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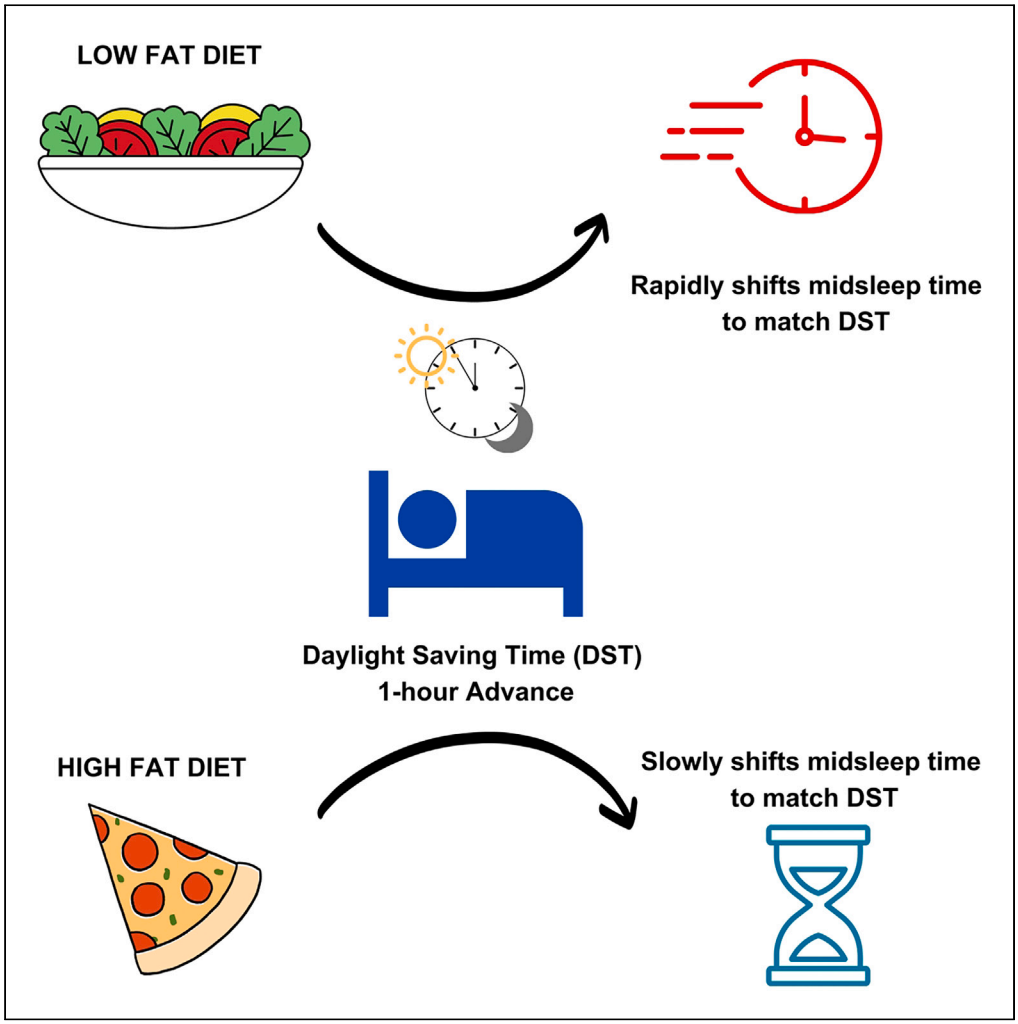

Andrew W. McHill, Akane Sano, Laura K. Barger, Andrew J.K. Phillips, Charles A. Czeisler, Elizabeth B. Klerman

mchill@ohsu.edu

Highlights

Sleep patterns are measured across DST as a natural experiment

A high-fat diet impairs the ability to shift sleep timing after DST

Impaired shifting is associated with lower GPA, general wellness, and higher BMI

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Adaptation of sleep to daylight saving time is slower in people consuming a high-fat diet

Andrew W. McHill,[1,2,9,*] Akane Sano,[3,4] Laura K. Barger,[5,6] Andrew J.K. Phillips,[6,7] Charles A. Czeisler,[5,6] and Elizabeth B. Klerman[5,6,8]

SUMMARY

Adaptation of the circadian clock to the environment is essential for optimal health, well-being, and performance. Animal models demonstrate that a high-fat diet impairs circadian adaptation to advances of the light-dark cycle; it is unknown whether this occurs in humans. Utilizing a natural experiment that occurs when humans must advance their behaviors to an earlier hour for daylight saving time (DST), we measured the influence of diet on sleep/wake timing relative to dim-light melatonin onset time. Students with a lower-fat diet rapidly altered their sleep-wake timing to match the imposed time change, whereas those with a high-fat diet were slower to adapt to the time change. Moreover, a faster shift in timing after DST was associated with higher general health, lower body mass index, and higher grade point average. These data suggest that diet may influence the speed of sleep and circadian adaptation, which could have implications for health and performance.

