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McNeil, J, Forest, G, Hintze, LJ et al. (4 more authors) (2017) The effects of partial sleep restriction and altered sleep timing on appetite and food reward. Appetite, 109. pp. 48-56. ISSN 1095-8304

https://doi.org/10.1016/j.appet.2016.11.020

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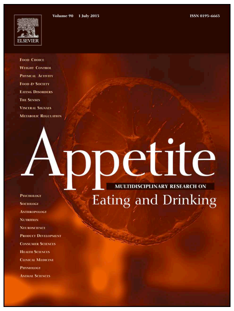

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Jessica McNeil, Geneviève Forest, Luzia Jaeger Hintze, Jean-François Brunet, Graham Finlayson, John E. Blundell, Éric Doucet

PII: S0195-6663(16)30784-X

DOI: 10.1016/j.appet.2016.11.020

Reference: APPET 3227

To appear in: *Appetite*

Received Date: 23 June 2016

Revised Date: 12 September 2016

Accepted Date: 16 November 2016

Please cite this article as: McNeil J., Forest G., Hintze L.J., Brunet J.-F., Finlayson G., Blundell J.E. & Doucet E., The effects of partial sleep restriction and altered sleep timing on appetite and food reward, *Appetite* (2016), doi: 10.1016/j.appet.2016.11.020.

The effects of partial sleep restriction and altered sleep timing on appetite and food reward

Jessica McNeil[1], Geneviève Forest[2], Luzia Jaeger Hintze[1], Jean-François Brunet[2], Graham Finlayson[3], John E. Blundell[3], Éric Doucet[1]

[1] Behavioural and Metabolic Research Unit, School of Human Kinetics, University of Ottawa, Ottawa, Canada, K1N 6N5.

[2] Laboratoire du Sommeil, Département de Psychoéducation et de Psychologie, Université du Québec en Outaouais, Gatineau, Canada, J8X 3X7.

[3] BioPsychology Group, Institute of Psychological Sciences, University of Leeds, Leeds, United Kingdom, LS2 9JT.

Send correspondence and reprint requests to:

Éric Doucet, Ph.D.
Behavioural and Metabolic Research Unit
School of Human Kinetics
University of Ottawa
Ottawa, Ontario, Canada, K1N 6N5
Phone: 1-613-562-5800 extension: 7364
Fax: 1-613-562-5291
E-mail: edoucet@uottawa.ca

Abstract

We examined the effects of partial sleep restriction (PSR) with an advanced wake-time or delayed bedtime on measures of appetite, food reward and subsequent energy intake (EI). Twelve men and 6 women (age: 23±4 years, body fat: 18.8±10.1%) participated in 3 randomized crossover sessions: control (habitual bed- and wake-time), 50% PSR with an advanced wake-time and 50% PSR with a delayed bedtime. Outcome variables included sleep architecture (polysomnography), *ad libitum* EI (validated food menu), appetite sensations (visual analogue scales), the satiety quotient (SQ; mm/100 kcal) and food reward (Leeds Food Preference Questionnaire and the relative-reinforcing value (RRV) of preferred food task). Increased fasting and post-standard breakfast appetite ratings were noted following PSR with an advanced wake-time compared to the control and PSR with a delayed bedtime sessions (Fasting hunger ratings: 77±16 *vs.* 65±18 and 64±16; *P* = 0.01; Post-meal hunger AUC: 5982±1781 *vs.* 4508±2136 and 5198±2201; *P* = 0.03). Increased explicit wanting and liking for high- relative to low-fat foods were also noted during the advanced wake-time *vs.* control session (Explicit wanting: -3.5±12.5 *vs.* -9.3±8.9, *P* = 0.01; Explicit liking: -1.6±8.5 *vs.* -7.8±9.6, *P* = 0.002). No differences in the RRV of preferred food, the SQ and *ad libitum* lunch intake were noted between sessions. These findings suggest that appetite sensations and food reward are increased following PSR with an advanced wake-time, rather than delayed bedtime, *vs.* control. However, this did not translate into increased EI during a test meal. Given the increasing prevalence of shift workers and incidences of sleep disorders, additional studies are needed to evaluate the prolonged effects of voluntary sleep restriction with altered sleep timing on appetite and EI measurements.

Keywords: appetite, food reward, satiety quotient, sleep architecture, sleep deprivation

Introduction

Spiegel *et al.* (2004) were among the first to demonstrate increased feelings of hunger for calorie-dense foods following 2 days of 4 h *vs.* 10 h in bed/night. A recent functional magnetic resonance imaging (fMRI) study observed enhanced activation in the orbitofrontal cortex in response to visual food cues following partial sleep restriction (4 *vs.* 9 h in bed/night) (St-Onge et al., 2012). Activity in reward and food-sensitive areas of the brain was also increased in response to unhealthy *vs.* healthy food cues in these same participants following sleep restriction (St-Onge, Wolfe, Sy, Shechter, & Hirsch, 2014).

Sleep restriction protocols with differing bed- or wake-times have been shown to impact sleep architecture (Tilley & Wilkinson, 1984; Wu et al., 2010). More specifically, there is no difference in slow-wave sleep (SWS) duration when sleep was restricted to the first *vs.* second half of the night, whereas rapid eye movement (REM) sleep was greater when sleep was restricted to the second half of the night. As such, stage 2 sleep duration was reduced when sleep was restricted to the second half of the night. A recent study (Rutters et al., 2012) noted that participants with habitually lower amounts of SWS, independently of sleep duration, reported feeling hungrier and less full the following day, had increased food wanting and *ad libitum* energy intake (EI). Shechter *et al.* (2012) also noted a negative association between the changes in REM sleep duration and next day hunger ratings between a sleep restriction and control condition (4 *vs.* 9 h in bed/night). These results thus suggest that inter-individual variations in habitual sleep architecture, or changes in sleep stage durations in response to partial sleep restriction, may be linked to appetite sensations and food reward. However, it is unknown whether sleep restriction combined with altered bed or wake-times may impact appetite sensations and/or food reward differently. Additionally, it is unknown whether the changes in sleep architecture that occur in response to alterations in bed or wake-times during an imposed sleep restriction period may be associated with potential changes in these outcomes. The objective of this study was thus to investigate the influence of sleep timing when imposing a sleep restriction period on measures of appetite and food reward the following day with a within-subject design. Briefly, we evaluated the effects of a 50% sleep restriction during the first or second half of a habitual sleep period on appetite sensations and food reward. It was hypothesized that sleep restriction with an advanced wake-time would lead to increased appetite sensations and food reward when compared to habitual sleep duration. It was also hypothesized that these changes in appetite and food reward would be associated with changes in REM sleep duration between the control and advanced wake-time sessions.

