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Independent effects of the human circadian system and sleep/eating cycles on caloric intake in adolescents vary by weight status

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Late-day eating is linked to increased obesity risk; however, whether the endogenous circadian system independently influences caloric intake and if this control differs among individuals based on weight status is unknown. Here, we investigated in adolescents the independent roles of the endogenous circadian system and of the behavioral sleep/wake cycle (sleep/wake, fasting/eating, rest/activity, dark/dim light, social interaction, posture, etc.) on self-selected caloric intake using a Forced Desynchrony protocol. Fifty-one male and female adolescents across three weight status categories (24 with healthy weight, 13 with overweight, and 14 with obesity) completed the protocol where participants lived on seven 28-h sleep/wake cycles in dim light during wake and complete darkness during sleep. Results suggest that the circadian system and the behavioral cycle each affected caloric intake, with a decrease across the wake episode and an increase from circadian morning to circadian evening in caloric intake. The endogenous circadian rhythm in caloric intake showed a circadian peak-to-trough difference of 196 [CI 95% 164, 226] kcal per meal with peak timing of 296° [288°, 304°; equivalent to ~17:30 in these participants]. In those with overweight/obesity, more calories were consumed later in the waking episode and later in the circadian cycle, and with blunted amplitudes compared to those with healthy weight. Results implicate both the endogenous circadian system and the behavioral cycle in shaping the daily rhythm of food intake. Furthermore, these results help explain the increased drive for caloric intake toward the evening, especially in those at risk for obesity.

adolescent | circadian | weight status | caloric intake | Forced Desynchrony

Significance

Using an experimental protocol designed to disentangle the separate influences of the endogenous circadian timing system and the sleep/wake and fasting/eating cycle, we found that both the endogenous circadian timing system and behavioral cycle influence caloric intake. Youth with overweight or obesity compared to those with healthy weight ate more of their calories later in the circadian evening and those with obesity ate more calories later in the wake episode. Youth with overweight or obesity also showed a lower amplitude of the circadian influence on caloric intake.

Obesity prevalence continues to increase worldwide and is associated with increased risk for chronic diseases including type-2 diabetes, hypertension, cardiovascular disease, and various types of cancer (1). In the United States, obesity prevalence has increased to above 40% in adults and 20% in children and is expected to rise to 50% by 2030 (2, 3). The causes of obesity are complex and multifactorial. One factor that has been implicated is the influence of the circadian timing system on caloric intake and body weight. Evidence for this link comes from observational, genetic, experimental, and animal studies (4). Yet, to date, there has been no direct evidence for an endogenous circadian influence on caloric intake in humans. Second, it is unknown whether such circadian influence differs dependent on weight status. We addressed these questions in adolescents, a highly relevant group in which eating patterns and body weight are predictive for adult obesity (5). Therefore, here, we used a Forced Desynchrony protocol to distinguish the influence of the endogenous circadian system from the influences of behavioral and environmental cycles (6). The protocol included seven 28-h sleep/wake cycles under dim to no light conditions—thereby distributing the timing of sleep/wake, fasting/eating, and rest/activity cycles uniformly across the endogenous circadian cycle and minimizing the influence of light on the circadian system—to determine the influence of the endogenous circadian system on caloric intake regulation among adolescents who differed in weight status (i.e., healthy weight, overweight, and obese).

Results and Discussion

Participants were recruited to form roughly equally sized groups based on body mass index (BMI) percentile: 5th to 84th percentile (healthy weight, HW; n = 24) and ≥ 85th percentile (overweight/obese, OW/O; n = 27). Planned analyses compared adolescents with either OW (85%≤BMI%ile <95%, n = 13) or O (BMI%ile ≥95%, n = 14) classifications to those with HW. Exploratory analyses compared all three groups. Demographics by weight group

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Competing interest statement: F.A.J.L.S. served on the Board of Directors for the Sleep Research Society and has received consulting fees from the University of Alabama at Birmingham and Morehouse School of Medicine. F.A.J.L.S. interests were reviewed and managed by Brigham and Women's Hospital and Partners HealthCare in accordance with their conflict-of-interest policies. F.A.J.L.S. consultancies are not related to the current work. C.N.H. has received consulting fees from the University of South Carolina and serves as a consultant on a grant funded by the Novo Nordisk Foundation. C.N.H. interests were reviewed and managed by Temple University in accordance with their conflict-of-interest policies. These consultancies are unrelated to the current work. None of the other authors have competing interests to the work presented in this manuscript.

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are shown in Table 1, demonstrating minimal differences in age, self-reported sex, race, ethnicity, and self-reported pubertal status. As expected, those with higher weight classifications had higher estimated energy requirement, higher average of calories consumed per 28-h cycle, and higher weight gain across the study protocol. Those with obesity reported higher hunger ratings prior to meals. Postmeal surveys of tastefulness, satisfaction, and fullness did not differ by weight status. Our protocol for food choices was controlled in several ways, including restrictions for the number and amount of specific high-calorie and highly favored foods (e.g., ice cream, pop-tarts) and a diverse yet constrained menu. At the same time, menus and portion sizes provided all youth access to more than adequate calories each day to fulfill their caloric needs and to enable testing the hypotheses. In addition to examining differences among weight status groups, we also examined differences between self-reported sexes (male, female) and self-reported pubertal statuses (classified as early/mid vs. late).

Minimal Differences Between Weight Status Groups for Central Circadian Markers. Table 1 further shows a comparison of sleep and central circadian markers between weight status groups. We observed minimal between-group differences in circadian phase (timing) and circadian period (cycle length) as assessed across the Forced Desynchrony protocol by repeated measurement of the dim light melatonin onset (DLMO) phase, an established marker of the timing of the central circadian clock, derived from salivary melatonin concentrations. Furthermore, there were no significant differences in the area under the curves for melatonin (AUC) nor for self-reported chronotype. There were also minimal group differences in average total sleep time across cycles and variability of total sleep time across cycles. We conclude that under the controlled conditions of our study, no meaningful differences in the general functioning of the central circadian timing system were present among weight status groups. The absence of a significant difference in circadian phase and circadian period is consistent with a study using a (short) Forced Desynchrony protocol comparing middle-aged adults with healthy weight vs. obesity (7). The absence of a significant difference in the melatonin AUC by weight status in male and female youth in the current study, however, differs from a study in middle-aged men in whom melatonin levels were higher in individuals with obesity who did not have diabetes compared to healthy weight (although not different in those with obesity and diabetes) (8), a difference that may be explained by the large age difference between studies.