INTRODUCTION

Synchronization of the circadian clock to the 24-h cycle is vital for health. Even slight misalignment (<1 h) between the circadian clock and the environment can negatively impact health: individuals who live further west within a single time zone, and thus receive morning light at a later local clock time, have lower life expectancy and higher obesity, diabetes, and cancer rates.[1,2] Light is the most potent stimulus for the circadian clock, with morning light advancing the clock and evening light delaying the clock.[3] Recently, it was reported that the content of food can impact the circadian system's phase-shifting response to light in animal models. Rodents eating a high-fat diet had reduced ability to adapt their activity patterns to a new light-dark cycle.[4] Specifically, Mendoza and colleagues found that when mice were exposed to a 6-h advance in the light-dark cycle and fed a diet composed of ~50% of calories from fat for 3 weeks, the mice had a 20% slower rate of adaptation to the new light-dark cycle as compared to mice fed a low-fat diet.[4]

We hypothesized that a high-fat diet may impair how people respond to the socially imposed 1-h advance in local clock hour that arises from the Spring transition to daylight saving time (DST). We measured 1 week of diet via photographically recorded food diaries: circadian phase from an evening in-laboratory collection of salivary melatonin before DST and sleep and wakefulness timing from actigraphy before and after the DST shift in a group of undergraduate students (n = 37; Table S1), all living within the same city exposed to the same natural light-dark cycle. We also collected subjective levels of general health and measured body mass index (BMI). Because we were studying undergraduate students, we were also able to collect measures of academic performance (i.e., grade point average [GPA]) to identify potential cognitive metrics that might be affected by diet and/or rate of adaptation.

RESULTS

Although shifts in light-dark cycle timing in mice are not equivalent to the DST change in humans, they are informative to the question of the effects of light-dark cycle shifting and thus we aligned our analysis with the animal literature[4] and focused our investigation on the influence of a high-fat diet (defined here as a diet containing >40% of daily calories from fat) on sleep timing adaptation. The majority of the study population (n = 20, 10 male, 10 female; 54%) ate a low-fat diet (defined here as a diet containing <35% of daily calories from fat), with 19% (n = 7, 4 male, 3 female) eating a high-fat diet and 27% (n = 10, 5 male, 5 female) consuming an intermediate-fat diet (diet containing between 35% and 40% of daily calories from fat). In regard to timing of this food intake, there were no group differences in the timing of first, midpoint, or last

[1]Sleep, Chronobiology, and Health Laboratory, School of Nursing, Oregon Health & Science University, Portland, OR 97239, USA
[2]Oregon Institute of Occupational Health Sciences, Oregon Health & Science University, Portland, OR 97239, USA
[3]Department of Electrical and Computer Engineering, Rice University, Houston, TX 77005, USA
[4]Affective Computing Group, Media Lab, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[5]Division of Sleep and Circadian Disorders, Departments of Medicine and Neurology, Brigham and Women's Hospital, Boston, MA 02115, USA
[6]Division of Sleep Medicine, Harvard Medical School, Boston, MA 02115, USA
[7]Flinders Health and Medical Research Institute (Sleep Health), Flinders University, Bedford Park, SA, Australia
[8]Department of Neurology, Massachusetts General Hospital, Boston, MA 02114, USA
[9]Lead contact
*Correspondence: mchill@ohsu.edu
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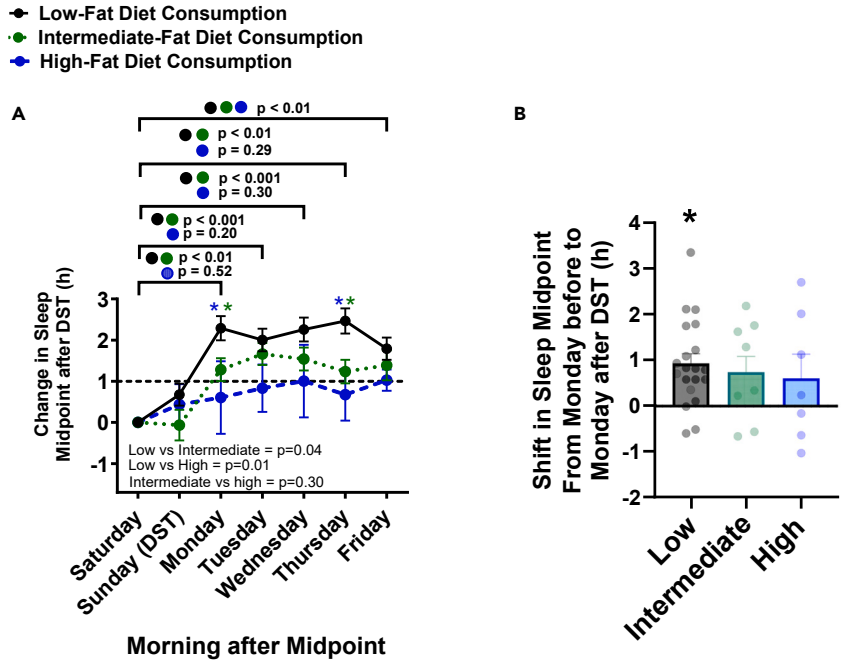

