

Acute partial sleep deprivation increases food intake in healthy men^{1–3}

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ABSTRACT

Background: Acute partial sleep deprivation increases plasma concentrations of ghrelin and decreases those of leptin.

Objective: The objective was to observe modifications in energy intake and physical activity after acute partial sleep deprivation in healthy men.

Design: Twelve men [age: 22 ± 3 y; body mass index (in kg/m^2): 22.30 ± 1.83] completed a randomized 2-condition crossover study. During the first night of each 48-h session, subjects had either ≈ 8 h (from midnight to 0800) or ≈ 4 h (from 0200 to 0600) of sleep. All foods consumed subsequently (jam on buttered toast for breakfast, buffet for lunch, and a free menu for dinner) were eaten ad libitum. Physical activity was recorded by an actimeter. Feelings of hunger, perceived pleasantness of the foods, desire to eat some foods, and sensation of sleepiness were also evaluated.

Results: In comparison with the 8-h sleep session, subjects consumed 559 ± 617 kcal (ie, 22%) more energy on the day after sleep restriction ($P < 0.01$), and preprandial hunger was higher before breakfast ($P < 0.001$) and dinner ($P < 0.05$). No change in the perceived pleasantness of the foods or in the desire to eat the foods was observed. Physical activity from 1215 to 2015 was higher after sleep restriction than after 8 h of sleep ($P < 0.01$), even though the sensation of sleepiness was more marked ($P < 0.01$).

Conclusions: One night of reduced sleep subsequently increased food intake and, to a lesser extent, estimated physical activity–related energy expenditure in healthy men. These experimental results, if confirmed by long-term energy balance measurements, suggest that sleep restriction could be a factor that promotes obesity. This trial was registered at clinicaltrials.gov as NCT00986492. *Am J Clin Nutr* 2010;91:1550–9.

INTRODUCTION

Today, obesity is considered a major disease worldwide and is sometimes regarded as a true “epidemic” (1). For the past 40 y, simultaneously with the increase in obesity, a reduction in the duration of sleep has been noted in industrialized countries. For example, the duration of sleep, which averaged 8–9 h/night in the United States in 1960 (2), fell to 7 h in 1995 (3) and from 8 h and 13 min in 1960 to 7 h and 32 min in 1995 in Japan (4). Although controversial (5), it has been suggested over the past decade that shorter periods of sleep could be a risk factor for weight gain and obesity (6, 7). Actually, several cross-sectional or prospective epidemiologic studies have observed a negative correlation between body mass index and sleep duration. As an example, this correlation was reported in Spain (8), France (9), Japan (10), and the United States (11–13). The mechanisms by which restriction of sleep may affect energy balance and lead to overweight are

unknown, but 3 main mechanisms have been put forward (7). First, an increase in free time to eat supposes that food is easily available and that subjects have a sedentary lifestyle (14). Second, an increase in appetite, in keeping with this hypothesis, has been noted that habitual short-sleepers ate proportionally more often (ie, >3 meals/d) than did longer-sleepers (15). Recently, it was also observed that sleep restriction or habitual short sleep duration increases hunger/appetite (16, 17) and plasma concentrations of ghrelin (a “hunger” hormone) (16–18) and decreases leptin concentrations (a “satiety” hormone) (16, 18–22). Along the same lines, epidemiologic studies have shown that sleep restriction is frequently associated with irregular food intake, nibbling, excessive use of condiments, and low consumption of vegetables (4, 23). Third, a reduction in energy expenditure after sleep restriction could result from a decrease in physical activity due to tiredness (24, 25) or modifications in thermoregulatory processes (26).

Surprisingly, only 3 experimental studies have observed the effect of sleep restriction on food intake in humans. The first study mentioned an “anecdotal” increase in food intake in adult subjects who were permitted ad libitum access to food during 3 d of total sleep restriction (27). The second study, conducted in overweight subjects, observed an increase in the consumption of snacks after 2 wk of 2 h of sleep restriction per night (28). However, in this study, the subjects (under laboratory conditions) showed a positive energy balance not only after the sleep restriction session, but also after the normal-sleep session, which renders the interpretation of the results difficult. The third study, conducted in subjects with a normal body weight under laboratory conditions, reported no change in food intake after 2 nights each of ≈ 4 h of sleep compared with 2 nights of regular sleep (29). However, the subjects were in a similar highly positive energy balance ($\approx 60\%$), regardless of the preceding sleep duration. Thus, to our knowledge, no epidemiologic (25, 30–33) or conclusive experimental human study in subjects with a normal

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body weight has yet highlighted a significant effect of sleep duration on energy intake. The present experiment was thus conducted most of the time under free-living conditions to determine whether acute partial sleep deprivation in humans had an effect on appetite and food energy intake and concomitantly on physical activity.

SUBJECTS AND METHODS

Subjects

The subjects were 12 normal-weight men with a mean (\pm SD) age of 22 ± 3 y (range: 18–29 y), body mass index (in kg/m^2) of 22.30 ± 1.83 (range: 19.0–24.6), height of 176.8 ± 4.6 cm, and weight of 69.8 ± 6.5 kg who gave their written consent to participate in the experiment. All subjects were students recruited by local advertisement. Inclusion criteria were general healthiness, absence of medication use, habitual nocturnal sleep duration of ≈ 7 h 30 min to 8 h, normal body weight as measured by the experimenter ($20 < \text{body mass index} < 25$), weight stability during the preceding 6 mo (± 0.5 kg), and moderate physical activity (irregular and < 5 h/wk). Smokers were accepted if they smoked < 5 cigarettes/d. Four subjects were smokers and were allowed to smoke during the 2 experimental sessions, but no more than usual. The subjects reported mean (\pm SD) habitual sleep duration was 7 h and 54 ± 52 min. Exclusion criteria were night work, psychostimulant and/or narcotic use, sleeping pills, eating disorders, excessive caffeine [> 3 cups (450 mL)/d] or alcohol (> 10 g/wk) consumption, dieting or fasting, food snacking (> 2 times/d), and aversions to the foods offered. Subjects were also excluded if they were

restrained, disinhibited, or hungry (score > 9 , > 11 , and > 9 , respectively) according to the Three-Factor Eating Questionnaire (34). The subjects' mean (\pm SD) scores for cognitive restriction of eating, eating disinhibition, and susceptibility to hunger were 5.8 ± 2.3 , 5.4 ± 3.2 , and 4.7 ± 2.3 , respectively. None of the subjects were informed about the aims of the experiment, the meal structure, the measurements performed, the duration of sleep, or the activities proposed. In each session, 3 subjects were tested simultaneously. The study was conducted in the month of August (duration of the night ≈ 9 h 50 min; GMT +2 h) and was approved by the Regional Ethics Committee of Caen (France).