Endogenous Circadian System Influences Caloric Intake, and an Effect that Differs between Weight Status Groups. For all participants combined, the circadian system significantly influenced caloric intake. The mesor (circadian-cycle-adjusted mean) was 573 [95% CI:523, 623] kcal/meal, and the circadian peak-to-trough amplitude (i.e., the difference in calories consumed at the circadian peak versus at the circadian trough) was 196 [164, 227] kcal/meal with an acrophase (timing of peak) of 296° [288, 304; 0° representing DLMO phase] (Fig. 1 and Table 2). Translating

Table 1. Sample characteristics

	Healthy weight	Overweight	Obese		
	n = 24	n = 13	n = 14	SMD	*P*
Age, mean (SD)	12.8 (1.0)	13.1 (1.0)	13.5 (0.9)	0.52	0.08
Female, n (%)	10 (42)	7 (54)	5 (36)	0.25	0.62
Hispanic, n (%)	3 (13)	1 (8)	1 (7)	0.12	0.83
White, n (%)	20 (83)	10 (77)	11 (79)	0.11	0.88
Late puberty group*, n (%)	10 (42)	8 (62)	9 (64)	0.31	0.31
BMI percentile, mean (SD)	51.8 (23.1)	89.5 (3.2)	97.07 (1.3)	2.72	<0.01
Estimated caloric need per 28-h d, mean (SD)	2214 (387)	2530 (436)	3299 (880)	1.16	<0.01
Average calories consumed per-28 h d, mean (SD)	2972 (619)	3213 (1146)	4394 (875)	1.10	<0.01
28-h caloric intake as a percentage of calculated 28-h caloric requirement, mean (SD)	135 (22)	125 (31)	135 (21)	0.28	0.42
Change in caloric intake for each meal from FD-1 to FD-7	−62 (95)	−75 (43)	−52 (74)	0.23	0.75
Weight change in kg across FD protocol, mean (SD)	1.15 (1.19)	1.39 (1.55)	2.53 (1.45)	0.66	0.01
Hunger prior to meal (0 to 100), mean (SD)	17.80 (13.41)	13.28 (8.03)	28.50 (14.42)	0.83	<0.01
Rating of food as "Tasty, Yummy, or Delicious" (1 to 9), mean (SD)	7.73 (0.95)	7.71 (0.77)	8.10 (0.87)	0.30	0.41
Rating of feeling satisfied following meal (1 to 9), mean (SD)	8.23 (0.86)	8.08 (0.74)	8.32 (0.78)	0.21	0.73
Rating of feeling full following meal (1 to 9), mean (SD)	8.66 (0.58)	8.76 (0.38)	8.69 (0.38)	0.14	0.86
Sleep and central circadian timing system variables					
Average total sleep time across FD cycles, mean (SD)	9 h 20 m (21 m)	9 h 25 m (22 m)	9 h 27 m (20 m)	0.22	0.59
Variability of total sleep time across FD cycles, mean (SD)	50 m (22 m)	45 m (12 m)	45 m (19 m)	0.18	0.67
Morningness/eveningness	36.6 (6.9)	39.9 (5.4)	35.5 (6.9)	0.46	0.21
Circadian Period estimate	24.2 h (0.2)	24.2 h (0.1)	24.2 h (0.2)	0.13	0.84
First DLMO time	21:24 (72 m)	21:24 (36 m)	21.18 (54 m)	0.08	0.95
AUC melatonin curve FD-3†	136.3 (87.5)	140.1 (78.1)	119.2 (61.0)	0.19	0.76

Notes: *Participants were categorized into two puberty groups: early-mid and late. SMD = standardized mean difference, DLMO = dim light melatonin onset phase, AUC = area under the curve (hours*pg/mL).
†For one person with Healthy Weight and one with Obesity, the AUC value was excluded from the analysis, because the full circadian night (from DLMO to DLMOff) could not be reliably captured.

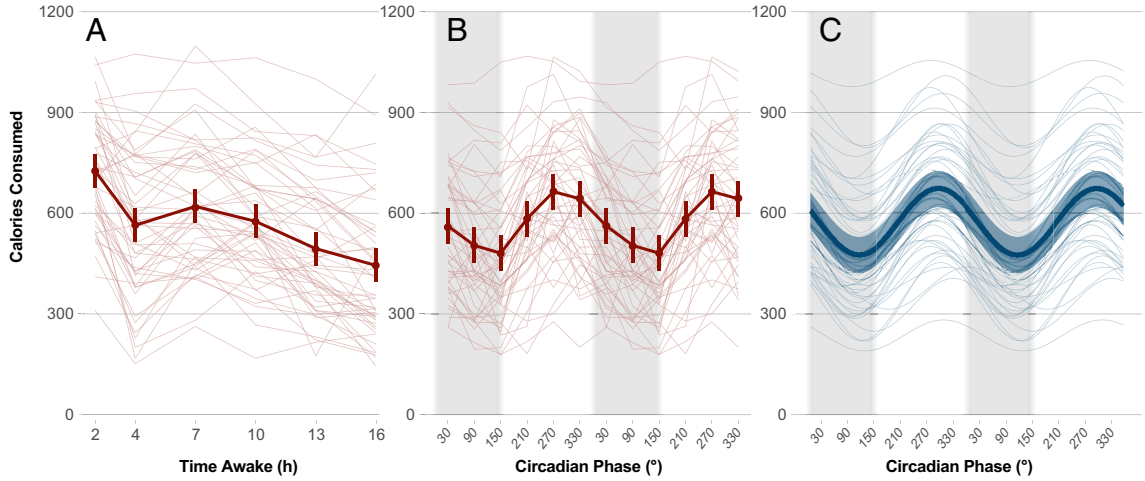

Fig. 1. Behavioral cycle and endogenous circadian influence on caloric intake. (*A*) Estimated means and 95% CI of calories consumed per meal across the behavioral cycle. Lighter lines represent individual participant means. (*B*) Estimated means and 95% CI across the endogenous circadian cycle using 60° circadian degree bins. Lighter lines represent individual participant means. (*C*) Estimated means and 95% confidence ribbon from the multilevel cosinor model. Lighter lines are best linear unbiased predictions from the cosinor model for individual participants. For circadian phase, 0° represents DLMO, ~21:21 [19:29; 23:13]. Shaded areas correspond to the interval between DLMOn and DLMOff.

the circadian acrophase to the average relative clock time in these participants meant that highest point of caloric intake due to the circadian system and independent from the behavioral cycle occurred at a relative clock time of ~17:30. Of interest, this circadian time of peak caloric intake was about 2 h earlier than the reported circadian maximum of hunger and appetite in adults, occurring at a circadian phase translated to a relative clock time of ~19:50 (9). The difference in acrophase may be due to age differences (adolescents here vs. adults in the previous study), outcome measure (caloric intake vs. hunger/appetite), and/or nutritional control (ad libitum intake vs. controlled intake). However, there is general consistency, also with other circadian studies assessing hunger in adults (10, 11), for a circadian peak in caloric intake (here) or drive for intake (prior studies) in the late afternoon or early evening and the minimum in the circadian morning.