Materials and Methods

Participants

Twenty-two participants who corresponded to all inclusion criteria were recruited. However, only 18 completed all sessions (12 men and 6 women; age: 23 ± 4 years; BMI: 22.7 ± 2.7 kg/m^2; body fat percentage: 18.8 ± 10.1%). Study methodologies are described in more detail elsewhere (16). Briefly, participants were between the ages of 18-45 years, non-smokers, weight stable (± 4 kg) within the last 6 months, did not have heart problems or diabetes, did not take medication that could have affected appetite or sleep, and reported not performing shift work nor taking regular daytime naps. They also reported having habitual sleep duration of 7-9 h/night. Only women taking monophasic, combined estrogen-progesterone birth control pills were recruited in order to control for the effects of menstrual cycle phase and sex-steroid hormones on sleep parameters (Baker et al., 2001) and food reward (Alonso-Alonso et al., 2011). This study was conducted according to the guidelines laid down in the Declaration of Helsinki and the University of Ottawa ethics committee approved all procedures involving human participants. Written informed consent was obtained from all participants.

Study design and preliminary session measurements

This study followed a randomized crossover design, which included a preliminary session, 2 weeks of sleep-wake monitoring with accelerometry (SenseWear Pro 3 Armbands©, HealthWear Bodymedia, Pittsburgh, PA, USA) and sleep diaries under free-living conditions, 2 habituation nights (1 in-lab and 1 outside of the lab) and 3 randomized experimental sessions (control with an habitual bed- and wake-time, 50% sleep restriction with an habitual bedtime and advanced wake-time, and 50% sleep restriction with a delayed bedtime and habitual wake-time). During the preliminary session, anthropometric data were collected and participants were given *ad libitum* access to a standard breakfast, which included whole-wheat toast, strawberry jam, peanut butter, cheddar cheese and orange juice. Participants were also asked to write down their favorite snack and fruit/vegetable that would be later used for the relative-reinforcing value (RRV) of a preferred food task (Temple et al., 2009), which was conducted during each of the 3 experimental conditions. Lastly, participants rated 202 food images that were divided into 4 categories according to fat content and taste (high-fat savory, low-fat savory, high-fat sweet, low-fat sweet) based on the following question: "How often do you consume this food item?". The 4 highest-rated food items within each category were then used to personalize the computer-based behavioral procedure called the Leeds Food Preference Questionnaire (LFPQ) (Finlayson, King, & Blundell, 2008) that was administered during each experimental session. Hence, the food items presented during this task may have differed between participants, but were standardized across sessions for the same participant. At the end of the preliminary session, the participants were given an accelerometer (SenseWear Pro 3 Armbands©, HealthWear Bodymedia, Pittsburgh, PA, USA) and a sleep diary to measure habitual sleep-wake patterns under free-living conditions for 2 weeks. The mean bed- and wake-times measured over 2 weeks for each participant were used to prescribe the time in bed for the control session, whereas the mean sleep midpoint was used to determine the advanced wake-time or delayed bedtime in the sleep restriction conditions. Hence, the assigned bed- and wake-times, as well as the timing of measurements the following morning, differed between participants but were standardized for each participant across sessions. The 3 experimental sessions were randomly assigned to each participant. As a result, 6 participants started with each of the 3 experimental sessions. No significant order effect was noted for hunger ratings (results not shown). A washout period of at least 7 days separated each experimental session.

Evening and overnight procedures and measurements

Each experimental session began 3 h prior to the set bedtime to allow enough time to place all the electrodes (≈ 90 min), set up the polysomnogram (≈ 30 min) and allow for some downtime before going to bed (≈ 60 min). Electroencephalography (EEG; C3, C4, O1, O2, F3 and F4), electromyography (EMG; bipolar submental) and electrooculography (EOG) were recorded on a Medipalm 22 (Braebon Medical Corporation, Kanata, Ontario, Canada) with the Pursuit Sleep Software (Braebon Medical Corporation, Kanata, Ontario, Canada). This setting was used to assess sleep inside the lab during each experimental session. Recordings were scored independently by 2 researchers according to the AASM 2007 criteria (The American Academy of Sleep, 2007) using 30-second epochs, and discrepancies were resolved by mutual agreement. When forced to remain awake during the night and the following morning, participants were allowed to take part in any type of sedentary activity (*e.g.* reading, watching movies) as long as they remained inside the lab with the evaluator.

Next morning procedures and measurements

The clock time at which all measurements were taken the next morning did differ according to each participant’s habitual wake-time (range: 6h18-8h37), but remained the same for each participant across sessions. Upon awakening, participants were given 1 h to shower. Body weight (HR-100; BWB-800AS, Tanita Corporation, Arlington Heights, IL, USA) and fasting appetite sensations were measured 75 min after habitual wake-time each morning for each experimental session. This took place prior to breakfast consumption, which contained the exact quantity and composition of the breakfast consumed during the preliminary session for each participant. There was a difference in the elapsed time between awakening and the start of next morning measurements (*i.e.* fasting appetite measurements and standard breakfast administration) during the sleep restriction with advanced wake-time condition *vs.* the control and sleep restriction with delayed bedtime conditions (≈ 320 min *vs.* 75 min). Fasting and post-meal (measured every 30 minutes for 3 h following breakfast) appetite sensations were recorded with 100-mm computerized visual analogue scales (VAS) (Marsh-Richard, Hatzis, Mathias, Venditti, & Dougherty, 2009). The following 4 questions were asked at every time point: desire to eat ("How strong is your desire to eat?": very weak - very strong), hunger ("How hungry do you feel?"; Not hungry at all - As hungry as I have ever felt), fullness ("How full do you feel?"; Not full at all - Very full), and prospective food consumption (PFC) ("How much food do you think you could eat?"; Nothing at all - A large amount). Post-meal area under the curve (AUC) was calculated with the trapezoid method, as previously described (Doucet, St-Pierre, Almeras, & Tremblay, 2003), and included appetite measurements taken at 0, 30, 60, 90, 120, 150 and 180 minutes post-breakfast intake. Appetite ratings for 1 participant at 120 minutes were not obtained; hence, the results of 17 participants for appetite ratings are presented herein.