Figure 1. Change in midpoint of sleep after the 1-h local clock-time advance to daylight saving time (DST) and the magnitude of shift as compared to the week prior to DST as stratified by fat consumption

Participants (n = 37) were separated into groups that either habitually consumed a low-fat (<35% of daily calories consisting of fat; denoted by black line; n = 20), intermediate-fat (between 35% and 40% of daily calories consisting of fat; denoted by green circles and dotted line; n = 10), or high-fat (>40% of daily calories consisting of fat; denoted by blue circles and dashed line; n = 7) diet.

(A) The change in sleep midpoint was compared within groups using paired t test and between groups across the week of DST using linear effects mixed models and independent t test.

(B) The magnitude of shift in sleep midpoint from the Monday prior to DST to the Monday after DST to account for class/work schedules was compared using paired t test. p values for the within-group comparisons for the shift in midpoint relative to the Saturday immediately before DST are displayed in the top portion of the figure, and a colored asterisk indicates a significant difference ($p < 0.05$) between either the high-fat group (blue asterisk) or the intermediate-fat group (green asterisk) and the low-fat group. The black asterisk in (B) denotes a significant difference ($p < 0.05$) in the low-fat groups shift from the Monday before DST. All data are presented as mean ± standard error of the mean.

caloric intake (ANOVA; all $p > 0.14$). Additionally, there were no group differences in the variability of the timing of midpoint or eating duration (ANOVA; both $p > 0.31$).

Adaptation of sleep timing, relative to circadian timing, after DST

To measure adaptation to DST, we examined the shift in local time of the midpoint of actigraphically determined sleep immediately before and after DST. In order to account for individual differences in circadian phase and sleep timing, sleep midpoint for each day was referenced to each individual's dim-light melatonin onset (DLMO) (i.e., phase angle of entrainment), which was collected prior to DST (average ± stdev; range 11.8 ± 7.5; 1–29 days before DST start). There was no significant difference in phase angle of sleep ($F(2) = 1.65$, $p = 0.21$) the day before DST started between the low-, intermediate-, and high-fat eating groups. Thus, the groups were similar in sleep timing relative to circadian phase prior to DST start.

After DST started, the low-fat group rapidly shifted their sleep timing midpoint to match the advance in social/local clock hour; this shift in midpoint was maintained throughout the week (planned within-group comparisons from day before DST; all $p < 0.0001$; Figure 1A). Similarly, the intermediate-fat group also rapidly shifted their midpoint (all within-group comparisons; $p < 0.01$; Figure 1A), though this response was attenuated compared to the low-fat group (linear mixed model group effect; $F_{1,111} = 4.2$, $p = 0.04$). Unlike those in the low-fat and intermediate-fat groups, however, those that ate a high-fat diet did not significantly shift their midpoint until the Friday after DST (Monday–Thursday within comparisons; all $p > 0.20$; Friday $p < 0.01$; Figure 1A). When comparing the magnitude of shift between the low-fat and high-fat groups, there was a significant group effect ($F_{1,99} = 6.8$, $p = 0.01$), such that the low-fat group displayed a greater shift in their midpoint compared to the high-fat group across the week following DST (Figure 1A); there was no group effect between the intermediate-fat and high-fat groups ($F_{1,60} = 1.1$, $p = 0.30$). In comparing the midpoint of sleep relative to DLMO (phase angle) on the Monday before DST to the Monday after DST, thereby controlling for day-of-the-week-related class/other schedules and the weekend drift that led to the larger apparent shift in the low-fat group (>2 h in Figure 1A), we found that the low-fat group significantly shifted their sleep midpoint by 56 min ($p < 0.001$), the intermediate-fat group displayed a non-significant trend in shifting 44 min ($p = 0.06$), whereas the high-fat group did not significantly shift their sleep midpoint