Between-group differences in the circadian timing of caloric intake were seen for the two-group analyses (likelihood ratio test: $\chi^2[2] = 5.91$, $P = 0.05$) with more uncertainty in the three-group analyses ($\chi^2[4] = 7.44$, $P = 0.11$; Fig. 2). The group with OW/O showed their highest caloric intake at a later circadian phase (303° [291°, 316°]) than those with HW [290° (279°, 300°)]. The 13° difference represent just under a 1-h difference on a 24-h cycle. The three-group analysis indicated that the circadian peak phase of intake for the group with O was the latest (310° [292°, 327°]), intermediate for the group with OW (296° [279, 313]), and earliest for the group with HW (290° [279°, 300°]). The difference between those with O and those with HW was 20° or roughly 1 h 20 m on a 24-h cycle. Remarkably, the group with OW/O showed a smaller circadian amplitude (172 [129, 215] kcal/meal) compared to the group with HW (224 [202, 247] kcal/meal), representing a 23% reduction in amplitude. There were minimal differences in circadian amplitudes between the groups with O versus OW, both with amplitudes lower than the group with HW. Minimal differences were seen for the circadian influence on caloric intake dependent on self-reported pubertal status ($\chi^2[2] = 1.64$, $P = 0.44$) or self-reported sex ($\chi^2[2] = 0.58$, $P = 0.75$, *SI Appendix*).

With respect to the premeal hunger rating and the postmeal ratings of tastefulness, satisfaction, and fullness, a circadian influence was found for hunger (4.69 [2.12, 7.26] hunger rating scale [0 to 100]; 30% of mesor), tastefulness (0.26 [0.14, 0.38] postmeal

Table 2. Endogenous circadian and behavioral cycle parameters for caloric intake

	Whole sample	Healthy weight	Overweight/obese	Overweight	Obese
Mesor (kcal/meal)	573 [523, 623]	498 [437, 560]	639 [575, 703]	540 [456, 624]	732 [651, 812]
Circadian acrophase (degrees)	296° [288, 304]	290° [279, 300]	303° [291, 316]	296° [279, 313]	310° [292, 328]
Circadian peak-to-trough amplitude (kcal/meal)	196 [164, 227]	224 [202, 247]	172 [129, 215]	181 [150, 212]	167 [137, 197]
Behavioral difference, meals 1 to 6 (kcal/meal)	281 [256, 306]	296 [260, 332]	267 [233, 301]	347 [298, 396]	193 [146, 240]
Behavioral difference, meals 3 to 6 (kcal/meal)	176 [151, 200]	187 [151, 222]	166 [132, 200]	220 [170, 268]	116 [69,163]
Circadian peak-to-trough amplitude (% of mesor),	34	45	27	34	23
Behavioral difference, meals 1 to 6 (% of mesor)	49	59	42	64	26
Behavioral difference, meals 1 to 3 (% of mesor)	31	38	26	41	16

Notes: To better understand the magnitude of the circadian and behavioral influences, circadian peak-to-trough amplitude and difference between meals 1 and 6 and meals 3 and 6 are compared to the mesor.

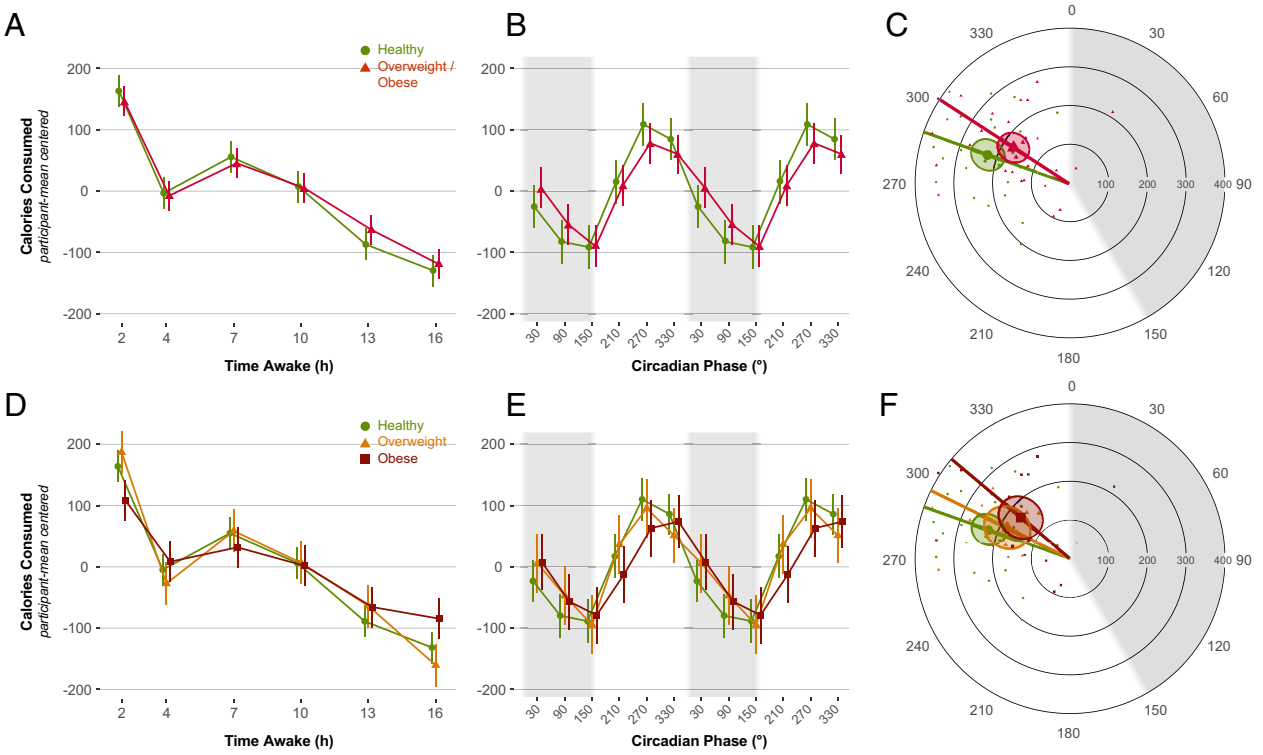

Fig. 2. Behavioral cycle and endogenous circadian influence on caloric intake by weight status group. Two weight status group data are shown in *A*, *B*, *C* as estimated mean and 95% CI for participant-mean centered calories consumed per meal across the behavioral cycle (*A*), double plotted estimated mean and 95% CI across the endogenous circadian cycle using 60° circadian degree bins (*B*), and radial plots depicting the sine term on the x-axis and the cosine term on the y-axis from the multilevel cosinor analysis (*C*). Plots D, E, F illustrate the same plots for the three weight status groups. In both radial plots, the angle from 0° depicts the acrophase, and the distance from the center shows the peak-to-trough amplitude; 95% confidence ellipses for the sine and cosine parameters are also plotted by weight status group. For circadian phase, 0° represents DLMO, ~21:21 [19:29; 23:13]. All shaded areas correspond to the interval between DLMOn and DLMOff.

scale [1 to 9]; 3% of mesor), and satisfaction (0.22 [0.11, 0.34] postmeal scale [1 to 9]; 3% mesor). The circadian peaks were at 279° [249, 309] for hunger, 316° [292, 341] for tastefulness, and 319° [294, 344] for satisfaction, translated to be around 16:30 to 18:30 in this population, remarkably consistent with the acrophase of caloric intake. Differences in amplitude for premeal hunger ratings occurred among weight status groups; those with OW/O showed small amplitude (1.94 [0.23, 3.64]; 12% of mesor) compared to a several-fold larger circadian rhythm in hunger for those with HW (7.79 [5.98, 9.59]; 52% of mesor). Tastefulness and satisfaction ratings were minimally different among groups. There was minimal variation among reports of fullness following meals with 79% of responses at the ceiling of the measure precluding analysis of this measure. Full results for the premeal hunger and postmeal ratings are presented in *SI Appendix*.