Fasting and mean post-meal appetite sensations over 180 minutes were also used to calculate the SQ for each appetite sensation question using the following equation (Green, Delargy, Joanes, & Blundell, 1997):

$$\textbf{SQ (mm/100kcal)} = \frac{\textbf{[fasting appetite sensation (mm) – mean post meal appetite sensation (mm)]}}{\textbf{energy content of the breakfast (kcal)}}$$

The SQ calculation for the fullness rating is reversed (*i.e.* mean post-meal fullness rating - fasting fullness rating). A mean SQ score including the 4 appetite ratings was also calculated. This SQ calculation has shown good reliability when assessed under controlled lab conditions (intra-class correlation coefficient of r = 0.7 for mean SQ) (Drapeau et al., 2013) over 60 minutes post-breakfast intake. A greater SQ score indicates a greater satiety response to the breakfast (Drapeau et al., 2013). No standardized scale or cut-off points are used to identify a high or low SQ since this measurement is dependent on the energy content of the breakfast (Green et al., 1997), which can vary from one study to another, or between participants within the same study as is the case for the present paper. Since breakfast intake was standardized for each participant across experimental sessions, the differences in SQ noted between sessions are entirely dependent on the derived changes in appetite sensations as a result of the standardized breakfast intake.

The RRV of food task (Temple et al., 2009) was administered 180 minutes following breakfast intake. This computer-based task measures the number of responses for a preferred snack item *vs.* a preferred fruit/vegetable using a fixed ratio of reinforcement for each item, hence providing a measure of the participants' "wanting" to gain access to a preferred item. Before initiating the task, participants were given 10 grams of each preferred item to consume, which acted as a primer. They had to consume both primers in their entirety before initiating the task. Once the task initiated, the participants had 2 minutes to earn points towards receiving the preferred snack and/or preferred fruit/vegetable, or may choose not to earn points towards either item, using a slot machine game that contained 3 boxes with different colored shapes. There was 1 slot machine game associated with each item, and when the left button on the mouse was pressed, the shapes changed. When all of the colored shapes matched, the participants earned a point towards that item. The ratio of reinforcement was fixed to provide 3 matching shapes, earning the participant a point towards the selected food item, for every 10 button presses on 1 slot machine game. For every 5 points earned (or 50 total button presses), the participants received access to 25 grams of that item. The quantity of each food item earned were then given to the participants during their *ad libitum* lunch, and the amount of each item consumed was determined by weighing the food before and after lunch.

The LFPQ (Finlayson et al., 2008; French et al., 2014) was completed at 60- and 180-minutes post-breakfast consumption, as well as following *ad libitum* lunch intake. This validated computer-based behavioral task (Finlayson et al., 2008) provides measures of the wanting and liking for an array of food images varying in both fat content and taste. A total of 16 different food items, divided into 4 categories according to fat content and taste (high-fat savory, *e.g.* pizza, sausage; low-fat savory, *e.g.* cucumber, carrots; high-fat sweet, *e.g.* chocolate cake, ice cream; low-fat sweet, *e.g.* banana, strawberries) formed the array for this task. The 16 food items presented to each participant were chosen according to personal preferences/familiarity during the preliminary session, meaning that these food images were standardized across each experimental session for the same participant but were different between participants. During the forced choice part of this task, each food image was presented with every other image in turn. For each pair of food images presented, the participants were instructed to select the food item they would "most want to eat now". A standardized implicit wanting score for each food item was calculated as a function of the reaction time in selecting that particular food item adjusted for the frequency of choice for images selected in each category (French et al., 2014). Participants were also asked to rate the extent to which they "liked" ("How pleasant would it be to experience a mouthful of this food now?") or "wanted" ("How much do you want to eat this food item now?") each randomly presented food item with a 100-mm visual analogue scale, which were used as a measure of explicit liking and wanting, respectively. Bias scores were calculated for all food reward variables and are analyzed in the present paper; the mean low-fat scores were subtracted from the mean high-fat scores (fat content bias) and the mean savory scores were subtracted from the mean sweet scores (taste bias). Positive scores indicate a preference for high-fat or sweet foods, negative values indicate a preference for low-fat or savory foods, and a score of 0 indicates an equal preference for both fat content and taste categories.

Lastly, an *ad libitum* lunch was selected by the participants from a validated food menu (McNeil, Riou, Razmjou, Cadieux, & Doucet, 2012). Briefly, participants were instructed to consume "as much or as little as you want" from the foods that they selected from the menu. They were also told to take the time needed to consume lunch, which was monitored. Energy and macronutrient intakes were assessed by weighing each food item before and after lunch consumption.

Statistical analyses

Statistical analyses were performed using SPSS (version 17.0; SPSS Inc., Chicago, IL, USA). Two-way repeated measures ANOVA tests were used to determine the main effects of sleep condition (control, 50% sleep restriction with advanced wake-time and 50% sleep restriction with delayed bedtime) and time (60 and 180 minutes post-breakfast consumption and after lunch for the LFPQ task; fasting and every 30 minutes for 3 h post-breakfast intake for appetite sensations) on LFPQ food reward measurements and appetite sensations. As a result of the difference in elapsed time between awakening and breakfast intake during the advanced wake-time *vs.* control and delayed bedtime conditions (≈ 320 min *vs.* 75 min), a sensitivity analysis was conducted to assess the strength of the associations between differences in elapsed time since awakening with differences in fasting hunger ratings and hunger AUC between these sessions (advanced wake-time-control and advanced wake-time-delayed bedtime). One-way repeated measures ANOVA tests (for normally distributed data) and the Friedman Exact non-parametric test (for non-normally distributed data according to the Shapiro Wilk test) were used to determine the main effects of sleep condition (control, 50% sleep restriction with advanced wake-time and 50% sleep restriction with delayed bedtime) on post-breakfast AUC, the SQ, *ad libitum* energy and macronutrient intakes over lunch, and the RRV responses (button presses) to the preferred snack and fruit/vegetable and the intake of these items. The Wilcoxon Signed Ranks Test was used to assess potential differences between sessions for variables that were not normally distributed according to the Shapiro-Wilk test. For normally distributed data, *post-hoc* tests with LSD adjustments were used to determine where significant differences existed. Linear regression models were used to assess the strength of the associations between changes in absolute sleep stage durations (minutes) with changes in hunger ratings (fasting and post-breakfast AUC), mean SQ, explicit wanting fat bias scores at 60 minutes post-breakfast intake, *ad libitum* EI and total RRV of food button presses between sessions (delta control-delayed bedtime, delta control-advanced wake-time, delta advanced wake-time-delayed bedtime). Sex, age and delta sleep duration between the compared sessions were added as covariates to these models. Values are presented as means ± standard deviations. Differences with P-values < 0.05 were considered statistically significant.