Sessions

Control period

Immediately before the first experimental session, over 2 consecutive days, the subjects had to record in a diary 1) the duration and quality of their sleep (bedtime, time of waking, and quality of sleep evaluated on a visual analog scale), 2) their physical activities (questionnaire) and 3) all of their ingested foods (nature and weight) (**Figure 1**). The ingested foods (difference between initial and final weights) had to be accurately reported by the subject himself (required accuracy to 1 g). For this purpose, the subjects were provided with a digital balance accurate to 1 g (Page; Soehnle, Nassau, Germany). This control period was designed to test the subjects' compliance with the study requirements without their knowledge (ie, appreciation of subjects' sleep habits and precision in weighing all the eaten foods) to accustom the subjects to the measurement techniques and to appreciate their usual habits.

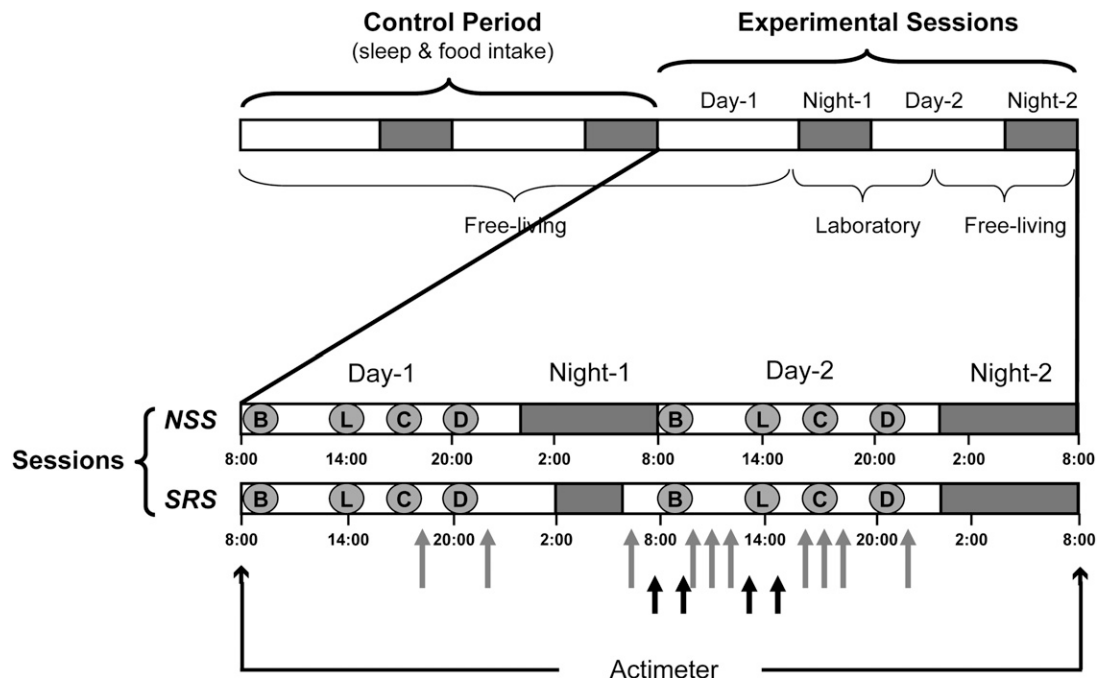


FIGURE 1. Timing of the experiment: Twelve subjects were studied during a 48-h control period before the first session and then during the Normal-Sleep Session (NSS) and the Sleep-Restriction Session (SRS). Measurements were made under either free-living or laboratory conditions. In the experimental sessions, the following factors were evaluated for 48 h: energy intake at breakfast (B), lunch (L), afternoon snack (C), and dinner (D); hunger, pleasantness of the foods, sleepiness, and “motivation to engage in physical activity” (gray arrows); “olfactory liking” for 4 foods and “wanting” for 6 other foods (black arrows); and physical activity (actimeter).

Experimental sessions

The two 48-h crossover sessions were held in random order, respecting a minimal interval of 5 d between sessions (Figure 1). The sessions differed by the sleep duration of the first night: in the Normal-Sleep Session (NSS), subjects had to go to bed at midnight and were awakened at 0800 (≈ 8 h of sleep); in the acute partial Sleep-Restriction Session (SRS), subjects had to go to bed at 0200 and were awakened at 0600 (≈ 4 h of sleep).

Chronologic design in the experimental sessions

The sessions started at 0800 (day 1) by installing an actimeter around the subjects' waists (RT3; Stayhealthy Inc, Monrovia, CA) and recording the duration of the preceding night's sleep (subjects' self-recorded bedtime and wake-up time). Then, from 0800 to 1900, the subjects were left in free-living conditions but had to record carefully each time they ate and each type of food eaten, as previously described.