Discussion of the Circadian System Influences. A growing body of literature suggests a link between the circadian timing system, caloric intake, and weight status (4, 12, 13). Late eating has been linked to increased body mass in adults, children, and adolescents in observational studies (14–19). Disrupted circadian timing due to shift work or social jet lag has been linked to weight status (20, 21). Associations are also found between weight status and later circadian phase of eating (17, 22), delayed rest–activity cycle (23), and genetic markers of the circadian system (24). Experimental work in humans has linked timing of caloric intake to the metabolic system (25–27), and evidence from clinical trials of overweight/obesity care programs show increased weight loss for interventions that encourage greater caloric intake earlier in the day (28–31). Evidence from clock-mutant mice suggests disruption to the circadian timing system results in attenuated 24-h rhythm amplitude of caloric intake and higher rates of obesity (32). While a few studies have tested for the existence of an endogenous circadian rhythm in eating-related outcomes such as hunger, appetite, or self-reported presence/absence of meals using circadian protocols (9, 11, 22, 33, 34), none of these previous studies assessed caloric intake under the necessary controlled conditions nor did they include participants with obesity.

The later circadian peak phase of caloric intake, representing the circadian evening, for those with OW or O is consistent with the observations that adults with OW or O tend to eat more of their calories later in the day (15, 16, 18). Investigating the neurological, neuroendocrine, and molecular mechanisms that link the delayed circadian and behavioral-cycle control of caloric intake with weight regulation is an important area for future work.

The circadian pattern identified in the group with OW/O was flatter (reduced amplitude), suggesting a reduced regulatory impact of the circadian system on calorie consumption for this combined group. Given the minimal differences in the markers of fundamental properties of the central circadian oscillator reported above, including the circadian period, phase, and amplitude based on melatonin profiles, it is unlikely that the central circadian signal per se is weaker in the adolescents with a higher body mass index. Alternative explanations include a weaker circadian modulation of the biological drivers of hunger (e.g., leptin, ghrelin), differences in sensitivity to biologically meaningful signals, or increased influence of other drivers for eating behaviors (e.g., hedonic drivers, habits). Of interest, delayed eating times, impaired weight loss success, and higher body mass index have been correlated to decreases in circadian or daily amplitude of molecular rhythms in adipose tissue (35), autonomic nervous system activity (36), and rest activity rhythms (37). In rodents, light at night, which reduces the circadian rhythm amplitude of the central circadian clock located in the suprachiasmatic nucleus of the hypothalamus (SCN) and of the feeding rhythm,

resulted in an increase in body mass, which could be rescued by reestablishing an active-phase eating regimen (38, 39). Consistently, a recent meta-analysis identified light at night as a significant risk factor for obesity (40). More work is needed to understand whether the greatly reduced circadian control of caloric intake contributes to an increased risk for OW/O and/or whether OW/O results in a blunted circadian control of caloric intake. More work is also needed to understand how the demonstrated endogenous circadian influences on caloric intake during controlled conditions may interact with environmental, social, and behavioral distractors, pressures, and expectations.

Behavioral Cycle Influences Caloric Intake Differently by Weight Status Group. As illustrated in Fig. 2, weight status groups differed in distribution of caloric intake across wake episodes. For all groups, greatest caloric intake occurred at the first meal after the longest fasting duration of 13 h 22 m. On average, participants consumed 725 [675, 776] kcal during the first meal (around 2-h after scheduled awakening) compared to 445 [394, 495] kcal during the last meal (around 16 h after scheduled awakening). This general pattern was similar between those with OW/O and those with HW (χ^2[5] = 4.62, P = 0.46). However, there were differences when examining the three weight status groups (χ^2[10] = 29.18, P < 0.01), with adolescents with O showing a muted change across the wake episode in which intake was lower for the first meal (O: 108 [75, 142] kcal more than the participant-mean intake across all meals, OW 187 [1532, 221]; HW: 164 [139, 189]) and higher for the sixth meal compared to the other groups (O: −85 [−118, −51]; OW −161 [−195, -126]; HW: −132 [−157, −106]). Differences by self-reported pubertal status (χ^2[5] = 21.22, P < 0.01) showed that more mature compared with less mature participants had a more uniform distribution of caloric intake across the waking day (*SI Appendix*). There were minimal differences by self-reported sex (χ^2[5] = 9.74, P = 0.08). With respect to the premeal hunger rating and the postmeal ratings of tastefulness, satisfaction, and fullness, hunger showed the highest rating prior to the first meal (43.81 [39.75, 47.87] hunger rating scale [0 to 100]) and then dropped down to 12.72 to 17.19 for the remaining meals. Postmeal rating of tastefulness was highest following the first meal (8.15 [7.89, 8.41] postmeal scale [1 to 9]) and lowest following the last meal (7.61 [7.36, 7.87]). A similar pattern was seen for satisfaction following the first meal (8.46 [8.22, 8.69] post meal scale [1 to 9]) and the last meal (8.06 [7.83, 8.29]). There was minimal variation for fullness across meals. For all pre- and postmeal questions, there were negligible differences in the patterns across meals among weight status groups. Full results for the premeal and postmeal ratings are presented in *SI Appendix*.

Discussion of the Behavioral Cycle Influences. The pattern for all groups was an overall higher percentage of calories at the *first* meal after waking when accounting for the influence of the circadian system. Superficially, this may appear to differ from reports of observational studies under natural conditions in which less food is consumed at breakfast compared to other meals during the day (41, 42). This difference may be due to a longer fasting period (13 h 22 m) than what is typical in naturalistic studies and in this way may have led to a larger variation of caloric intake due to the behavioral cycle influence than occurs in typical life. Furthermore, in naturalistic studies, the influence of the circadian system likely counteracts the influence of the behavioral cycle on food intake across the eating/fasting cycle. Indeed, the influence of the endogenous circadian system on hunger and appetite has been shown to result in a lower drive for food intake during the circadian morning (9), and in the current study, the same is shown both for the circadian minimum in hunger and caloric intake during the circadian morning. These factors could explain why under natural settings that include a sleep/wake and fasting/eating cycle, less food is consumed at breakfast. Importantly, the FD design decouples the behavioral cycle influences from the circadian system as the first meal (as well as each other meal) occurred in a distributed manner across the circadian cycle during the protocol. This enabled the assessment of behavioral cycle influences separately from the circadian-driven modulation of caloric intake. Moreover, many of the social or contextual cues for what and how much should be eaten at various times of the waking day were removed by design. For example, our participants were presented with the same menu for each meal, had six meals at fixed times since scheduled awakening each day, ate their food by themselves in their rooms, and were in a dim light environment with no temporal cues. The observed behavioral cycle pattern is thus primarily driven by time since scheduled awakening (and the associated behaviors, including the eating schedule) and not necessarily consistent with what would be seen when the time awake is aligned with social context and circadian influences. Both our circadian and behavioral cycle findings are consistent with previous literature showing that adolescents with OW or O eat more calories later in the day compared to those with HW (15, 16, 18).