Results

As previously reported (McNeil et al., 2016) and presented in **Table 1**, absolute stage 1, stage 2 and REM sleep durations were increased during the control *vs.* both sleep restriction conditions. Stage 1 and stage 2 sleep durations were also increased during the advanced wake-time *vs.* delayed bedtime session. Conversely, REM sleep duration was decreased during the advanced wake-time *vs.* delayed bedtime session. SWS was only significantly increased during the control *vs.* advanced wake-time session. Lastly, there were no differences in body weight between sessions (control: 69.2±9.2, advanced wake-time: 69.4±9.3, delayed bedtime: 69.2±9.4 kg; $F\ (2, 34) = 0.34$, $P = 0.72$; partial $\eta^2 = 0.02$).

Fasting and post-meal appetite ratings are presented in **Figure 1**. Desire to eat (P = 0.003), hunger (P = 0.01) and PFC (P = 0.004) ratings were increased following sleep restriction with an advanced wake-time *vs.* control. Fullness ratings were also decreased following sleep restriction with an advanced wake-time *vs.* control (P = 0.01). Hunger ratings were increased following sleep restriction with an advanced wake-time *vs.* delayed bedtime (P = 0.04). Additionally, the AUCs for hunger (P = 0.02), fullness (P = 0.02) and PFC (P = 0.01) were increased following sleep restriction with an advanced wake-time *vs.* control (**Figure 2**). Lastly, the sensitivity analysis revealed no significant associations between the differences in elapsed time since awakening and the differences in fasting hunger ratings and hunger AUC between the advanced wake-time and control conditions, as well as between both sleep restriction conditions (results not shown).

Increases in stage 1 sleep duration was associated with decreases in fasting hunger ratings in the control-delayed bedtime sessions (β = -1.2 mm, 95% CI for β = -2.3 to -0.04 mm; P = 0.04). Decreases in REM sleep duration were also correlated with increases in post-breakfast hunger AUC between the advanced wake-time-delayed bedtime conditions (β = -80.0, 95% CI for β = -148.2 to -11.84; *P* = 0.03). No other significant correlations were noted between changes in sleep stage durations with delta hunger ratings between sessions (results not shown).

The fat and taste bias scores for the implicit wanting, explicit wanting and explicit liking for foods assessed at 60 and 180 minutes post-breakfast, as well as after lunch are presented in **Table 2**. Increased explicit liking and wanting for high-fat relative to low-fat foods were noted during the advanced wake-time compared to the control session (**Figure 3**). No significant correlations between changes in sleep stage durations with delta explicit wanting fat bias scores at 60 minutes post-breakfast intake were noted between sessions (results not shown).

Results from the RRV of preferred food task, the SQ for each appetite sensation, as well as *ad libitum* energy and macronutrient intakes during lunch are presented in **Table 3**. No differences in these variables were noted between sessions. No significant correlations between changes in sleep stage durations with mean SQ, total RRV button presses, or *ad libitum* EI were noted between sessions (results not shown).

Discussion

To our knowledge, this is the first study to investigate changes in appetite and food reward in response to partial sleep restriction combined with altered sleep timing. Furthermore, the present study assessed the strength of the associations between changes in these outcome variables with changes in sleep stage durations between conditions, in addition to exerting control over inter-individual circadian rhythms by personalizing each participant's assigned bed- and wake-times. Collectively, our findings suggest that most fasting and post-meal appetite ratings are increased following partial sleep restriction with an advanced wake-time compared to the control and partial sleep restriction with a delayed bedtime conditions. The explicit liking and wanting for high- relative to low-fat foods were increased during the advanced wake-time compared to the control session. These results corroborate our initial hypothesis. However, these changes in appetite and food reward did not lead to increased EI during an *ad libitum* lunch. No differences in SQ and RRV of preferred food responses were noted between sessions. Changes in REM sleep duration between the control and advanced wake-time sessions were not associated with changes in hunger ratings and explicit wanting bias scores. We therefore reject our second hypothesis. However, decreases in REM sleep duration were associated with increases in post-breakfast hunger AUC between the advanced wake-time-delayed bedtime conditions.

These results first suggest that partial sleep restriction with an advanced wake-time leads to increased subjective appetite sensations and explicit food reward for high- relative to low-fat foods. These results add to previous studies reporting increased hunger and/or activation in food-sensitive centers of the brain following partial sleep restriction (Benedict et al., 2012; Spiegel, Tasali, Penev, & Van Cauter, 2004; St-Onge et al., 2012; St-Onge et al., 2014). Although the degree of sleep restriction is relatively similar (≈ 4-6 hours in bed/night) between studies that have assessed appetite, food reward and/or EI as outcome variables, the sleep protocols used often differ in the timing of the imposed sleep restriction period; some studies imposed a later bedtime coupled with earlier wake-time (Brondel, Romer, Nougues, Touyarou, & Davenne, 2010; Markwald et al., 2013; Nedeltcheva et al., 2009; Spiegel et al., 2004; St-Onge et al., 2011), whereas others imposed a later bedtime only (Schmid et al., 2009; Spaeth, Dinges, & Goel, 2013). Therefore, the use of a within-subject design to assess the influence of sleep timing when imposing a sleep restriction period on measures of appetite and food reward is novel. Previous studies have reported reductions in REM sleep duration (Tilley & Wilkinson, 1984; Wu et al., 2010) and sleep efficiency (Guilleminault et al., 2003) when sleep was restricted to the first *vs.* second half of the night, which corroborate our findings. Although differences in REM sleep duration were not associated with changes in appetite and food reward ratings between the control and advanced wake-time conditions, decreases in REM sleep duration were associated with increases in post-breakfast hunger AUC between both sleep restriction conditions. These findings add to those previously reported by St-Onge *et al.* (2013), where it was reported that individuals with smaller reductions in REM sleep duration following partial sleep restriction also had reduced changes in insula activation. Shechter *et al.* (2012) also noted a negative association between REM sleep time and hunger ratings. Gonnissen *et al.* (2013) reported increased post-dinner desire to eat ratings following 1 night of fragmented sleep that led to a significant reduction in REM sleep duration compared to 1 night of non-fragmented sleep. Although these findings do not provide direct cause-and-effect associations, it can be hypothesized that imposing a sleep restriction period with an advanced wake-time, rather than a delayed bedtime, may exert a greater effect on appetite sensations and food reward as a result of reduced REM sleep duration and/or sleep efficiency. Studies aimed at imposing reductions in REM sleep duration are needed to test this hypothesis.