The following 17 h (from 1900 to 1400 the next day) were spent in the laboratory. On arrival at 1900, each subject was given a private room, in which he was left alone to eat, sleep (during the permitted period), attend to personal hygiene, and fill in the questionnaires. Before dinner (from 2000 to 2030), each subject had to complete a questionnaire to rate preprandial Hunger (H), Pleasantness (P) of the meal, and sensation of Sleepiness (S). Postprandial H, P, and S were evaluated immediately after dinner. Then, from 2030 to the time to sleep, subjects joined the experimenter for discussions, games, and movies. At midnight in the NSS and at 0200 in the SRS, the subjects went to bed (night 1). The subjects were awakened at 0800 in the NSS and at 0600 in the SRS. In the SRS, from 0000 to 0200 as well as from 0600 to 0800, the subjects had to remain in a calm reclining position watching movies together with the experimenter. After waking (day 2), the subjects were asked to indicate the time they fell asleep and to rate the duration or quality of their sleep. A standard breakfast was offered between 0800 and 0830. The breakfast was preceded and followed by before and after evaluations of H, P, and S, but also by evaluations of "olfactory liking" for 4 foods and "wanting" for 6 other foods (*see below*). Then, in the morning, the subjects went for a walk outside the laboratory together with the experimenter. At 0900, 1030, and 1200, the subjects were questioned about their H and S and their "motivation to engage in physical activity" (M). From 1230 to 1315, lunch was offered in the form of a buffet. The lunch was preceded and followed by evaluations of H, P, S, M, "olfactory liking" for 4 foods, and "wanting" for 6 other foods.

From 1400 to 0800 the next morning, the subjects returned to free-living conditions. During this period, the subjects were left free to eat whatever they wanted during the afternoon and at dinner (with the exception of tea, coffee, and energy drinks), but all eating times and weights of all eaten foods had to be accurately reported in the diary. The subjects were also left free to engage in the activities of their choice (except sleeping before 2000, which was assessed by the actimeter). At 1530, 1700, and 1830, evaluations of H, S, and M were recorded. Dinner was preceded and followed by evaluations of H, S, and M. After 2000, the subjects could go to sleep at any time they wanted (night 2). The next morning, the subjects were allowed to wake up when they wanted to. They then filled out a questionnaire concerning the time they thought they had fallen asleep and the duration and

quality of their sleep. The actimeters were removed after they awoke (ie, after 48 h of recording).

Description of the meals

During the first day (day 1), breakfast and lunch were unrestricted (in amount and composition) but were accurately weighed by using a digital balance (precision: ± 1 g; Page; Soehnle). During dinner, the subjects had to eat a standard meal composed of ravioli pasta, apple compote, and natural yogurt (Table 1). Ingested quantities during dinner were ad libitum in the first session, but subjects had to eat the same food quantities in the second session.

During the second day (day 2), the choice of foods proposed for breakfast was fixed (jam on buttered toast), semifixed for lunch (buffet), and unrestricted for dinner. Each meal was eaten ad libitum. Subjects ate alone in the laboratory during breakfast and lunch, but there were no specified conditions for dinner. Breakfast was composed of 16 to 32 pieces of toast (≈ 9 g each) with butter and strawberry jam and 200 mL coffee or tea with sugar (same quantities in the 2 sessions according to the individuals' preferences). Subjects could eat as much toast as they wanted. The quantities of jam on buttered toast eaten were found by calculating the difference between initial and final weights (precision: ± 3 g; Page; Soehnle). At lunch, the subjects were

TABLE 1

Foods served at dinner before the 8-h or 4-h sleep session (day 1) and during the following day (day 2)¹

	Energy intake	Carbohydrates	Fat	Proteins
	<i>kcal/100 g wet wt</i>	%	%	%
Dinner (day 1)				
Ravioli pasta	100	51	31	18
Apple compote	92	95	3	2
Yogurt	75	69	11	20
Breakfast (day 2)				
Jam on buttered toast	351	58	36	5
Lunch (day 2)				
Apple	49	96	6	2
Apple compote	92	95	3	2
Banana	89	94	3	5
Biscuits with fruit	337	76	19	5
Breast of chicken	102	4	13	83
Chips	521	33	62	4
Fruit salad	102	98	1	1
Grated carrots	97	36	60	4
Gruyere cheese	377	0	69	31
Ham	113	1	24	75
Macedonia salad and mayonnaise	127	24	70	6
Marshmallow	380	100	0	0
Hazelnut spread	533	43	52	5
Potted mince	436	0	87	13
Sandwich bread	284	77	13	10
Soft white cheese	79	18	39	43
Surimi	81	30	8	62
Sweet biscuits	437	69	22	8
Taboulé	222	67	18	14
Savory biscuits	448	68	24	8

¹ Foods were served as a standard meal for dinner on day 1, as standard toast for breakfast, and as a buffet for lunch on day 2. The composition of dinner on day 2 was left free.

invited to eat whatever they wanted from 20 different foods from the buffet (Table 1). They served themselves and were allowed to serve themselves again. All ingested foods were carefully weighed (precision ± 3 g; Page). During the afternoon and at dinner, subjects could eat whatever they wanted but had to weigh all foods ingested (Page). From the weight of the foods eaten, macronutrients were evaluated and energy intake was calculated a posteriori by using Bilnut software (version 4.0; SCDA Nutrisoft, Cerelles, France).

Ratings

The questions used to evaluate H and S were “How hungry do you feel at this moment?” and “How sleepy do you feel at this moment?”, respectively. Subjects were instructed to answer the question by placing a mark on a 10-cm line anchored with “not at all” (0) and “extremely” (+10) at its extremities. To evaluate the pleasantness for the meals before and after ingestion, the quality of sleep, the duration of sleep, and the motivation to engage in physical activity, the questions asked were “At this moment, how pleasant does this meal seem?”; “What was the quality of your sleep?”; “Did you sleep enough?”; and “At present, how strong is your desire to engage in physical activity?,” respectively. The 10-cm scales ranged from “extremely unpleasant” (−5) to “extremely pleasant” (+5), “not satisfactory” (0) to “extremely satisfactory” (+10), “not enough” (0) to “too much” (+10), and “none” (0) to “extremely” (+10).

“Olfactory liking” and “wanting”

The 2 explicit components of the food reward system (ie, liking and wanting) were evaluated as described by Berridge (35). “Olfactory liking” was measured separately for 4 food items immediately before and after breakfast and lunch during day 2. The foods smelled were melted butter, mayonnaise, honey, and maple syrup (2 items were rich in fat and the other 2 in carbohydrates). Each food item was presented in a random order separately in small cups and smelled orthonasally for ≈ 10 s at a distance of 10 to 15 cm from the nose, with a pause of ≈ 30 s between 2 foods (total duration of olfactory evaluation was 2–3 min). The question to assess “olfactory liking” for each item was “Does this odor make it seem pleasant to eat the food right now?” The 10-cm scales ranged from “extremely unpleasant” (−5) to “extremely pleasant” (+5).