Comparison of Circadian and Behavioral Cycle Influences. To compare the strength of the circadian and behavioral cycles, we calculated the circadian peak-to-trough amplitude and the difference between meals 1 and 6 as percent of the mesor. The strength of the circadian peak-to-trough amplitude (34% of mesor) was lower than the kcal/meal difference from meal-1 to meal-6 (49% of mesor). Because the fasting interval between the scheduled meals ranged between 3 h and 13 h 22 m, we also compared the variation in caloric intake between those meals that were preceded by the same fasting interval of 3 h (i.e., meals-3 through-6), which was similar to the circadian peak-to-trough amplitude (31% of mesor). The difference between the circadian peak-to-trough amplitude and the kcal/meal difference from meal-1 to meal-6 was smallest for those with obesity (23% vs 26% of mesor), followed by those with healthy weight (45% vs 59%) and largest for those with overweight (34% vs 64%). Differences among weight status groups were largely driven by the distribution of caloric intake across the behavioral cycle.

Summary. The endogenous circadian system—separate from any influence of behavioral and environmental influences—showed a substantial variation in caloric intake in youth with a peak in the late circadian afternoon and a trough in the circadian morning. This circadian rhythm in caloric intake was weaker and more delayed in youth with overweight and obesity as compared to those with healthy weight. In parallel, caloric intake showed less variation across the waking day separated from the circadian influence for youth with overweight or obesity compared to those with healthy weight. The strengths of the protocol included the Forced Desynchrony protocol that enables the separation of endogenous circadian vs. behavioral cycle influences; controlled assessment of caloric intake and associated ratings of hunger and satisfaction; and a study population of youth across several weight status groups. Future studies are needed to determine underlying neuroendocrine, metabolic, and molecular mechanisms and their translational relevance.

Materials and Methods

Fifty-nine participants were admitted into the in-laboratory study and fifty-one (85%) adolescents (mean age: 13.7 y; range 12.4 to 15.9 y; 22 female) completed the study

between 2014 and 2018 with usable data. Of those who did not complete the protocol, one left early due to non-serious illness unrelated to study procedures, five withdrew due to home sickness, and two had unusable data. Participants were recruited to form roughly equal groups of those with healthy weight (HW; 5%<BMI%ile <85%) and those with overweight (85%≤BMI%ile <95%) or obesity (95%≥BMI%ile) based on CDC guidelines (43). Eligible participants were aged 12 to 17 y, able to speak and read English, and with at least one English-speaking parent. Exclusion criteria were the following: history of sleep, medical, or psychological disorders; self or first-degree relative with bipolar illness diagnosis or genetically transmitted neurological disorder; irregular sleep schedules (i.e., vary >3 h across the week by self-report); evidence of learning disabilities or a physical handicap that would interfere with testing; travel beyond two time zones in the two months before in-laboratory assessments; or presence of food allergy or restricted dietary regimen (e.g., religious requirements), including current weight loss attempt or treatment. Current use of psychoactive substances or other drugs that might affect the sleep/wake cycle, sleepiness/alertness, or circadian timing were also exclusionary and absence was confirmed with urine toxicology screening. All participants were in normal range for the parent- and youth-reported Child Behavior Checklist (44) and Center for Epidemiological Studies Depression Scale (45). The study was approved by the Rhode Island Hospital Institutional Review Board for Human Subjects (FWA00001230), and participants were treated in accordance with the Declaration of Helsinki for Medical Research involving Human Subjects. Parents and participants were paid in compensation for their time. Written parental consent and participant assent were obtained.

Prior to coming into the laboratory, participants slept on a fixed 10-h (21:30 to 07:30) stabilization schedule at home for approximately 14 nights (wearing eyeshades for sleeping hours) (*SI Appendix*, Fig. S1). Actigraph monitoring (46), daily sleep diary, and evening and morning calls to the laboratory's time-stamped answering machine were used to confirm adherence to this schedule. The in-laboratory portion of the study lasted 11 d and 10 nights and began with a 10-h (22:00 to 08:00) "adaptation night" to allow participants to adapt to the laboratory setting and to screen for sleep-disordered breathing and periodic limb movements (none were detected). The adaptation night was delayed by 30 min relative to the fixed sleep timing at home to facilitate the capture of the first DLMO phase. The adaptation night was followed by an "adaptation day" during which participants learned and practiced study-related tasks. The meal protocol was also introduced where participants were given tasting "bites" of unfamiliar menu items, and the meal ordering system was practiced.

The 28-h FD schedule began at bedtime on the adaptation day and continued for seven cycles (*SI Appendix*, Figs. S1 and S2) (47), in which 17.5 h were scheduled for wake and 10.5 h were scheduled for sleep. To avoid suppressing melatonin production, the light level in the laboratory was completely dark (0 lux) during the scheduled hours of sleep and dim (mean = 6.58 lux, SD = 3.58 lux, measured beside the eyes in the angle of gaze) during the waking hours. Light levels of less than 10 lux have been shown to have a negligible effect on the circadian system in humans (48), and similar light levels have been used in many FD protocols (6). Participants were never informed of the clock time of day to minimize expectancies based on awareness of time. Internet, mobile phone, live radio, TV, and video game play were not permitted; instead, a camp-like atmosphere was implemented for intervals that involved no testing. Activities included board games, craft making, brief stretching (tai chi), and video movie watching. By completing seven FD cycles, participants were scheduled for both sleep and wake across a full range of circadian phases.

Caloric Intake. Meals were scheduled regularly across the 17.5 waking hours with the first meal occurring around 2 h following the start of the scheduled wake episode, the second occurring around 2 h after the first, and the four subsequent meals at 3-h intervals. The shorter lag between the first and second meals was due to delaying the first meal to accommodate morning routines (i.e., showering, removing night-time polysomnography hookups, etc.).

Participants were presented with a menu for each meal approximately 50 min before the meal was served. The menu included a set of entrée items and options of "side" items: vegetable, fruit, dessert, beverage (*SI Appendix*, Fig. S3). Participants were asked to select 1 main item, 1 bread item, 2 sides, 1 sweet, and 1 drink at each meal, with salad items and condiment items being optional at each meal. Entrees and sweet item selections were not repeatable on consecutive meals on the same scheduled wake period. The menus were informed by pilot work and designed by H.R. for quantities of each food type option to have roughly equivalent energy densities. Selected meals were prepared, measured, and weighed by study personnel, and consumed by participants in private to minimize social influences on eating. The menu and serving sizes were the same for all participants and more than the expected 28-h needs. Participants were given approximately 18 min to eat, were not required to finish the provided food, and the unconsumed food was weighed. This design allowed a more structured assessment of the circadian control of caloric intake during standardized eating events where distractors were removed. If dedicated eating events had not been implemented, then, for example, eating events could have occurred while participants were in the middle of playing a game, engaged in a conversation, or immersed in a book. Indeed, if people are in the middle of such activities, they may be less likely to think about and/or initiate a meal. Furthermore, this also allowed us more social control, such that eating choices and eating behaviors would be less influenced by social expectations or pressures.