A different study completed in our lab assessed habitual sleep parameters under free-living conditions following acute exercise interventions and revealed that decreased sleep duration and earlier wake-times were associated with increased food reward the next morning (McNeil, Cadieux, Finlayson, Blundell, & Doucet, 2015). However, the elapsed time between measured wake-time and completion of the food reward task, which was standardized across sessions for all participants, was an important confounder in the abovementioned study. Our sensitivity analysis revealed no significant associations between the changes in elapsed time since awakening and hunger ratings. Despite these results, it is possible that the difference in elapsed time between the end of the sleep period and the completion of next morning measurements during the advanced wake-time session *vs.* control and delayed bedtime sessions may have influenced the observed results. Studies designed to assess appetite and food reward following standardized wake-times, rather than clock time, are needed to test this hypothesis.

The ability to modulate EI with higher cognitive processes, even when presented with a physiological "need" or greater "wanting" for food (Berridge, 1996), may in part explain the observed lack of association between appetite and food reward with actual EI during an *ad libitum* lunch. A *post-hoc* analysis of the main effects of sleep conditions on appetite ratings assessed at 180 minutes post-breakfast intake showed no significant differences in appetite ratings between conditions (results not shown). Hence, it is possible that the greater feelings of appetite observed following sleep restriction with an advanced wake-time may have subsided by the time the *ad libitum* lunch was offered to the participants. Additionally, the use of an *ad libitum* lunch to assess EI late morning/early afternoon (≈ 11h00-13h00) during each experimental session was not able to capture potential increases in EI that may occur during the overnight hours as a result of an imposed sleep restriction. Indeed, studies have previously noted increased late night and/or post-dinner snack intake during the sleep restriction *vs.* control conditions (Markwald et al., 2013; Nedeltcheva et al., 2009; Spaeth et al., 2013). The present study did not permit EI during the time when participants were forced to remain awake because of the use of standardized measurement times for study outcomes (*i.e.* appetite sensations and food reward) across experimental sessions. Future studies should monitor the timing of EI, or permit *ad libitum* EI at any time of day, to help further explain the link between sleep restriction and EI (St-Onge & Shechter, 2014).

These findings are limited to a small sample size of healthy adults with very high sleep efficiency (≈ 93-97% when assessed inside the lab). This limits generalizability of these findings to individuals with sleep complaints or disorders. All outcomes were assessed following 1 night of sleep restriction with altered bed or wake-time, which does not account for day-to-day variations in these outcomes, nor can they be compared to studies imposing prolonged sleep restriction protocols. The food images presented during the LFPQ were not the same as those offered on the menu. Likewise, the RRV task was administered prior to an *ad libitum* lunch. These limitations may influence the participants' responses on each of these tasks, and contribute to the observed dissociation between food reward and EI across sessions.

The findings presented and discussed herein suggest that appetite and food reward are increased when sleep restriction is combined with an advanced wake-time, rather than a delayed bedtime, *vs.* control. However, this did not lead to increased EI during a test meal. Studies are needed to investigate these outcomes in individuals experiencing regular circadian misalignment and voluntary sleep loss, given the increasing prevalence of shift workers and incidences of sleep disorders (McNeil, Chaput, Forest, & Doucet, 2013).

Acknowledgements

The authors would like to thank the participants for their involvement in this study. The authors would also like to thank Isabelle Chaumont, Émilie Langlois, Riley Maitland and Alexandre Riopel for their involvement in data collection. J McNeil was a recipient of the Ontario Graduate Scholarship during the time of data collection.

Conflicts of interest

The authors declare no conflict of interest.

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Figure Captions

Figure 1. The fasting and post-breakfast desire to eat (A), hunger (B), fullness (C) and prospective food consumption (PFC) (D) ratings during the 3 experimental sessions. Values are presented as means for 17 participants with standard errors of the mean represented by vertical bars.

Figure 2. Post-breakfast desire to eat (A), hunger (B), fullness (C) and prospective food consumption (PFC) (D) area under the curve (AUC) values during the 3 experimental sessions. Values are presented as means for 17 participants with standard errors of the mean represented by vertical bars.

Figure 3. The explicit liking (A) and explicit wanting (B) for high- relative to low-fat foods during the 3 experimental sessions. Values are presented as means for 18 participants with standard errors of the mean represented by vertical bars.

Note: A positive score indicates relatively greater explicit liking/wanting for high *vs.* low- fat foods. A negative score indicates a relatively greater explicit liking/wanting for low- *vs.* high-fat foods. A score of 0 indicates an equal explicit liking/wanting score between fat categories.

Table 1. Sleep stage durations measured with polysomnography during each session (n = 18)*

	Control	**Advanced wake-time**	**Delayed bedtime**	**Main effect analysis**
	Mean ± SD	*Mean ± SD*	*Mean ± SD*	*F/χ^2 test results; partial η 2*
Sleep duration (min)	463 ± 30^{a}	229 ± 17^{b}	236 ± 17^{c}	*F (2, 34) = 1770.17, P* = 0.0001; partial η^2 = 0.99
*Sleep efficiency (%)***	95 ± 3^{a}	93 ± 4^{a}	97 ± 2^{b}	*χ^2 (2) = 12.37, P* = 0.001
Stage 1 sleep (minutes)	18 ± 10^{a}	7 ± 4^{b}	4 ± 3^{c}	*F (2, 34) = 33.17, P* = 0.0001; partial η^2 = 0.66
Stage 2 sleep (minutes)	245 ± 35^{a}	113 ± 29^{b}	101 ± 31^{c}	*F (2, 34) = 314.80, P* = 0.0001; partial η^2 = 0.95
SWS (minutes)	92 ± 32^{a}	76 ± 33^{b}	80 ± 31^{a}	*F (2, 34) = 4.16, P* = 0.03; partial η^2 = 0.20
REM sleep (minutes)	108 ± 24^{a}	34 ± 7^{b}	51 ± 17^{c}	*F (2, 34) = 166.90, P* = 0.0001; partial η^2 = 0.91

Note: Means not sharing the same letter are significantly different from each other ($P < 0.05$).

*Data adapted from McNeil *et al.* (2016).

**Sleep efficiency is calculated as [(sleep time/time in bed) * 100].

REM, rapid eye movement; SWS, slow-wave sleep; SD, standard deviation

Table 2. The implicit wanting, explicit wanting and explicit liking for high- relative to low-fat foods, and sweet relative to savory foods between conditions, across time (60 and 180 minutes post-breakfast intake, and after lunch), and condition*time interactions (n = 18).