“Wanting” was evaluated separately for 6 food items immediately after evaluation of “olfactory liking.” The 6 foods were shown in photographs (10 \times 15 cm) and presented in random order. The photographs showing ham, fried egg, rice, corn flakes, apple, and yogurt (3 items were savory and 3 were sweet). The total duration of the “wanting” evaluation was 2–3 min. The question to assess “wanting” for each item was “At present, how strong is your desire to eat this food?” The 10-cm scales ranged from “not at all” (0) to “extremely” (+10).

Actimetry

To evaluate the subjects’ physical activity, the actimeter (RT3; Stayhealthy Inc) was continuously worn around the subjects’ waist for the two 48-h sessions. Later on, mean “activity counts-3 axis/min¹” and mean “activity calories” given by the manufacturer’s software (version 3.19.03; Stayhealthy Inc) were

calculated for different periods: morning (0815 to 1215), afternoon (1215 to 2015), evening (2015 to 0015), and night (0015 to 0815).

Statistical analysis

Values are expressed as means \pm SDs. The 2 experimental sessions were compared with each other according to 2 periods: the pretreatment period (before the 8-h/4-h sleep) to evaluate the preceding 24-h period (regular night duration, moderate physical activity, and usual food intake with the standard meal eaten at dinner) and consequently to assess the occurrence of unusual events (eg, intense physical activity); a posttreatment evaluation—during which intake, physical activity, and night duration were left free—was conducted to evaluate the effect of sleep restriction on the subsequent 24 h (under either laboratory or free-living conditions).

To compare the variations in P, “olfactory liking,” “wanting,” H (total and pre- and postprandial H), S, and M over time (factor a) in the 2 sessions (factor b) as well as the influence of the order of treatment (factor a) in the measured variables (factor b) and the possible difference in the measured variables (factor a) in the 6 participants who ate the most and the 6 who ate the least in the SRS during day 2 (factor b), 2-factor repeated-measures ANOVAs were used. Whenever statistical differences were detected, Tukey’s post hoc test was applied to screen for differences between sessions. For the sleep variables, preprandial hunger/intake before dinner on day 2 and actimetry parameters (ie, values measured only once in the laboratory or in free-living conditions), differences between the 2 experimental sessions were analyzed by using paired *t* tests. Analyses were conducted by using SigmaStat software (version 3.1; Systat Software Inc, Richmond, CA).

RESULTS

Sleep

During night 1, as expected, sleep duration was shorter in the SRS than in the NSS: it was 3 h 46 \pm 14 min and 7 h 14 \pm 40 min according to the actimeters and 3 h 44 \pm 11 min and 7 h 14 \pm 36 min according to the subjects’ estimations ($P < 0.001$ for both). The subjects found the duration of their sleep insufficient in the SRS in comparison with the NSS ($P < 0.001$), but both periods of sleep were judged satisfactory in terms of quality. As shown in **Figure 2**, A and B, the shorter sleep duration in the SRS subsequently induced a stronger sensation of sleepiness ($P < 0.001$) but a similar motivation to engage in physical activity during the morning.

During night 2 (ie, night of recovery), bedtimes were similar for the 2 sessions (0013 \pm 58 min compared with 0020 \pm 80 min according to the actimeters and 0012 \pm 61 min compared with 0010 \pm 85 min according to the time the subjects estimated that they fell asleep). The duration of sleep during night 2 was longer after the SRS than after the NSS (8 h 21 min \pm 1 h 58 min compared with 7 h 33 min \pm 1 h 36 min according to the actimeters and 8 h 52 min \pm 2 h 02 min compared with 8 h 00 min \pm 2 h 24 min according to the subjects’ estimations; $P < 0.05$ for both). Sleep during on night 2 was judged to be similar in quantity and quality for the 2 sessions.