The difference between the pre- and postmeal weights was used to calculate the quantity (grams) of each food item consumed. The macronutrient content of each food item on the menu was obtained by comparing three sources, the Nutrition Data System for Research (NDSR) (49), the USDA National Nutrient Database for Standard Reference (50), and the product label. For 73 of 92 menu items, all three sources were similar (i.e., <10% discrepancy). For these items, the NDSR was used as it provided the most comprehensive nutrient information of the three sources. The discrepancy for the remaining 19 items was due to the NDSR not having a good match for the menu item. For these items, the USDA standard reference was used for 13 items, and the product label was used for 6 items. Consensus decisions about which nutrient information to reference were made by the study team. Participants' weights were measured at the beginning of their in-lab participation on the morning after the adaptation night and at the end of their stay on the morning before their departure.

Circadian Phase Determination. The study used salivary DLMO to determine the endogenous circadian phase of the central clock (51). Salivary (vs. plasma) melatonin measurement is particularly apt for children and adolescents, especially as in this study when frequent sampling is needed over a long interval. Saliva samples (~5 mL) were collected using Salivettes (Sarstedt Inc., Newton, NC) during FD waking episodes at 20 to 45-min intervals, most often 30 min. Samples were centrifuged and frozen (−20° C) within 4 h of collection and analyzed by radioimmunoassay (Solid Phase, Portland, ME using Alpco melatonin kits, Bühlmann Laboratories, Allschwil, Switzerland) with a sensitivity of 0.3 pg/mL, intraassay coefficient of variation 7.9%, and interassay coefficient of variance 11.7%. DLMO phase (i.e., circadian phase) was determined for each participant by linear interpolation between rising values crossing a threshold value of 4 pg/mL (the standard threshold to determine salivatory melatonin onset in this age group) (51, 52). This measure was calculated for each day when the rising threshold occurred during waking hours. The intrinsic circadian period for each participant was subsequently estimated using linear regression of all DLMO phase determinations. Each meal was then assigned a circadian phase (0° to 360°, with 0° representing DLMO) by subtracting the first estimated DLMO from the mealtime and rescaling using each individual's computed period. For this sample, the mean initial DLMO phase was a clock time of ~21:21 [95% CI=19:29; 23:13]).

Other Measures.

Sleep. Continuous polysomnographic recordings during all sleep episodes were made using Compumedics Grael recording systems (Charlotte, NC), digitized, and stored with a sampling rate of 400 samples per second. Polysomnograms were analyzed using VitaScore software; records were visually scored in 30-sec epochs according to standard criteria (Rechtschaffen & Kales, 1968). Sleep scoring technologists have inter- and intrarater reliability assessed every 10 records to a level of >0.85.

Pubertal development. Self-reported pubertal stage was assessed using the Pubertal Development Scale (53). Responses on the questionnaire were scored to convert to a 1 to 5 scale score, with 1 indicating that the individual is prepubertal and 5 indicating that the individual is postpubertal. Due to few participants in pre/early puberty and on the basis of a recent validation study (54), we classified participants into two groups defined as "early puberty" (stages 1,2,3; N = 24) and "late puberty" (stages 4,5; N = 28).

Estimated Energy Requirement. For each participant for the 28-h sleep/wake cycle during the FD was calculated based on age, gender, height, and weight according to formulas published by the Institute of Medicine (55) and proportionally scaled up to meet the longer 28-h sleep/wake cycle and using a physical

activity coefficient of 1.0, as the activity level for participants was low while in the laboratory setting.

Morningness/eveningness preference. As part of the final screening process, participants completed the 13-item morningness scale of Smith et al. (56), which provides a continuous score ranging from 13 to 55, with lower scores indicating a greater evening preference.

Premeal hunger. Participants completed a set of visual analog measures at approximately 30-min intervals throughout all waking phases of the in-lab protocols to assess sleepiness, mood, and hunger. The hunger measure administered just prior to each meal was included in analyses (2 min prior to meal 1 of the day; 27 min prior to meals 2 through 6).

Postmeal scales. A 3-item scale was administered at the completion of each meal. On a 9-point Likert scale, participants were asked the following questions: "Now that you have finished your meal, please circle a number to rate how tasty, yummy, delicious it was to you" with ratings ranging from 1 = "not at all delicious" to 9 = "extremely delicious"; "Now that you have finished your meal, please circle a number to rate how satisfied you feel by what you ate" with ratings ranging from 1 = "not at all satisfied" to 9 = "extremely satisfied"; and "Now that you have finished your meal, please circle a number to rate how full you feel by what you ate" with ratings ranging from 1 = "not at all full" to 9 = "extremely" full.

Statistical Analysis.

Demographics. Demographic differences among weight status groups were analyzed using chi-square and general linear models depending on the variable. Effect sizes were estimated using standardized mean differences to place all effect size estimates in the same metric (57) using the tableone R v0.13.0 package.

Circadian variables. General linear models were used to evaluate between-group differences in initial DLMO phase and estimated circadian period across the entire FD protocol. We also examined group differences in the melatonin curves from the third protocol day (FD-3) as the wake episode overlapped with the biological night allowing for the observation of the full melatonin curve for all but two participants. We calculated the area under the curve for each participant using the trapezoidal method.

Circadian influence on caloric intake and meal-related questions. A multilevel cosinor analysis was used to evaluate the hypothesis that caloric intake would be under endogenous circadian control (i.e., independent of behavioral and environmental factors) and that participants with higher weight status would consume more calories at a later circadian phase. A cosine transformation with period equal to the circadian period for each participant was used to transform the cyclical circadian pattern into a linear pattern that could be estimated using Bayesian linear mixed effect (BLME) regression (58, 59). Fixed effects included the sine and cosine parameters from the transformation, time awake entered as a categorical covariate, and time since start of the FD protocol entered as a linear effect to account for any trends across the in-laboratory protocol. Individual-level random effects included the intercept, sine, and cosine parameters. Estimates for the mesor (Midline Estimating Statistic of Rhythm, or rhythm-adjusted mean), acrophase (phase of peak), and peak-to-trough amplitude were produced through nonlinear transformations with SE and 95% CI calculated using Taylor series expansion (58). We chose to present peak-to-trough amplitude to enable direct comparison of the range of circadian variation with the range across the behavioral cycle. We used a minimally informative Wishart prior for the covariance matrix of random effects using the blme v1.0-5 R-package. The minimally informative prior helped reduce singular covariance matrices. Differences among groups were evaluated by including group in the model and allowing the group variable to interact with the other fixed effects. Likelihood ratio tests were used to evaluate group differences across both sine and cosine parameters. The nested models that were compared included one where fixed effects were constrained across groups and one where they were allowed to vary. Fig. 1 included model-derived best linear unbiased predictions for each participant. Cosinor estimates were depicted using radial plotting, where the cosine term from the linear regressions is plotted on the y-axis and the sine term on the x-axis. The angle from 0° illustrates the acrophase, and the distance from the center of the radial shows the peak-to-trough amplitude. Confidence ellipses (95%) for these two parameters were calculated and shown. Radial plots included individual-level cosinor estimates generated using linear regression. We also show plots from analyses where circadian degree was collapsed into 60° bins. Binned parameters were estimated using BLME with fixed effects including circadian bins, time awake, and time since start of protocol and an individual-level random effect for intercept. Fig. 1 included individual participant means across the FD protocol for each bin.