	Control	**Advanced wake-time**	**Delayed bedtime**	**Condition effect**	**Time effect**	**Condition*Time interaction**
	Mean ±SD	*Mean ±SD*	*Mean ±SD*	*F test results; partial η 2**	*F test results; partial η 2**	*F test results; partial η 2**
Implicit wanting						
Fat bias				*F (2, 34) = 1.16*, *P* = 0.33; partial η^{2} = 0.06	*F (2, 34) = 0.66*, *P* = 0.52; partial η^{2} = 0.04	*F (4, 68) = 0.47*, *P* = 0.76; partial η^{2} = 0.03
60 min after breakfast	-33±25.9	-21.0±30.0	-26.4±34.6			
180 min after breakfast	-24.8±29.6	-20.7±45.2	-19.9±40.1			
After lunch	-33.6±28.1	-25.8±43.5	-24.1±35.2			
Taste bias						
60 min after breakfast	29.2±35.5	25.7±43.9	33.1±40.3	*F (2, 34) = 0.02*, *P* = 0.98; partial η^{2} = 0.001	*F (2, 34) = 6.17*, *P* = 0.01; partial η^{2} = 0.27	*F (4, 68) = 0.30*,*P* = 0.88; partial η^{2} = 0.02
180 min after breakfast	6.7±48.8	5.0±47.7	4.7±49.6			
After lunch	27.7±48.5	30.8±37.7	27.5±42.7			
Explicit wanting						
Fat bias				*F (2, 34) = 4.17*, *P* = 0.02; partial η^{2} = 0.20	*F (2, 34) = 5.34*, *P* = 0.01; partial η^{2} = 0.24	*F (4, 68) = 1.95*, *P* = 0.11; partial η^{2} = 0.10
60 min after breakfast	-13.2±14.1	-4.3±9.7	-9.3±15.5			
180 min after breakfast	-12.2±18.2	-4.9±13.9	-6.9±17.6			
After lunch	-2.4±5.6	-1.4±5.8	-1.5±8.3			
Taste bias						
60 min after breakfast	8.4±11.3	6.5±17.2	11.1±15.9	*F (2, 34) = 1.95*, *P* = 0.16; partial η^{2} = 0.10	*F (2, 34) = 3.88*, *P* = 0.03; partial η^{2} = 0.19	*F (4, 68) = 0.85*, *P* = 0.50; partial η^{2} = 0.05
180 min after breakfast	-1.9±15.4	1.9±20.6	3.3±18.6			
After lunch	1.9±6.6	5.5±8.8	5.8±12.3			
Explicit liking						
Fat bias				*F (2, 34) = 5.58*, *P* = 0.01; partial η^{2} = 0.25	*F (2, 34) = 2.78*, *P* = 0.08; partial η^{2} = 0.14	*F (4, 68) = 1.80*, *P* = 0.14; partial η^{2} = 0.10
60 min after breakfast	-10.6±13.1	-2.1±8.8	-7.7±15.6			
180 min after breakfast	-9.2±14.6	-1.6±13.8	-4±13.8			
After lunch	-3.7±7.2	-1.2±6.5	-1.3±9.9			
Taste bias						
60 min after breakfast	9.9±14.5	8.0±17.0	-2.1±8.8	*F (2, 34) = 1.44*, *P* = 0.25; partial η^{2} = 0.08	*F (2, 34) = 3.82*, *P* = 0.03; partial η^{2} = 0.18	*F (4, 68) = 0.66*, *P* = 0.62; partial η^{2} = 0.04
180 min after breakfast	2.1±15.8	4.1±20.0	-1.6±13.8			
After lunch	3.9±11.4	7.1±10.5	-1.2±6.5			

Note: A positive score indicates a relative preference for high- relative to low fat, or sweet relative to savory, foods. A negative score indicates a relative preference for low- relative to high-fat, or savory relative to sweet, foods. A score of 0 indicates an equal preference between fat and taste categories. SD, standard deviation.

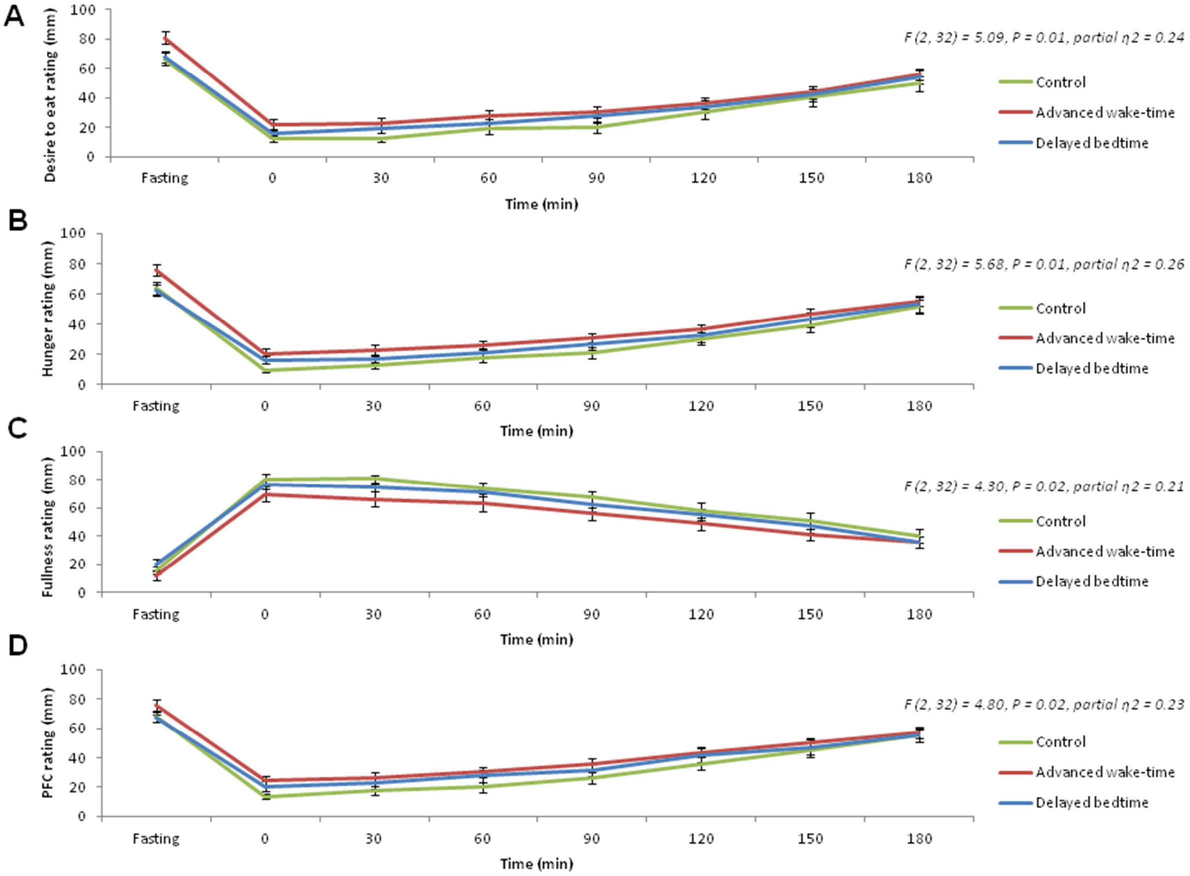
Table 3. The satiety quotient, relative reinforcing value of a preferred food results, as well as *ad libitum* energy and macronutrient intakes during each session (n = 18)