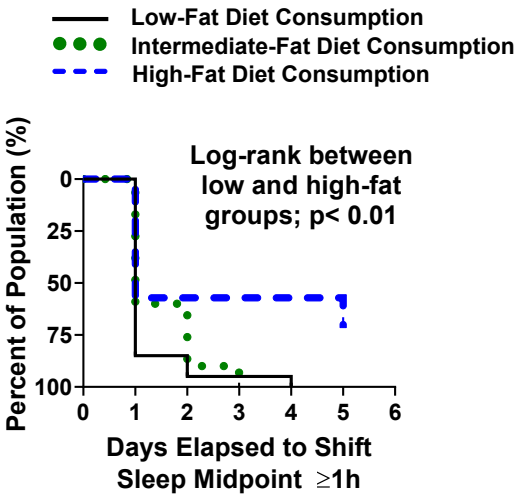

Figure 2. Speed of adaptation of sleep midpoint after the 1-h local clock-time advance to daylight saving time (DST) as stratified by fat consumption

Participants (n = 37) were separated into groups that either habitually consumed a low-fat (<35% of daily calories consisting of fat; denoted by black line; n = 20), intermediate-fat (between 35 and 40% of daily calories consisting of fat; denoted by green dotted line; n = 10), or high-fat (>40% of daily calories consisting of fat; denoted by blue dashed line; n = 7) diet. The speed of the shift in midpoint between groups was compared using Kaplan-Meier survival curves.

(36 min; p = 0.29), demonstrating a 35% attenuation in Monday entrainment as compared to the low-fat group (Figure 1B). We further tested this with matching other weekdays (e.g., Tuesdays before and after the DST shift) to again account for potential differences in class/other schedules and found that the observed significant differences in midpoint when matching weekdays persisted in the low-fat group throughout the week (all $p < 0.05$) but did not significantly shift (all $p > 0.18$) in the high-fat group until Thursday ($p < 0.01$).

Speed of the adaptation of sleep timing, relative to circadian timing, between differing fat composition diets

One way to quantify the speed of adaptation between the groups is to calculate the proportion of people in each group who shifted their midpoint by at least 1 h (to match the advance in the local clock) on each day after DST began. Overall, the low-fat diet group was able to shift their sleep midpoint more rapidly than the high-fat eating group (hazard ratio [HR] 0.12, 95% confidence interval [CI] 0.02–0.60; $p < 0.01$). On the Monday immediately after DST, 85% of the low-fat eating group, and 57% of the high-fat eating group, had shifted their sleep midpoint by 1 h (Figure 2). This proportion grew to 95% of the low-fat eating group, with no change in the high-fat eating group, by the Tuesday after DST. The remainder of the low-fat group shifted their sleep midpoint 1 h by the Thursday after DST, whereas 29% of the high-fat eating group had not shifted their midpoint by the Friday after DST (Figure 2). There was no significant difference in speed of adaptation between the low- and intermediate-fat (HR 0.58, 0.14–2.4; p = 0.46) or intermediate- and high-fat group (HR 1.8, 0.66–5.0; p = 0.10).

Implications of adaptation on health and well-being

To examine the potential dose-response relationship between fat intake and adaptation, we next tested the association between the percentage fat content in each individual's diet and the difference in phase angle between the day immediately before DST (Saturday) and the Monday immediately after DST. We found a significant negative relationship, such that those that ate more fat displayed a smaller shift in midpoint (Figure 3). We then investigated the relationship of circadian adaptation rate with health and performance. Specifically, we tested the association of shift in midpoint, fat content in diet, average sleep duration, and activity level with subjective feelings of general health, BMI, and overall academic performance (GPA) using correlation analyses. We focused on the difference on Monday as (1) it would correspond to the most severe circadian misalignment, and (2) it would be akin to the weekly misalignments that occur when individuals stay up late on the weekend/free day and then must awaken early on the following weekday/workday.[5,6] Though one day of impairment in the speed of adaptation likely does not directly result in these outcomes, impairment in the speed of adjusting to the artificial shift of 1 h may be indicative of smaller impairments the student is experiencing in shifting their sleep/wake schedule daily, which could chronically impair performance and health. We found significant correlations, such that the larger the shift in midpoint, the higher the students rated their level of general health, the lower their BMI, and the higher the student's GPA at the end of the Spring semester (Figure 3). No other variables, including activity or sleep duration, significantly predicted general health, BMI, or GPA (all $p > 0.06$), with the exception of fat content in diet, which was significantly associated with BMI (p = 0.04). Due to the significant association between fat content in diet and BMI, and because physical activity has been shown to influence phase shifting,[7] we next conducted multiple linear regression with fat content in diet, percent of days with exercise, and BMI as independent variables and magnitude of the shift as an independent variable. The model was significant ($F(3, 36) = 5.52$, p = 0.0035, R^2 = 0.33) with fat content in the diet as a significant predictor ($t = -3.03$, p = 0.005) while percent of days with exercise (t = 0.55, p = 0.59) and BMI were not ($t = -1.19$, p = 0.24).