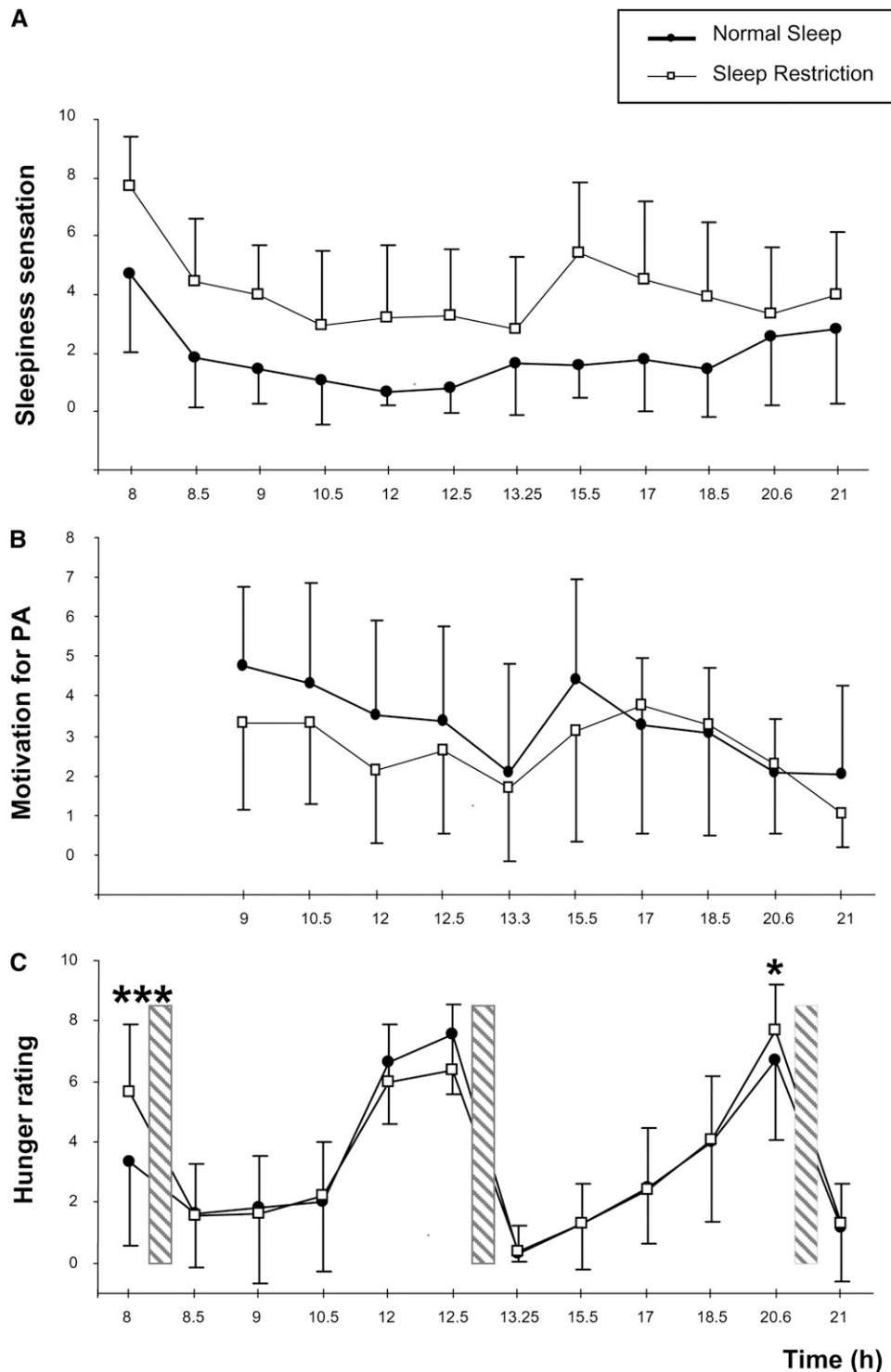


FIGURE 2. Time course evolution of the sensation of sleepiness (A), motivation to engage in physical activity (PA; B), and hunger rating (C) after the 8-h or 4-h sleep session (day 2). Values are means \pm SDs and were derived by using 10-cm visual analog scales. Hatched bars (C) represent meal times. For the 12 subjects, 2-factor repeated-measures ANOVA indicated a significant difference for the sensation of sleepiness ($P < 0.001$) and no difference for the motivation to engage in PA between the 2 sessions, with no significant interaction for either factor. During laboratory conditions (ie, 0800–1400), preprandial hunger was similar between the Sleep-Restriction Session and Normal-Restriction Session, but a significant interaction ($F_{2,22} = 5.98$, $P < 0.01$) between sessions and time was observed. Tukey's post hoc test showed greater preprandial hunger before breakfast in the Sleep-Restriction Session ($***P < 0.001$). During the free-living conditions (ie, 1400–2030), preprandial hunger before dinner was also greater in the Sleep-Restriction Session than in the Normal-Restriction Session ($*P < 0.05$, paired t test).

Food intake and ratings

During day 1, neither energy nor macronutrient intakes differed between the 2 sessions (Table 2). During day 2, 2-factor

repeated-measure ANOVAs showed no significant difference for hunger sensation during the entire day (pre- and postprandial values) between the 2 sessions. However, considering the 3

preprandial hunger values or the 2 preprandial values during the laboratory conditions, preprandial hunger before the breakfast was greater in the SRS than in the NSS ($P < 0.001$; Figure 2C). Similarly, considering the preprandial hunger values during the free-living conditions, hunger was greater before the dinner in the SRS than in the NSS ($P < 0.05$).

Energy intake was 22% higher ($+559 \pm 617$ kcal; $P < 0.01$) in the SRS than in the NSS (Table 2). In detail, 9 subjects ate more (+36%) and 3 subjects ate less (-15%) in the SRS than in the NSS. The increase in energy intake was observed during breakfast (45%; $P < 0.01$) and dinner (56%; $P < 0.001$) but not at lunch or during the afternoon. During the laboratory conditions (breakfast and lunch), energy intake was not significantly different between the 2 sessions ($P = 0.09$), but this difference became significant during the free-living conditions (afternoon collation and dinner; $P < 0.05$).

The duration of intake was also longer in the SRS than in the NSS at breakfast (25.7 ± 4.3 min compared with 20.3 ± 3.9 min; $P < 0.01$) but not at lunch (28.4 ± 5.6 min compared with 25.9 ± 8.2 min) and at dinner (30.6 ± 21.7 min compared with 25.0 ± 19.4 min); during the afternoon, no data were recorded because few subjects had spontaneous intake. Finally, no difference in water intake was noted between the 2 sessions, regardless of the period of the day.

The proportion of macronutrient intake did not differ between the 2 sessions at breakfast, because the composition of jam on buttered toast was fixed. At lunch, the same proportions of macronutrients were eaten in both sessions during the buffet, but less chicken (-35%) and more bread (+20%) were ingested in the SRS than in the NSS ($P < 0.05$ for both; data not shown). During the dinner, a higher amount of lipids (+98%) was consumed in the SRS than in the NSS ($P < 0.001$; Table 2). Taken together, a similar fat intake was noted during the laboratory conditions (breakfast and lunch) in the SRS and the NSS, but this difference became significant during the free-living condition (afternoon collation and dinner; $P < 0.01$).

The sensation of pleasantness induced by breakfast, lunch, and dinner (before and after intake as well as the change in pleasantness from before to after intake) did not differ between the 2 sessions (data not shown). In the same way, there was no significant difference between the 2 sessions in terms of "olfactory liking" for the 4 food items (rich in fat or in carbohydrates) or for "wanting" the 6 food items (savory or sweet) before and after intake of breakfast and lunch (data not shown).

Physical activity

During day 1, physical activity (total number of activity counts-3 axis) was similar in the 2 sessions (Table 3). As expected, during night 1 (from 0015 to 0815), physical activity was higher in the SRS than in the NSS ($P < 0.01$), because the SRS subjects slept for a shorter period of time.