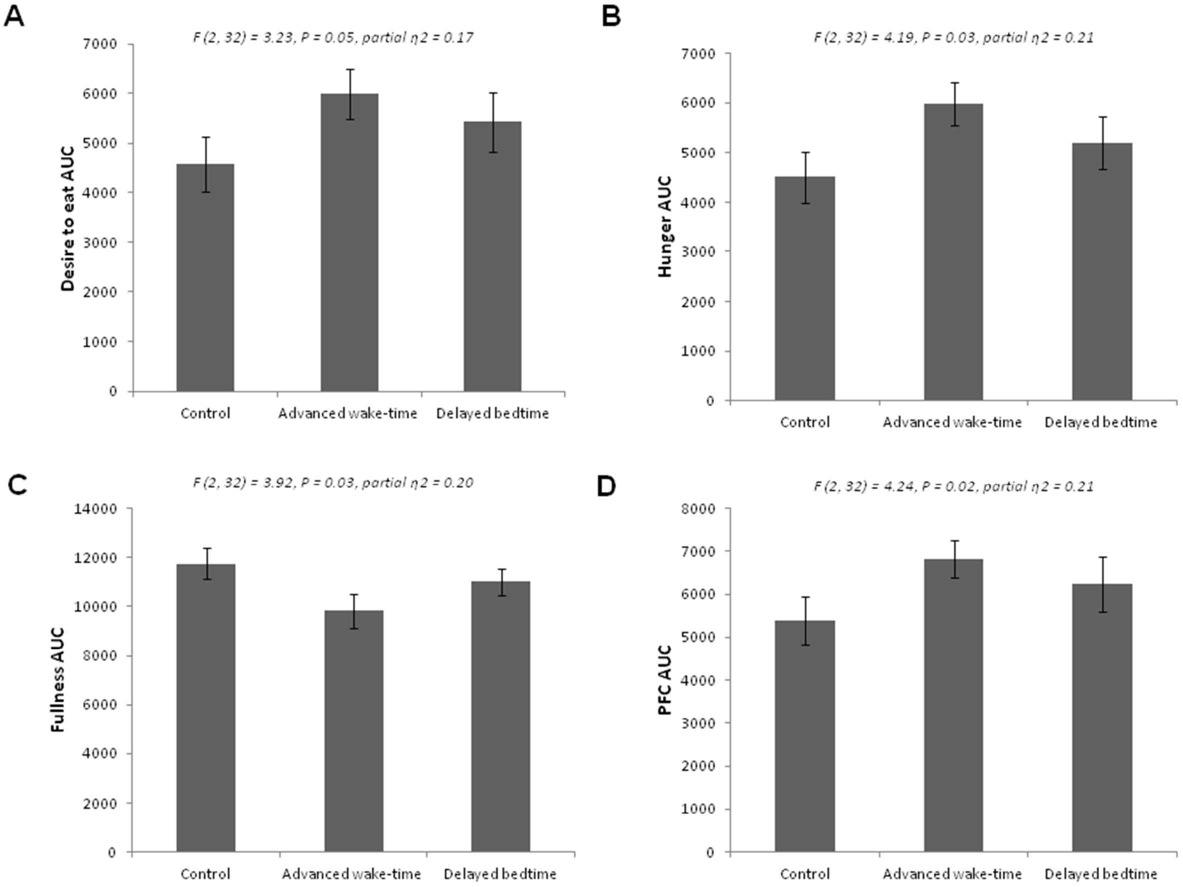
	Control	**Advanced wake-time**	**Delayed bedtime**	**Main effect analysis**
	Mean ± SD	*Mean ± SD*	*Mean ± SD*	*F/χ^2 test results; partial η 2**
Satiety Quotient (mm/100 kcal)				
Desire to eat	5.6 ± 3.8[a]	6.4 ± 4.0[a]	5.3 ± 3.7[a]	*χ^2 (2) = 1.44,P* = 0.53
Hunger	5.4 ± 3.5[a]	5.6 ± 2.9[a]	4.7 ± 2.8[a]	*F (2, 34) = 0.44, P* = 0.65; partial η^2 = 0.03
Fullness	7.0 ± 2.9[a]	5.6 ± 2.4[a]	5.6 ± 2.4[a]	*F (2, 34) = 2.30, P* = 0.12; partial η^2 = 0.12
Prospective food consumption	5.2 ± 2.1[a]	5.2 ± 2.8[a]	4.4 ± 1.9[a]	*χ^2 (2) = 3.44, P* = 0.19
Mean	5.8 ± 2.8[a]	5.7 ± 2.7[a]	5.0 ± 2.4[a]	*F (2, 34) = 0.59, P* = 0.56; partial η^2 = 0.03
Relative reinforcing value of preferred foods				
Preferred snack responses (button presses)	47 ± 69[a]	48 ± 52[a]	35 ± 40[a]	*χ^2 (2) = 2.33, P* = 0.33
Preferred fruit responses (button presses)	92 ± 82[a]	67 ± 52[a]	62 ± 37[a]	*χ^2 (2) = 0.37, P* = 0.85
Total responses (button presses)	139 ± 139[a]	115 ± 95[a]	97 ± 64[a]	*χ^2 (2) = 0.60, P* = 0.76
Preferred snack intake (kcal)	80 ± 121[a]	75 ± 90[a]	55 ± 77[a]	*χ^2 (2) = 0.93, P* = 0.67
Preferred fruit intake (kcal)	34 ± 30[a]	27 ± 24[a]	30 ± 28[a]	*χ^2 (2) = 0.09, P* = 0.97
Total preferred food intake (kcal)	113 ± 144[a]	102 ± 102[a]	85 ± 86[a]	*χ^2 (2) = 1.20, P* = 0.56
Lunch Intake				
Energy intake (kcal)	627 ± 258[a]	682 ± 227[a]	707 ± 323[a]	*F (2, 34) = 0.94, P* = 0.40; partial η^2 = 0.05
Carbohydrate intake (kcal)	383 ± 182[a]	407 ± 151[a]	430 ± 228[a]	*F (2, 34) = 0.63, P* = 0.54; partial η^2 = 0.04
Fat intake (kcal)	157 ± 99[a]	169 ± 91[a]	179 ± 78[a]	*F (2, 34) = 0.62, P* = 0.55; partial η^2 = 0.04
Protein intake (kcal)	95 ± 53[a]	111 ± 52[a]	108 ± 61[a]	*F (2, 34) = 1.39, P* = 0.26; partial η^2 = 0.08
Lunch intake time (minutes)	15 ± 6[a]	18 ± 6[a]	17 ± 6[a]	*F (2, 34) = 1.65, P* = 0.21; partial η^2 = 0.09