DISCUSSION

In summary, we found that individuals eating a high-fat diet had slower adaptation of sleep timing immediately after the shift to DST. This slower adaptation at the beginning of a school/workweek is important, as sudden cardiac death occurs more often on Monday mornings

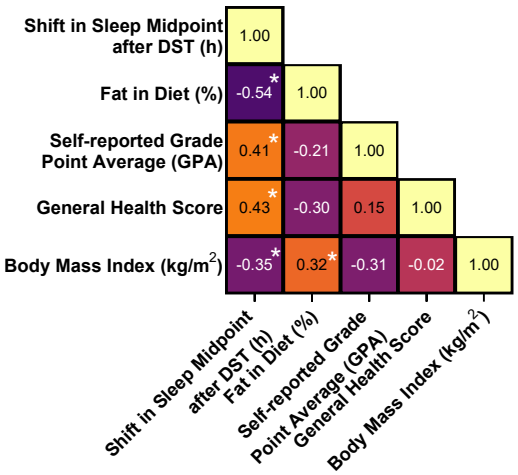

Figure 3. The association between sleep adaptation after the 1-h local clock-time advance to daylight saving time (DST) with health and academic performance

The relationship between the shift in sleep midpoint from the day prior to DST and the Monday after DST and percent of fat in diet, self-reported general health, body mass index (BMI), and self-reported GPA were assessed using Pearson correlations. R values are displayed in the matrix, with color denoting the strength of correlation; darker purple color denotes larger negative associations and darker orange color denotes larger positive associations. Asterisks indicate significant differences in association ($p < 0.05$).

than other weekdays,[8,9] myocardial infarction and traffic accidents increase following DST as compared to the weeks preceding,[10,11] and within a single time zone,[12] living further westward and thereby receiving morning light at a later local clock hour is associated with a lower life expectancy and higher obesity rates, diabetes, and more cancers than living more eastward.[1,2] Thus, any behavior, such as diet, that impairs adaptation could exacerbate these poor outcomes. Our findings support this concept, as those that adapted more slowly had a lower subjective level of general health, higher BMI, and lower GPA.

Mechanistically, it is not yet clear why diet would influence adaptation. One possibility is a potential dietary contribution to circadian light sensitivity, as there are large differences between people in the circadian clock's sensitivity to light,[13] with lower sensitivity in those with a higher fat diet. Another possibility is that those eating high-fat diets eat (and have light exposure) at later clock hours; this later light exposure would be expected to delay the circadian clock relative to local clock time, impeding adaptation to DST. There were no group differences in food timing, however, which also suggests that the timing of eating may not be an important factor in this relationship. Moreover, we recognize that other factors beyond the shift in phase angle may be driving these outcomes, particularly as it pertains to health outcomes and academic performance.

In rodent models, high-fat diets have been shown to disorganize sleep and circadian timing.[14–16] There has been limited examination, however, of how composition of diet acts on the sleep and circadian timing in humans. Kräuchi and colleagues examined the influence of the timing of a single high-carbohydrate meal and found that meals in the morning shifted the core body temperature rhythm earlier, potentially driven by the masking of sleep, but had no impact on melatonin rhythms.[17] Though the authors altered diet composition, it was an acute stimulus, and the primary focus was on the timing of that stimulus. Wehrens and colleagues[18] reported that shifting the timing of calories to a later circadian phase, with a standard low-fat diet, shifts peripheral circadian clocks, but has no impact on the central circadian clock. While these studies focused on shifting the timing of calories in eliciting a shift in phase, few studies to date have examined how the composition of a chronic diet influences sleep and circadian timing. Pivovarova and colleagues examined the impact of 6 weeks of a high-fat diet on mathematically predicted circadian phase (derived from few time points) on several physiological outputs and found a significant delay in a measured diurnal cortisol rhythm and several peripheral circadian markers.[19] Our findings provide additional evidence supporting the hypothesis that diet composition may impact sleep and circadian timing.