Alternative specification. The number of calories consumed at each meal was expected to be influenced by time since scheduled waking, circadian phase, individual characteristics (weight status, gender, pubertal status, among others), and time since the start of the FD protocol. The specification described above maintains an interpretable metric of calories consumed per meal but assumes a linear influence for time since start of FD protocol and does not account for other individual characteristics other than the one being evaluated in the model (e.g., weight status, gender, pubertal status). An alternative specification would be to calculate the percent of total calories consumed during each waking episode for each meal by individual, which effectively normalized the data by individual and waking episode. This approach removes the influence of individual characteristics and time since start of protocol, but it also removes between-day variation in the total number of calories consumed on protocol days that occurred at different circadian phases. This alternative approach showed more pronounced differences among participants with different weight status groups (*SI Appendix*).

Behavioral cycle influence on caloric intake and meal-related questions. BLME regression was again used to test the hypothesis that participants with a higher BMI would consume more of their calories later in the wake episode. Fixed effects included time awake defined by scheduled mealtime from protocol lights-on and entered as a categorical variable (i.e., meal number), weight status group, the interaction between weight status group and meal number, sine, cosine, and time-in-study. Intercept was included as a random effect. Figures were generated using participant-mean centered data to emphasize the distribution of scores across meals and minimize the overall differences among weight status groups. Fig. 1 included individual participant means across the FD protocol for each meal.

Sex and pubertal development. To examine the influence of sex and pubertal development, we replaced weight status with sex and then pubertal development for all models. We did not cross the weight status, sex, and pubertal development groups due to limited sample size for such comparisons.

Data, Materials, and Software Availability. Anonymized Analytic Datasets and R Syntax used to generate results data have been deposited in ICPSR (https://doi.org/10.3886/E212602V1) (60).

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1. M. Blüher, Obesity: Global epidemiology and pathogenesis. *Nat. Rev. Endocrinol.* **15**, 288–298 (2019).
2. B. Stierman *et al.*, NHSR 158. National Health and Nutrition Examination Survey 2017–March 2020 Pre-Pandemic Data Files (2021). https://stacks.cdc.gov/view/cdc/106273. Accessed 15 June 2023.
3. E. A. Finkelstein *et al.*, Obesity and severe obesity forecasts through 2030. *Am. J. Prev. Med.* **42**, 563–570 (2012).
4. J.-P. Chaput *et al.*, The role of insufficient sleep and circadian misalignment in obesity. *Nat. Rev. Endocrinol.* **19**, 82–97 (2023).
5. M. Simmonds, A. Llewellyn, C. G. Owen, N. Woolacott, Predicting adult obesity from childhood obesity: A systematic review and meta-analysis. *Obes. Rev.* **17**, 95–107 (2016).