During day 2, physical activity in the SRS was not significantly different from that in the NSS, particularly during the morning (ie, from 0815 to 1215) when activities were imposed (Table 3). However, physical activity was higher in the SRS during the afternoon (from 1215 to 2015; $P < 0.05$) or during the afternoon plus the evening (from 1215 to 0015; $P < 0.01$), when activities were left free. During night 2 (ie, night of recovery), physical activity was lower in the SRS than in the NSS ($P < 0.05$; Table 3).

Additional results

Statistical analysis showed no effect of the crossover nature of the experimental design for any of the measured variables (Appendix A), except for "olfactory liking" for mayonnaise ($P < 0.05$) and duration of lunch ($P < 0.05$), which were higher during the first session than during the second session.

During day 2, the subjects had a higher energy intake than on day 1 (SRS: +46%, $P < 0.01$; NSS: +15%, $P < 0.05$) with, in both sessions, a higher proportion of energy from fat (SRS: 41%

TABLE 2

Total energy intake and macronutrient composition (% energy) of the foods consumed before the 8-h or 4-h sleep session (day 1) and during the following day (day 2)¹

	Normal-Sleep Session				Sleep-Restriction Session			
	Energy intake <i>kcal</i>	Carbohydrate <i>% of energy</i>	Fat <i>% of energy</i>	Proteins <i>% of energy</i>	Energy intake <i>kcal</i>	Carbohydrate <i>% of energy</i>	Fat <i>% of energy</i>	Proteins <i>% of energy</i>
Day 1								
Breakfast	333 ± 178	71 ± 15	21 ± 13	8 ± 4	393 ± 227	67 ± 21	26 ± 22	8 ± 3
Lunch	778 ± 529	39 ± 26	38 ± 23	21 ± 7	749 ± 350	43 ± 24	30 ± 22	18 ± 11
Afternoon	183 ± 162	64 ± 16	37 ± 29	7 ± 4	75 ± 16	69 ± 28	21 ± 22	10 ± 6
Dinner	864 ± 181	51 ± 0	30 ± 1	20 ± 0	864 ± 181	51 ± 0	30 ± 1	20 ± 0
Total	2158 ± 524	50 ± 6	33 ± 5	17 ± 4	2081 ± 445	50 ± 12	32 ± 12	17 ± 4
Day 2								
Breakfast	485 ± 149	62 ± 5	33 ± 4	5 ± 1	703 ± 262 ²	61 ± 3	34 ± 3	5 ± 1
Lunch	1279 ± 328	45 ± 7	40 ± 5	15 ± 3	1292 ± 484	44 ± 8	41 ± 7	15 ± 3
Afternoon	85 ± 155	65 ± 28	23 ± 22	11 ± 9	61 ± 121	83 ± 15	5 ± 9	12 ± 3
Dinner	630 ± 320	42 ± 11	37 ± 14	21 ± 9	982 ± 470 ³	35 ± 12	48 ± 13 ³	17 ± 5
Total	2478 ± 512	48 ± 6	38 ± 6	14 ± 3	3037 ± 853 ²	45 ± 7	41 ± 6 ²	13 ± 3

¹ All values are means ± SDs; $n = 12$. Energy intake during day 2 was higher in the Sleep-Restriction Session ($F_{1,33} = 9.831$, $P < 0.01$) than in the Normal-Sleep Session, with a significant interaction between sessions and time ($F_{3,33} = 5.393$, $P < 0.01$). Tukey's post hoc test showed a higher intake at breakfast ($P < 0.01$) and at dinner ($P < 0.001$). Fat intake during day 2 was also higher in the Sleep-Restriction Session ($F_{1,33} = 15.11$, $P < 0.01$) than in the Normal-Sleep Session, with a significant interaction between sessions and time ($F_{3,33} = 7.704$, $P < 0.01$) and a higher fat intake at dinner ($P < 0.001$).

^{2,3} Significantly different from the Normal-Sleep Session: ² $P < 0.01$, ³ $P < 0.001$.

TABLE 3

Physical activity evaluated by actimetry before (day 1) and after (day 2 and night 2) the 8-h or 4-h sleep session (night 1)¹

Time	Normal-Sleep Session	Sleep-Restriction Session
Day 1		
0815–1215	133 ± 70	169 ± 135
1215–2015	412 ± 191	464 ± 189
2015–0015	35 ± 11	37 ± 18
Total (0815–0015)	580 ± 203	670 ± 279
Night 1		
0015–0815	19 ± 8	44 ± 15 ²
Day 2		
0815–1215	183 ± 53	174 ± 38
1215–2015	328 ± 264	417 ± 187 ³
2015–0015	85 ± 52	91 ± 57
Total (0815–0015)	596 ± 311	682 ± 195
Night 2		
0015–0815	56 ± 45	19 ± 20 ⁴

¹ All values (total number of activity counts measured by triaxial accelerometer for all 3 axes every second for 1 min) are means ± SDs; $n = 12$. Two-factor repeated-measures ANOVA showed a significant interaction between sessions and time on day 2 for physical activity ($F_{2,20} = 3.797$, $P < 0.05$).

^{2,4} Significantly different from the Normal-Sleep Session (paired t test; $n = 11$): ² $P < 0.01$, ⁴ $P < 0.05$.

³ Significantly different from the Normal-Sleep Session, $P < 0.01$ (2-factor repeated-measures ANOVA).

compared with 32%; NSS: 38% compared with 33%, respectively; $P < 0.01$ for both) but similar estimated activity-related energy expenditure than on day 1 from 0815 to 0015 (SRS: +3%; NSS: +2%).

During the 24 h after night 1, according to the calculations of the energy expenditure from the actimeters (**Table 4**), the subjects were nearly at equilibrium in terms of energy balance in the NSS (intake = 2478 ± 512 kcal; estimated expenditure = 2544 ± 389 kcal) but in a state of positive energy balance in the SRS (intake = 3037 ± 853 kcal; estimated expenditure = 2593 ± 357 kcal).

Compared with the 6 subjects who had the lowest increase in intake in the SRS during day 2, the 6 subjects with the highest increase had a lower eating disinhibition score ($P < 0.05$) and were less sleepy in the morning as well as throughout day 2 (mean scores; $P < 0.05$), but no other significant differences, in particular for their body mass index or their physical activity, was observed. Finally, smoking had no effect on intake and physical activity during day 2.