Diet composition may potentially be a relatively low-cost intervention to help individuals change circadian timing (e.g., for exogenous circadian rhythm sleep disorders such as jet lag or shift work or endogenous circadian rhythm sleep disorders such as delayed, advanced, non-24-h, or irregular sleep-wake sleep disorders) or maintain stable entrainment.

Limitations of the study

There are several limitations to consider. (1) This was an observational study in 37 people. (2) The population studied was mostly healthy college students. (3) We only had one assessment of DLMO and thus could not precisely track how the circadian timing system was shifting after DST and had to use shift in sleep midpoint relative to DLMO measured prior to DST as an estimate. Our study of three DLMO collections over 3 months in college students, nonetheless, found a stable DLMO.[20] (4) Though no participants reported consuming sleep aiding medications in their daily questionnaires, we have limited knowledge of any substances the participants may have consumed that could impact sleep during the week of DST transition and thus cannot fully account for these potential exogenous influences on the sleep and circadian timing observed. However, due to the naturalistic nature of the study, we might be able to assume that individuals consuming substances that impact sleep and circadian timing may be continuing behaviors that they followed before the DST transition, and these influences may thus be partially controlled in our analysis. (5)The smaller sample size does not allow for comparison of sex differences in combination with diet and the response to the phase shift, which may be important with documented sex differences in sleep and circadian regulation,[21,22] and (6) our assessment of exercise/activity level was limited to self-report. Future work such as a randomized-crossover trial systematically testing

the impact of diet, timing and level of activity, and sex of the participant on the circadian timing system is needed to fully elucidate these relationships.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

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- METHOD DETAILS
  - Participants
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  - Inpatient study procedures
  - Meal, general health, and GPA documentation
- QUANTIFICATION AND STATISTICAL ANALYSIS

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.isci.2024.110677.

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AUTHOR CONTRIBUTIONS

All authors designed research, performed research, and wrote and/or edited the paper. A.W.M., E.B.K., and C.A.C., secured funding. A.W.M., analyzed data.

DECLARATION OF INTERESTS

A.W.M. reports consulting for Pure Somni Corporation. A.S. has received travel reimbursement or honorarium payments from Leuven Mindgate, American Epilepsy Society, IEEE, and Apple. A.S. has also received research support from Microsoft, Sony Corporation, NEC Corporation, Pola Chemicals, and Meta and consulting fees from Gideon Health and Suntory Global Innovation Center. L.K.B. has received consulting funds from Boston's Children's Hospital, University of Helsinki, AAA Foundation, University of Arizona, and University of British Columbia. A.J.K.P. has received research funding from Versalux and Delos; he is co-founder and co-director of Circadian Health Innovations PTY LTD. C.A.C. reports grants and contracts to Brigham and Women's Hospital from Axsome Therapeutics, CDC Foundation, City of San Francisco, Dayzz Live Well, Delta Airlines, Jazz Pharmaceuticals PLC Inc, Puget Sound Pilots, and Regeneron Pharmaceuticals/Sanofi during the conduct of the study; reports personal fees from Axsome Therapeutics, Associated Professional Sleep Societies, Bryte Foundation, Clement Law Firm, Institute of Digital Media and Child Development, Klarman Family Foundation, Law Offices of James L Mitchell, Law Office of Yolanda Huang, Massachusetts Medical Society, National Council for Mental Wellbeing, National Sleep Foundation, Puget Sound Pilots, Rabb and Rabb LLC, Segal Law Firm, Shaked Law Firm, P.A., Simpson & Simpson, Tencent Holdings Ltd, Teva Pharma Australia, The Armstrong Firm, PLLC, Vanda Pharmaceuticals Inc, With Deep, Inc., and Zehl Law Firm during the conduct of the study; reports research/education support to Brigham and Women's Hospital from Abbaszadeh Foundation, Alexandra Drane, Apnimed, Inc., Avadel Pharmaceuticals, Bryte Foundation, Casey Feldman Foundation, Cephalon, DR Capital, Eisai Co., LTD, f.lux Software, LLC, Idorsia Pharmaceuticals LTD, Mary Ann & Stanley Snider via Combined Jewish Philanthropies, Harmony Biosciences LLC, Jazz Pharmaceuticals PLC, Inc, Johnson & Johnson, NeuroCare, Inc., Optum, Peter Brown and Margaret Hamburg, Philips Respironics Inc, Regional Home Care, ResMed Foundation, San Francisco Bar Pilots, Sleep Number Corp., Stuart F. and Diana L. Quan Charitable Fund, Summus, Inc., Takeda Pharmaceutical Co., LTD, Teva Pharmaceuticals Industries Ltd, ResMed, Sanofi, Philips, Vanda Pharmaceuticals, and Whoop, Inc. during the conduct of the study; and is the incumbent of an endowed professorship provided to Harvard University by Cephalon Inc. during the conduct of the study; report serving as an expert witness in legal cases, including those involving Advanced Power Technologies, Aegis Chemical Solutions LLC, Amtrak, Bombardier, Inc., Casper Sleep Inc, C&J Energy Services, Delta Airlines/Comair, Enterprise Rent-A-Car, FedEx, Greyhound Lines, Inc., Puget Sound Pilots, Steel Warehouse, FedEx, Greyhound Lines, Product & Logistics Services LLC, San Francisco Sheriff's Department, Schlumberger Technology Corp., Union Pacific Railroad, UPS, and Vanda Pharmaceuticals during the conduct of the study; reports having an equity interest in Vanda Pharmaceuticals, With Deep, Inc, and Signos, Inc. during

