the association between %TEI after 20:00 and TEI. This study also showed that TEI mediated the relationship between % TEI after 17:00 and BMI. As stipulated by the authors, these results highlight a possible link between late eating and overconsumption via eating behaviour traits. Whether individual differences in chronotype influence these relationships remains to be examined.

Assessment of food reward and diurnal considerations

Food hedonics or food reward is expressed through food liking and wanting of food attributes such as salt, sugar and fat which determine food preference and choice[62]. Food liking is defined as the degree of sensory pleasure obtained from foods, and wanting is the motivation or attraction towards certain foods[62]. Importantly, homeostatic processes interact with hedonic processes in the overall expression of appetite, which in turn will determine food intake[35]. Indeed, hedonic processes can override homeostatic signals, leading to overconsumption[63]. For example, food liking can increase the risk of overeating by increasing the size of a meal by overriding satiation signals and wanting can increase the risk of overeating by overriding satiety signals and leading to an unplanned meal or snack in between eating episodes.

Among the behavioural methodologies for the assessment of food reward in humans, the Leeds Food Preference Questionnaire (LFPQ)[62] and the Steno Biometric Food Preference Task (SBFPT)[64] use arrays of validated food images that compare sensory (sweet *v.* savoury) and nutrient (high- *v.* low-fat) qualities of foods. Food liking is measured with subjective ratings and food wanting is measured by a forced-choice reaction time task. An important consideration for the diurnal assessment of food reward is that the included foods need to be perceived as appropriate or acceptable to consume across the day. We therefore sought to validate new panels of food images to assess the influence of food

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intake and/or exercise timing, and chronotype on food reward. The first validation we conducted was on the British version of the LFPQ[65] and we followed this with a Danish validation of the SBFPT for individuals ranging in BMI with and without type 2 diabetes (abstract by Beaulieu *et al.*[66] published in this issue).

Interaction between food intake/exercise timing and chronotype on appetite control and eating behaviour

Following the diurnal validation of the British LFPQ, we conducted the first (and only to our knowledge) study examining whether chronotype moderates the impact of food intake timing on appetite and food reward[65]. We recruited 44 university students between the age of 18–25 years and divided them into early and late chronotype groups based on MEQ score median split (8 males and 14 females in each chronotype group). Participants attended the laboratory on two occasions in the morning (08:00–10:00) and in the late afternoon/early evening (16:00–18:00) to consume a 300-kcal test meal (diurnally appropriate) and complete appetite and food reward assessments. As reported previously[14,17,26], we found a relationship between chronotype and BMI, with earlier chronotype associated with a lower BMI. In response to the test meal, appetite ratings over 60 min were greater in the evening compared to the morning. No significant difference in appetite was found between chronotypes, but there appeared to be a weaker suppression of appetite in the late chronotype across both meals. Moreover, following consumption, the test meal was perceived as more filling in the morning compared to evening, and by early chronotype compared to late chronotype. There was also greater prospective consumption in the evening compared to morning, but no differences between chronotypes. In terms of food reward, liking and wanting for high-fat relative to low-fat food was greater in the evening than in the morning. When groups were pooled together, we found an inverse association between MEQ score and wanting for high-fat relative to low-fat food, such that early chronotype had lower wanting. No relationship was found between MEQ score and liking. These data suggest that the impact of food intake timing and chronotype on appetite and food reward appears to be additive rather than interactive. Early meal timing was associated with lower appetite, increased perceived fillingness and lower liking and wanting for high-fat relative to low-fat food, whereas evening chronotype was associated with higher BMI, weaker suppression of appetite and greater wanting but not liking for high-fat relative to low-fat food. Sex differences were not assessed in this study but given the sex-by-chronotype interaction mentioned above[60], it would be interesting for future studies to explore this.

We subsequently explored whether chronotype moderated the impact of exercise timing on appetite and food reward[67]. Previous studies examining the impact of exercise timing on appetite and energy intake showed minimal effects but had not considered the effect of chronotype[68–71]. We included 45 Saudi males between 18 and 39 years with a BMI between 18·5 and 39·9 kg/m^2 and divided them into early and late chronotype groups based on MEQ score median split. Participants attended the laboratory on two occasions in the morning (08:00–10:00) and in the early evening (17:00–19:00) in random order to perform a 30-min moderate intensity (4·8 METs) cycling bout and complete appetite and food reward assessments pre- and post-exercise. In this randomised cross-over study we found no association between MEQ score and BMI. However, an interaction was found between chronotype and exercise timing on hunger ratings. In the early chronotypes, hunger appeared to decrease to a greater extent in response to morning than evening exercise, whereas in the late chronotypes, hunger appeared to decrease to a greater extent in response to evening than morning exercise. In terms of food reward (measured following the appetite visual analogue scales immediately before and after the exercise), liking and wanting for high-fat relative to low-fat food were greater overall in evening relative to morning. Wanting for sweet relative to savoury food was overall greater in evening compared to morning. It is important to note that the food reward results may have been confounded by the fact that a non-diurnal version of the Arabic LFPQ was used. Nevertheless, the interaction between appetite suppression and exercise timing by chronotype requires confirmation as this might provide a potential target for personalised exercise interventions to improve appetite control.