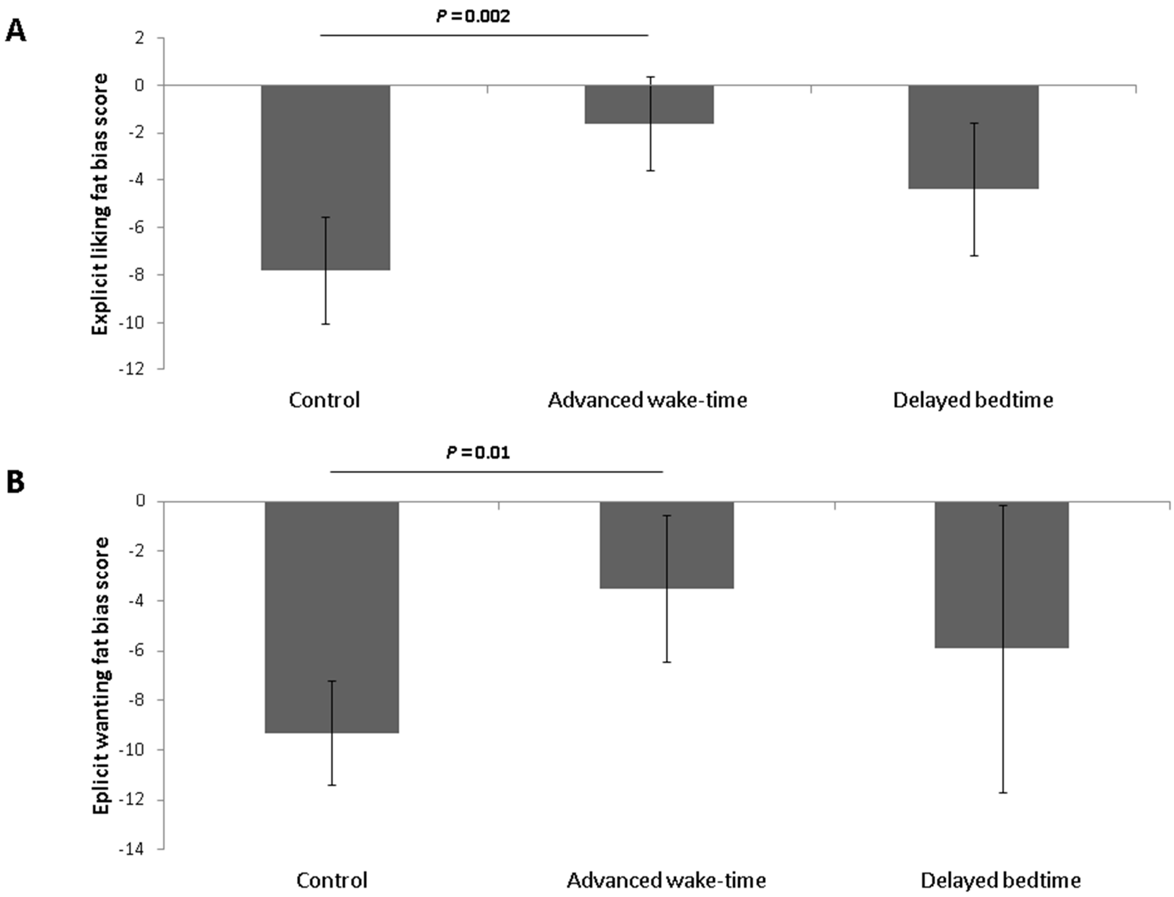
Note: Means not sharing the same letter are significantly different from each other ($P < 0.05$).

*Partial η 2 were not available for variables that were compared using the Friedman Exact non-parametric test.

kcal, kilocalories; SD, standard deviation


A
Desire to eat rating (mm)
100
80
60
40
20
0
Fasting
0
30
60
90
120
150
180
Time (min)
F (2, 32) = 5.09, P = 0.01, partial η2 = 0.24
Control
Advanced wake-time
Delayed bedtime
B
Hunger rating (mm)
F (2, 32) = 5.68, P = 0.01, partial η2 = 0.26
C
Fullness rating (mm)
F (2, 32) = 4.30, P = 0.02, partial η2 = 0.21
D
PFC rating (mm)
F (2, 32) = 4.80, P = 0.02, partial η2 = 0.23


A
F (2, 32) = 3.23, P = 0.05, partial η2 = 0.17
Desire to eat AUC
7000
6000
5000
4000
3000
2000
1000
0
Control
Advanced wake-time
Delayed bedtime
B
F (2, 32) = 4.19, P = 0.03, partial η2 = 0.21
Hunger AUC
7000
6000
5000
4000
3000
2000
1000
0
Control
Advanced wake-time
Delayed bedtime
C
F (2, 32) = 3.92, P = 0.03, partial η2 = 0.20
Fullness AUC
14000
12000
10000
8000
6000
4000
2000
0
Control
Advanced wake-time
Delayed bedtime
D
F (2, 32) = 4.24, P = 0.02, partial η2 = 0.21
PFC AUC
8000
7000
6000
5000
4000
3000
2000
1000
0
Control
Advanced wake-time
Delayed bedtime


A
P = 0.002
Explicit liking fat bias score
2
0
-2
-4
-6
-8
-10
-12
Control
Advanced wake-time
Delayed bedtime
B
P = 0.01
Eplicit wanting fat bias score
0
-2
-4
-6
-8
-10
-12
-14
Control
Advanced wake-time
Delayed bedtime