DISCUSSION

The main results of the present study, conducted in normal-weight men who spent 31 h during the 48 h of measurement in free-living conditions, indicate that acute partial sleep deprivation subsequently increases food intake, preprandial hunger at breakfast and dinner, and estimated physical activity-related energy expenditure. These results cannot be attributed to 24-h pretreatment conditions because food intake, sleep duration during the night preceding the experimental sessions, and estimated energy expenditure were very similar in the 2 sessions (<4%, <1%, and <3%, respectively).

TABLE 4

Estimated energy expenditure before (day 1) and after (day 2 and night 2) the 8-h or 4-h sleep session (night 1)¹

Time	Normal-Sleep Session	Sleep-Restriction Session
Day 1	<i>kcal</i>	<i>kcal</i>
0815–1215	342 ± 75	445 ± 144
1215–2015	1054 ± 204	1096 ± 211
2015–0015	443 ± 157	353 ± 25
Total (0815–0015)	1839 ± 228	1894 ± 353
Night 1		
0015–0815	661 ± 42	676 ± 52
Day 2		
0815–1215	504 ± 59	491 ± 51
1215–2015	970 ± 288	1068 ± 263 ²
2015–0015	430 ± 100	431 ± 104
Total (0815–0015)	1904 ± 381	1990 ± 328
Night 2		
0015–0815	691 ± 63	642 ± 56 ³

¹ All values are means ± SDs. Two-factor repeated-measures ANOVA showed a significant interaction between sessions and time at day 2 for estimated energy expenditure ($F_{2,20} = 3.677$, $P < 0.05$).

² Significantly different from the Normal-Restriction Session, $P < 0.01$ (2-factor repeated-measures ANOVA).

³ Significantly different from the Normal-Restriction Session, $P < 0.05$ (paired t test; $n = 11$).

Sleep

Sleep was shorter in the SRS than in the NSS, but both periods of sleep were centered on 0400 to minimize the change in circadian rhythms (36) and to center the sleep with regard to food intake (37, 38). To our knowledge, the influence of the duration of sleep restriction into the night, the timing of awakening, and the time period spent awake before breakfast has never been studied in humans.

Food intake and food rating

Ingested quantities (weight and energy) and durations of intake were higher during the day after the short sleep than during the day after the 8-h sleep (+19%, +22%, and +19%, respectively). This increase in food consumption was noted during breakfast and dinner, particularly during free-living conditions, and was preceded by greater sensation of hunger. This result is consistent with some previous studies in humans. Actually, it has been reported that acute partial sleep deprivation or habitual short sleep duration led to an increase in hunger (16, 17), an increase in the orexigenic factor ghrelin (16–18) and a decrease in the anorexigenic hormone leptin (16, 18–21). In contrast, the present study is not consistent with 2 recent studies, which studied food intake after sleep restriction (28, 29). Nedeltcheva et al (28) observed, in 11 overweight subjects (5 women and 6 men aged 34–49 y with a body mass index of 24 to 29), that a 122-min reduction in sleep per night for 14 d did not induce significant changes in intake of energy from meals, although it increased the consumption of energy from snacks (28). A comparison between the present experiment and the above-mentioned study raises several questions because the subjects' anthropometric measures (overweight compared with normal-weight subjects), experimental conditions (laboratory compared with free environmental condition), sleep (curtailment and

experimental duration), and foods proposed (profusion of palatable compared with habitual foods) were different. Very recently, Schmid et al (29) also observed in 15 normal-weight men (age: 20–40 y; BMI: 22.9 ± 0.3) that 2 nights of 4 h sleep restriction each induced energy intakes similar to those after 2 nights of regular sleep. However, the subjects were in a highly positive energy balance ($\approx 60\%$) regardless of the preceding sleep duration because of the high energy intake (≈ 4000 kcal). The presence of a large standardized buffet and a large snack buffet, which remained in the experimental room throughout the day, could explain the difference between this observation and the present study. The fact that epidemiologic studies that attempted to quantify energy intake also found no relation between sleep duration and dietary intake (30–33, 39) could be attributed to the difficulty in highlighting a discrete increase in intake linked to sleep restriction, in so far as environmental factors (eg, stress, activity) and interindividual differences could interfere.

A significantly higher fat intake was also noted on the day after sleep restriction, particularly at dinner. A higher preference for fatty foods after sleep restriction has been reported anecdotally in humans (27). Interestingly, Shi et al (40) observed in Chinese adults that those who slept <7 h/night ate more fat (and less carbohydrates) than did those who slept 7–9 h/night. The higher intake of fatty foods is also in line with Spiegel et al's (16) observation that subjects had a greater appetite for calorie-dense foods after 2 nights of restricted sleep of 4 h, although the desire to specifically eat carbohydrates and fatty foods was not evaluated in this study. The higher intake of fatty foods was also in line with Schmid et al's (29) study, which found a higher fat intake after sleep restriction.

Hedonic sensations induced by foods did not markedly differ between the NSS and the SRS in the morning and at lunch. Actually, the results were similar in these 2 sessions for 1) hedonic sensations induced by breakfast, lunch, and dinner; 2) "olfactory liking" for the 4 food items (rich in fat or in carbohydrates), and 3) "wanting" the 6 food items (savory or sweet). Thus, the palatability and the 2 components of the food reward system (ie, liking and wanting) as described by Berridge (35), did not seem to be affected by the duration of the preceding night's sleep.

Physical activity, sensation of sleepiness, and motivation to perform physical activity

Physical activity, assessed by actimetry, was significantly higher after the short sleep session. This increase was noted during the free time period (ie, during the afternoon and the evening when subjects were not with the experimenter) and not during the morning when activities were imposed (ie, when the subjects had to visit museums and music/book shops with the experimenter). This increase in physical activity contrasts with the expected higher sensation of sleepiness. After sleep restriction, the strong sensation of tiredness or a feeling of fatigue was previously described (24), but the higher physical activity after acute partial sleep deprivation, which is not consistent with the lower physical activity noted in Schmid et al's study (29), is an original observation in humans.