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Biological samples		
Human saliva	This study	N/A
Critical commercial assays		
Salivary Melatonin Assays	BÜHLMANN Direct Saliva Melatonin RIA, Schönenbuch, Switzerland	https://buhlmannlabs.com/products-solutions/chronobiology/melatonin/
Software and algorithms		
SAS, Version 9.4	NC, USA: SAS Institute Inc	https://www.sas.com/en_us/software/stat.html
GraphPad Prism, Version 10	GraphPad Software, La Jolla California, USA	https://www.graphpad.com/
ActionW	Ambulatory Monitoring, Ardsley, NY	https://www.ambulatory-monitoring.com/software
REDCap	Vanderbilt University	https://projectredcap.org/

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources should be directed to the lead contact, Andrew W. McHill (mchill@ohsu.edu).

Materials availability

This study did not generate new unique reagents.

Data and code availability

- **Data:** All data generated or analyzed during this study are included in the manuscript and supplementary tables and figures.
- **Code:** The manuscript does not report original code. DOIs are listed in the key resources table.
- **Additional information:** Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

METHOD DETAILS

The protocol was approved by the Partners Healthcare (#2012P001631) and Massachusetts Institute of Technology (#1209005240) Institutional Review Boards and performed in accordance with the Declaration of Helsinki. The primary outcomes for the larger study were registered on clincialtrials.gov (NCT02846077). All participants provided written informed consent.

Participants

Data used were from a larger study in which volunteers with an age range of 18-22 years participated in a cross-sectional 30-day protocol to document sleep and circadian timing.[20,23–27] Recruitment included paper flyers, email, and verbal communication. Participants were excluded from the study if they reported travel of more than one time zone 3 months prior to and during the protocol, working an overnight shiftwork schedule, and an inability to wear the actigraphy monitor or download phone applications. Participants provided written informed consent and the Partners Healthcare (#2012P001631) and Massachusetts Institute of Technology (#1209005240) Institutional Review Boards approved all study procedures. The primary outcomes for the larger study were registered on clincialtrials.gov (NCT02846077).

For this study, only individuals with sleep/wake data that crossed the dates of DST start were analyzed (n=37; 19 male).

Sleep, wakefulness, medication, and activity level monitoring

On the day prior to starting the ~30-day sleep-wake monitoring protocol (data collection began in February), participants met with study staff to learn about specific study procedures, provide informed consent, and obtain a wrist actigraphy monitor (MotionLogger; Ambulatory Monitoring, Ardsley, NY). Participants were instructed to wear the device on their non-dominant arm at all times. Participants were asked to complete electronic sleep-wake, exercise, and medication diaries that were sent to the participants once each morning (sent at 07:00) and once each evening (sent at 20:00) throughout the ~30-day protocol. Actigraphy monitors were downloaded and checked at weekly meetings and electronic diaries were checked daily to ensure completion and accuracy of sleep-wake timing. If the actigraphy monitor was checked,

downloaded, and reinitialized during the week after DST, thereby syncing the monitor to DST, a correction factor of one hour was implemented in order to keep the actigraphy data in Standard Time across the week for analysis. Sleep timing and duration were manually scored from actigraphy and corroborated with diary sleep-wake times.[28] Activity level was defined as the percentage of days the participant reported exercising during the ~30-day protocol. No participants reported taking sleep aiding medications across the week of DST transition.