To our knowledge, we are the only group that has examined in experimental studies the moderating influence of chronotype on the relationship between food intake/exercise timing and appetite. The observational study from Xiao and colleagues[26] mentioned above about the circadian food intake timing-by-chronotype interaction on odds of being overweight/obesity and our exercise timing results highlights the need to consider chronotype (either by controlling for or examining chronotype differences) when investigating the influence of food intake/exercise timing on appetite and body weight control. Examined from a different perspective, an earlier Spanish observational study showed a BMI-by-chronotype interaction on %TEI distribution[72]. In individuals with a BMI within the healthy range, a difference in %TEI at dinner between early and late chronotypes following the expected chronotypical eating pattern was apparent (27·6 *v.* 32·3 %) whereas it was not in those with a BMI within the overweight/obesity range (31·1 *v.* 30·7 %). These data suggest a misalignment between chronotype and food intake timing in individuals with a greater BMI. However, it is important to note that food intake timing in this study was based on meal classification obtained from a single 24-h recall[72]. Nevertheless, it further highlights that chronotype appears to be an important influencing factor.

While not manipulating food intake and exercise timing per se, a relevant recent laboratory-based study to mention here is one from Malin and colleagues, who compared the appetite and gut hormone response to a morning 75-g oral glucose tolerance test between early (3 males and 18 females) and late (5 males and 23 females) chronotypes in adults with metabolic syndrome[73]. Appetite sensations were similar between both chronotype groups in the fasted state and in the early postprandial phase (0–30 min); however, fullness and satisfaction were greater in the early chronotype group in the late postprandial phase (60–120 min). Some differences in gut hormones were apparent but did not reach statistical significance. While self-reported total daily energy intake (on 2 weekdays and 1 weekend day) did not differ between groups, intake at different meals differed between groups (larger meals later in the day for late chronotype), especially at the afternoon snack where late chronotype ate significantly more than early chronotype. Despite only being performed in the morning, these results corroborate our previous findings[65] of what appears to be greater appetite suppression to food/nutrient intake in early chronotype.

Future directions

As a follow-up to our previous studies, we have recently conducted a randomised cross-over acute exercise timing study at Steno

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Diabetes Center Copenhagen to assess homeostatic and hedonic appetite in individuals with overweight/obesity with and without type 2 diabetes (clinicaltrials.gov NCT05768958). The specific objectives are to assess whether energy intake during an ad libitum meal, appetite ratings, food reward using the validated diurnal SBFPT, and metabolic markers differ after acute exercise *v.* rest in the morning or evening. We will examine whether these responses differ between individuals with and without type 2 diabetes as it is known that individuals with type 2 diabetes have different diurnal patterns in insulin sensitivity[74] and how this might impact appetite remains to be elucidated. Differences between chronotypes will also be explored and we will be able to add to prior research by examining ad libitum energy intake, food reward and subjective and metabolic markers of appetite at different times of the day (in the rest condition) and in response to exercise. A strength of this study is the inclusion of 58 participants which is large for this type of trial and of metabolic markers to complement the wide array of behavioural measurements (food intake, perceived appetite, food reward and eating behaviour traits, among others) to be collected.

A search on the Open Science Framework (OSF) database and the World Health Organization (WHO) International Clinical Trials Registry Platform identified some other ongoing/future studies investigating chronotype, but only one in addition to the two already mentioned (clinicaltrials.gov NCT05941871 and NCT05768958) in the area of appetite, eating behaviour and weight management. The primary aim of the study is to examine 12 weeks of early time-restricted eating *v.* late time-restricted eating *v.* active control on change in body fat mass in individuals with overweight/obesity with morning chronotype (clinicaltrials.gov NCT04618133).

Research on the role of chronotype in eating behaviour, appetite control and weight management is in its infancy. The following quote that was originally published by Almoosawi *et al.* in 2019[15] still applies now: 'It is not clear based on the currently available literature whether or not chronotype is a determinant (causal factor) of eating patterns or food intake or merely a reflection of a complex set of behaviours that also affect diet (associated to diet owing to confounding factors). Furthermore, it may be that chronotype is a consequence of (caused by) the entraining effect of food constituents or eating patterns on the peripheral clocks.' There still is a need to tease apart or account for the interplay between chronotype, food intake, exercise and sleep, among other lifestyle behaviours/confounders.

Given that the association between circadian timing of food intake and odds of having overweight/obesity appears to vary according to chronotype[26], it has been proposed by others to calculate meal timing relative to the midpoint of sleep (e.g. timing of dinner relative to midpoint of sleep; TDM)[75]. Using this approach, two studies have shown that TDM is associated with BMI, one in a non-linear (*U*-shape) relationship[75] and the other in an inverse relationship with shorter dinner timing relative to midpoint of sleep associated with greater BMI[76]. Ultimately, we need a uniform methodological approach to conceptualise chronotype, food intake and exercise timing to ensure adequate comparison across studies and advancement of the field.

Another question that remains to be investigated is whether it is more important to adapt lifestyle interventions to an individual's chronotype, to try to shift late chronotypes to earlier chronotypes, or a combination of the two. More interventional studies and randomised controlled trials are needed to find feasible lifestyle approaches to improve health, lifestyle behaviours and weight outcomes that account for individual differences in chronotype.

Conclusion

Late chronotype is a phenotype associated with multiple health risks and unhealthy lifestyle behaviours. Early chronotype appears to be associated with better weight outcomes, whereas late chronotype is associated with increased susceptibility to overconsumption. More studies examining the interplay between an individual's chronotype, food intake/exercise timing and sleep are required as this could be of importance to inform personalised dietary and exercise prescriptions to promote better appetite control and weight management outcomes. Hopefully, this review will encourage the scientific community to contribute to the small evidence base in this area.

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