Epidemiologic studies reported conflicting results concerning physical activity: a reduction (8, 33, 41), no relation (4, 25, 42–

44), or an increase (30, 45) in physical activity. In their study, Chaput et al (30) noted that short-duration sleepers had greater participation in vigorous physical activity than did 7–8-h sleepers, whereas Patel et al (45) observed a higher reported physical activity in men who slept 5–7 h/night than in those who slept >7 h/night.

Estimated energy balance

For the 24-h period after sleep restriction, the increase in energy intake was greater than the increase in estimated energy expenditure: energy intake increased by 559 kcal, whereas estimated physical activity–related energy expenditure according to the actimetry-manufacturer's calculations increased by 48 kcal. Because some studies reported only a modest decline (46–48) or no change (28, 30) in resting metabolic rates after sleep restriction and no association between sleep duration and total energy expenditure assessed by doubly labeled water (28, 49), one may think that energy balance was positive after acute partial sleep deprivation in our experimental conditions. If confirmed with more accurate measurement techniques of energy expenditure than actimeters and in long-term experimental studies, these results could indicate that sleep restriction could contribute to obesity as observed in several epidemiologic studies (6, 7).

Limits and perspectives

The strengths of this experimental study performed most of the time under free-living conditions, as recommended by Chaput et al (50), include the simultaneous measurements of food intake, food preferences, and physical activity. However, the small sample size, the narrow specifications of the tested population (young men), the lack of precise energy expenditure measurements, the absence of blood samples (which limits the determination of the homeostatic mechanisms), the timing of awakening and the time periods before the food could be consumed before the breakfasts (51), and above all the short duration of the sleep-restriction period mean that these results cannot be generalized. Additional studies, which avoid these limitations, need to be performed to confirm the findings of epidemiologic studies.

In conclusion, the present study provides for the first time evidence that sleeping less than usual for only one night increases food intake and, to a lesser extent, estimated physical activity–related energy expenditure in young adults of normal body weight. These experimental results suggest, as observed in several epidemiologic studies, that sleep restriction could be one of the environmental factors that contribute to the obesity epidemic.

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APPENDIX A

Effect of the crossover nature of the experimental design for some significant variables measured before (day 1) and after (day 2 and night 2) the 8-h or 4-h sleep session (night 1)¹

	Normal-Sleep Session		Sleep-Restriction Session	
	First session (subjects 1–6)	Second session (subjects 7–12)	Second session (subjects 1–6)	First session (subjects 7–12)
Day 1				
Energy intake at breakfast (kcal)	276 ± 217	390 ± 175	439 ± 279	347 ± 145
Energy intake at lunch (kcal)	467 ± 323	1089 ± 655	561 ± 356	937 ± 423
Energy intake during collation (kcal)	193 ± 132	172 ± 210	114 ± 132	35 ± 7
Energy intake at dinner (kcal)	739 ± 375	990 ± 175	739 ± 375	990 ± 175
Physical activity (counts/min)	0.549 ± 0.115	0.519 ± 0.252	0.724 ± 0.338	0.612 ± 0.243
Estimated energy expenditure (kcal)	1850 ± 204	1822 ± 272	1949 ± 412	1813 ± 284
Night 1				
Sleep duration (min)	451 ± 25	417 ± 46	228 ± 9	225 ± 18
Physical activity (counts/min)	0.040 ± 0.017	0.037 ± 0.017	0.113 ± 0.031	0.069 ± 0.012
Estimated energy expenditure (kcal)	664 ± 51	657 ± 35	680 ± 69	672 ± 34
Day 2				
Preprandial hunger at breakfast on VAS	3.4 ± 2.7	3.3 ± 3.0	5.6 ± 2.9	5.8 ± 1.7
Preprandial hunger at lunch on VAS	6.9 ± 2.4	8.0 ± 1.4	6.4 ± 2.3	6.4 ± 2.2
Preprandial hunger at dinner on VAS	5.8 ± 3.5	7.6 ± 1.2	7.2 ± 2.0	8.2 ± 0.8
Energy intake at breakfast (kcal)	508 ± 131	462 ± 175	831 ± 241	574 ± 231
Energy intake at lunch (kcal)	1322 ± 401	1235 ± 268	1393 ± 563	1190 ± 416
Energy intake during collation (kcal)	156 ± 199	14 ± 35	50 ± 37	72 ± 176
Energy intake at dinner (kcal)	773 ± 388	486 ± 160	1197 ± 535	766 ± 297
Fat intake at breakfast (% of energy)	34 ± 2	33 ± 6	35 ± 1	33 ± 3
Fat intake at lunch (% of energy)	43 ± 3	37 ± 5	46 ± 2	36 ± 6
Fat intake during collation (% of energy)	31 ± 20	1 ± 1	2 ± 2	28 ± 28
Fat intake at dinner (% of energy)	43 ± 14	31 ± 14	51 ± 11	45 ± 14
Mean pleasantness before intake on VAS	7.5 ± 1.9	6.4 ± 2.3	7.5 ± 1.4	7.8 ± 1.0
Mean liking before intake on VAS	5.0 ± 1.5	4.7 ± 1.0	4.5 ± 1.0	5.1 ± 0.8
Mean wanting before intake on VAS	5.4 ± 0.7	4.5 ± 1.7	4.8 ± 1.6	5.0 ± 0.7
Physical activity (counts/min)	0.780 ± 0.372	0.515 ± 0.265	0.828 ± 0.314	0.690 ± 0.276
Estimated energy expenditure (kcal)	2038 ± 419	1773 ± 286	2047 ± 390	1941 ± 301
Night 2				
Sleep duration (min)	490 ± 122	408 ± 131	517 ± 87	484 ± 151
Physical activity (counts/min)	0.103 ± 0.070	0.133 ± 0.126	0.029 ± 0.023	0.050 ± 0.057
Estimated energy expenditure (kcal)	694 ± 67	700 ± 65	624 ± 64	660 ± 47

¹ All values are means ± SDs. VAS, visual analog scale. Two-factor repeated-measures ANOVA showed no effect of the crossover nature of the experimental design (first compared with second session) for the above variables.