Inpatient study procedures

Once during the 30-day protocol, participants were admitted to the Brigham and Women's Hospital Center for Clinical Investigation Intensive Physiologic Monitoring Unit for an ~16-hour overnight stay to collect hourly salivary melatonin samples collected prior to the start of DST (average 11.8±7.5 days before DST start). Upon arrival to the unit, participants' height and weight were measured for body mass index (BMI) calculation and they were then admitted to a dimly-lit (<4 lux) study suite and not allowed to use any personal electronic devices (e.g., computer, or cell-phone) to control for the influence of additional lighting on our outcome measures.[29,30] Prior to each saliva collection, participants were asked to remain in a constant posture and not eat or drink any foods for 20 minutes prior to collection; participants were allowed to move-about freely or sleep between collections. If they were asleep, participants were awakened by research staff immediately prior to saliva collection. After assay, the dim-light melatonin onset (DLMO) was calculated as the linear interpolated point in time at which salivary melatonin levels crossed a 5 pg/ml threshold.[31] A related study found <0.35 hours in variability of DLMO across 3 months in individuals from the same college population.[20]

Meal, general health, and GPA documentation

Participants recorded all food and beverages they consumed for 1-week using the phone application MealLogger™ (Wellness Foundry, New York, NY). Tracking of meals occurred 8.2±4.1 days before the start of DST. The phone application enabled participants to photographically record their meal and include a detailed description of the meal content. Participants were taught via comprehensive presentations how to precisely take a photo of each eating occurrence with an item of known size (e.g., spoon, pencil, dollar bill) within the frame of reference for portion size estimation and how to include a detailed description of each meal to identify correct nutrient content (e.g., ingredients in a burrito, ketchup on a bun, or sweetener in tea). After the eating occurrence was recorded, data were immediately available to dieticians and study staff via online access. Dieticians and/or study staff would contact participants within 24-hours after each eating occurrence was recorded for any needed clarifications of food composition was needed. If food or drink was not fully consumed after the initial recording, participants took a second photo to document what food or drink remained.

Upon conclusion of the 30-day protocol, participants were asked to complete an end-of-study questionnaire in which they reported their general health and GPA. Specifically, participants assessed their own health in response to the prompt "In general, would you say your health is…" by selecting either excellent, very good, good, or fair. GPA was reported with an open comment box; median GPA was 4.5 on a 5-point scale for the study population.

QUANTIFICATION AND STATISTICAL ANALYSIS

Each food and drink item consumed was scored by the Brigham and Women's Hospital Center for Clinical Investigation dietary staff for caloric and nutrient content (i.e., percentage of meal containing fats, carbohydrates, proteins, etc.,). Each item was scored independently by two nutritionists to determine portion size; discrepancies were solved prior to scoring for nutrient content. Items were scored using University of Minnesota Nutrition Data System for Research software.[32,33] Participants needed a minimum of 4 days recorded to be included in analysis. Caloric timing was measured as the average time in which participants ate their first and last daily calories and also with their caloric midpoint, or the average time in which participants consumed 50% of their daily calories.[23] Seven participants (6 in low-fat diet group, 1 in the intermediate-fat group) underwent their melatonin collections during the week after DST start, and one person (low-fat) did not have usable DLMO data, and thus these individuals were not included in the analysis leaving a final sample size of n=37. When the 7 participants with melatonin data during the week of DST were included in the analysis, all findings remained the same. Group comparisons of pre-DST sleep midpoint relative to DLMO and caloric timing were done using one-way ANOVA. All group comparisons for testing the magnitude of sleep midpoint shift across study days between differing fat-consuming groups were first performed using linear mixed effect models with diet group and day as fixed effects and participant as a random effect. Paired t-tests were then used to test for differences in midpoint relative to DLMO between the day before and days after DST within groups and also to compare the weekday-to-weekday comparisons (e.g., Monday midpoint relative to DLMO the day before DST vs Monday midpoint relative to DLMO after DST, Tuesday before vs Tuesday after, and so on). Un-paired t-tests were used for planned comparisons between groups each day. Kaplan-Meier survival curves of time to shift 1h in phase angle between groups were compared using Log-Rank tests.[34] Multiple linear regression analysis and Pearson correlations were used to test for the associations between the shift in sleep midpoint from the day before DST to the Monday after DST, percent of fat content in each participant's habitual diet, average sleep duration and percent of days with exercise and the general health score, BMI, and GPA. All statistics were performed using SAS 9.4 (SAS Institute Inc., Cary, NC).