6. W. Wang *et al.*, Desynchronizing the sleep–-wake cycle from circadian timing to assess their separate contributions to physiology and behaviour and to estimate intrinsic circadian period. *Nat. Protoc.* **18**, 579–603 (2023).
7. A. W. McHill *et al.*, Obesity alters the circadian profiles of energy metabolism and glucose regulation in humans. *Obes. Silver Spring Md* **32**, 315–323 (2024).
8. S. Mäntele *et al.*, Daily rhythms of plasma melatonin, but not plasma leptin or leptin mRNA, vary between lean, obese and type 2 diabetic men. *PloS One* **7**, e37123 (2012).
9. F. A. J. L. Scheer, C. J. Morris, S. A. Shea, The internal circadian clock increases hunger and appetite in the evening independent of food intake and other behaviors. *Obes. Silver Spring Md* **21**, 421–423 (2013).
10. A. W. McHill, J. T. Hull, C. J. McMullan, E. B. Klerman, Chronic insufficient sleep has a limited impact on circadian rhythmicity of subjective hunger and awakening fasted metabolic hormones. *Front. Endocrinol.* **9**, 319 (2018).
11. S. M. T. Wehrens *et al.*, Meal timing regulates the human circadian system. *Curr. Biol. CB* **27**, 1768–1775.e3 (2017).
12. Y. Serin, N. Acar Tek, Effect of circadian rhythm on metabolic processes and the regulation of energy balance. *Ann. Nutr. Metab.* **74**, 322–330 (2019).
13. H. L. Boege, M. Z. Bhatti, M.-P. St-Onge, Circadian rhythms and meal timing: Impact on energy balance and body weight. *Curr. Opin. Biotechnol.* **70**, 1–6 (2021).
14. S. Bo *et al.*, Consuming more of daily caloric intake at dinner predisposes to obesity. A 6-year population-based prospective cohort study. *PloS ONE* **9**, e108467 (2014).
15. R. K. Golley, C. A. Maher, L. Matricciani, T. S. Olds, Sleep duration or bedtime? Exploring the association between sleep timing behaviour, diet and BMI in children and adolescents *Int. J. Obes.* **2005 37**, 546–551 (2013).
16. N. Martínez-Lozano *et al.*, Late eating is associated with obesity, inflammatory markers and circadian-related disturbances in school-aged children. *Nutrients* **12**, 2881 (2020).
17. A. W. McHill *et al.*, Later circadian timing of food intake is associated with increased body fat. *Am. J. Clin. Nutr.* **106**, 1213–1219 (2017).
18. A. L. Miller, J. C. Lumeng, M. K. LeBourgeois, Sleep patterns and obesity in childhood. *Curr. Opin. Endocrinol. Diabetes Obes.* **22**, 41–47 (2015).
19. J. B. Wang *et al.*, Timing of energy intake during the day is associated with the risk of obesity in adults. *J. Hum. Nutr. Diet. Off. J. Br. Diet. Assoc.* **27**, 255–262 (2014).
20. Q. Liu *et al.*, Is shift work associated with a higher risk of overweight or obesity? A systematic review of observational studies with meta-analysis. *Int. J. Epidemiol.* **47**, 1956–1971 (2018).
21. A. Arab, E. Karimi, M. Garaulet, F. A. J. L. Scheer, Social jetlag and obesity: A systematic review and meta-analysis. *Obes. Rev. Off. J. Int. Assoc. Study Obes.* **25**, e13664 (2024).
22. A. W. McHill *et al.*, Caloric and macronutrient intake differ with circadian phase and between lean and overweight young adults. *Nutrients* **11**, 587 (2019).
23. S. Ogbagaber, P. S. Albert, D. Lewin, R. J. Iannotti, Summer activity patterns among teenage girls: Harmonic shape invariant modeling to estimate circadian cycles. *J. Circadian Rhythms* **10**, 2 (2012).
24. M. Garaulet *et al.*, Timing of food intake predicts weight loss effectiveness. *Int. J. Obes.* **37**, 604–611 (2013).
25. C. Bandín *et al.*, Meal timing affects glucose tolerance, substrate oxidation and circadian-related variables: A randomized, crossover trial. *Int. J. Obes.* **39**, 828–833 (2015).
26. C. N. Hart *et al.*, Effect of changes in children's bedtime and sleep period on targeted eating behaviors and timing of caloric intake. *Eat. Behav.* **45**, 101629 (2022).
27. N. Vujović *et al.*, Late isocaloric eating increases hunger, decreases energy expenditure, and modifies metabolic pathways in adults with overweight and obesity. *Cell Metab.* **34**, 1486–1498.e7 (2022).
28. D. Jakubowicz, M. Barnea, J. Wainstein, O. Froy, High caloric intake at breakfast vs. dinner differentially influences weight loss of overweight and obese women. *Obes. Silver Spring Md* **21**, 2504–2512 (2013).
29. M. Lombardo *et al.*, Morning meal more efficient for fat loss in a 3-month lifestyle intervention. *J. Am. Coll. Nutr.* **33**, 198–205 (2014).
30. H. A. Raynor, F. Li, C. Cardoso, Daily pattern of energy distribution and weight loss. *Physiol. Behav.* **192**, 167–172 (2018).
31. I. E. Young, A. Poobalan, K. Steinbeck, H. T. O'Connor, H. M. Parker, Distribution of energy intake across the day and weight loss: A systematic review and meta-analysis. *Obes. Rev. Off. J. Int. Assoc. Study Obes.* **24**, e13537 (2023).
32. F. W. Turek *et al.*, Obesity and metabolic syndrome in circadian Clock mutant mice. *Science* **308**, 1043–1045 (2005).
33. J. Waterhouse *et al.*, Lack of evidence for a marked endogenous component determining food intake in humans during forced desynchrony. *Chronobiol. Int.* **21**, 445–468 (2004).
34. C. A. Rynders, S. J. Morton, D. H. Bessesen, K. P. Wright, J. L. Broussard, Circadian rhythm of substrate oxidation and hormonal regulators of energy balance. *Obes. Silver Spring Md* **28**, S104–S113 (2020).
35. M. Arredondo-Amador *et al.*, Circadian rhythms in hormone-sensitive lipase in human adipose tissue: Relationship to meal timing and fasting duration. *J. Clin. Endocrinol. Metab.* **105**, e4407–e4416 (2020).
36. M.-T. Lo *et al.*, CLOCK 3111T/C genetic variant influences the daily rhythm of autonomic nervous function: Relevance to body weight control. *Int. J. Obes.* **42**, 190–197 (2018).
37. J. Qian *et al.*, Blunted rest-activity rhythms link to higher body mass index and inflammatory markers in children. *Sleep* **44**, zsaa256 (2021).
38. C. P. Coomans *et al.*, Detrimental effects of constant light exposure and high-fat diet on circadian energy metabolism and insulin sensitivity. *FASEB J. Off. Publ. Fed. Am. Soc. Exp. Biol.* **27**, 1721–1732 (2013).
39. L. K. Fonken, Z. M. Weil, R. J. Nelson, Dark nights reverse metabolic disruption caused by dim light at night. *Obes. Silver Spring Md* **21**, 1159–1164 (2013).
40. K. Y. Lai, C. Sarkar, M. Y. Ni, J. Gallacher, C. Webster, Exposure to light at night (LAN) and risk of obesity: A systematic review and meta-analysis of observational studies. *Environ. Res.* **187**, 109637 (2020).
41. J. M. de Castro, The time of day of food intake influences overall intake in humans. *J. Nutr.* **134**, 104–111 (2004).
42. S. Gill, S. Panda, A smartphone app reveals erratic diurnal eating patterns in humans that can be modulated for health benefits. *Cell Metab.* **22**, 789–798 (2015).
43. R. J. Kuczmarski *et al.*, CDC growth charts: United States. *Adv. Data* **314**, 1–27 (2000).
44. T. M. Achenback, Rescorla, *Manual for the ASEBA School-Age Forms & Profiles* (ASEBA, Burlington, VT, 2001).
45. L. S. Radloff, The CES-D scale: A self-report depression scale for research in the general population. *Appl. Psychol. Meas.* **1**, 385–401 (1977).
46. C. Acebo andamp, M. K. LeBourgeois, Actigraphy. *Respir. Care Clin. N. Am.* **12**, 23–30 (2006).
47. R. S. Herz *et al.*, The influence of circadian timing on olfactory sensitivity. *Chem. Senses* **43**, 45–51 (2017).
48. J. M. Zeitzer, D. J. Dijk, R. Kronauer, E. Brown, C. Czeisler, Sensitivity of the human circadian pacemaker to nocturnal light: Melatonin phase resetting and suppression. *J. Physiol.* **526**, 695–702 (2000).
49. Nutrition Coordinating Center, *Nutrition Data System for Research Software* (University of Minnesota, Minneapolis, MN, 2014).
50. US Department of Agriculture, *Agricultural Research Service, Nutrient Data Laboratory, USDA National Nutrient Database for Standard Reference Release 27* (US Department of Agriculture, 2015).
51. M. A. Carskadon, C. Acebo, G. S. Richardson, B. A. Tate, R. Seifer, An approach to studying circadian rhythms of adolescent humans. *J. Biol. Rhythms* **12**, 278–289 (1997).
52. S. J. Crowley *et al.*, Estimating the dim light melatonin onset of adolescents within a 6-h sampling window: The impact of sampling rate and threshold method. *Sleep Med.* **20**, 59–66 (2016).
53. M. A. Carskadon, C. Acebo, A self-administered rating scale for pubertal development. *J. Adolesc. Health Off. Publ. Soc. Adolesc. Med.* **14**, 190–195 (1993).
54. M. E. Koopman-Verhoeff, C. Gredvig-Ardito, D. H. Barker, J. M. Saletin, M. A. Carskadon, Classifying pubertal development using child and parent report: Comparing the pubertal development scales to Tanner staging. *J. Adolesc. Health* **66**, 597–602 (2020). 10.1016/j.jadohealth.2019.11.308.
55. Institute of Medicine, *Dietary Reference Intakes for Energy, Carbohydrate, Fiber, Fat, Fatty Acids, Cholesterol, Protein, and Amino Acids* (The National Academies Press, Washington, DC, 2005). https://Doi.Org/10.17226/10490.
56. C. Smith, C. Reilly, K. Midkiff, Evaluation of three circadian rhythm questionnaires with suggestions for an improved measure of morningness. *J. Appl. Psychol.* **74**, 728–738 (1989).
57. D. Yang, J. E. Dalton, "A unified approach to measuring the effect size between two groups using SAS®" in *Proceedings of the SAS Global Forum 2012 Conference* (SAS Institute Inc., Cary, NC, 2012). https://support.sas.com/resources/papers/proceedings12/335-2012.pdf. Accessed 27 January 2020.
58. G. Cornelissen, Cosinor-based rhythmometry. *Theor. Biol. Med. Model.* **11**, 16 (2014).
59. R. Refinetti, G. C. Lissen, F. Halberg, Procedures for numerical analysis of circadian rhythms. *Biol. Rhythm Res.* **38**, 275–325 (2007).
60. M. Carskadon, D. Barker, Caloric intake in adolescents using a forced desynchrony design. OpenICPSR. https://doi.org/10.3886/E212602V1. Deposited 19 December 2024.