The Relationship between Sleep Deprivation, Food Motivation, and Energy Intake in Normal-Weight and Obese Females

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The Relationship Between Sleep Deprivation, Food Motivation, and Energy Intake in Normal-Weight and Obese Females

Lora Light Romney

A thesis submitted to the faculty of Brigham Young University in partial fulfillment of the requirements for the degree of Master of Science

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ABSTRACT

The Relationship Between Sleep Deprivation, Food Motivation, and Energy Intake in Normal-Weight and Obese Females

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Objective: Sleep deprivation has been proposed as a potential correlate of obesity, particularly influencing energy intake. Therefore, the purpose of this study was to compare neural indices of attention related to food motivation and energy intake in normal-weight and obese women under two separate sleep conditions: 1) sleep-restricted (<5 hours) and 2) recommended sleep (~8 hours). This study used a combined cross-over and ex post facto design with condition order counter-balanced. Methods: Twenty-two normal-weight (age=30.9±9.5 y, BMI=22.0±1.6 kg/m²) and 18 obese (age=29.7±10.7 y, BMI=36.4±5.3 kg/m²) women completed both sleep conditions. To confirm sleep levels, participants recorded sleep quality and quantity via sleep logs and wore a wrist actigraph. Following each condition, participants reported to the laboratory under the same fed state (energy shake ~10% of total daily needs) to verify they followed the sleep protocol. Subsequently, motivation for food was tested using electroencephalogram (EEG); participants completed a computerized passive-viewing task of food and flowers, while event-related brain potentials (ERPs) were recorded. After EEG testing, participants continued their normal routine but recorded all energy intake using weighed food scales. There were no instructions or limitations on dietary intake. Analyses included P300 and LPP amplitudes in response to picture type, total next day energy intake, and energy intake by several periods of the day. Results: Participants averaged 4.7±0.4 hours of sleep during the sleep-restricted condition and 7.7±0.3 hours during the recommended sleep condition (F=1057.02; P<0.0001). There was no group*condition interaction for next day food motivation (P300: F<2.896, P>0.09; LPP: F<2.967, P>0.093). Next day total energy intake also did not differ by group*condition (F=1.81; P=0.187). When participants were pooled, there was no difference in energy intake by sleep condition (F=0.00; P=0.953). However, when participants’ energy intake was analyzed during the lunch period (following testing to 1:30pm) there was a significant group*condition interaction (F=6.12; P=0.018). The obese women ate significantly more (~300 kcal) during the sleep-deprived condition compared to the recommended condition, whereas the normal-weight women did not. Conclusion: Compared to suggested levels of sleep, sleep restriction and obesity do not influence next day food motivation or total next day energy intake. However, sleep restriction and obesity may influence feeding during certain portions of the day.

Keywords: Obesity, sleep deprivation, food motivation, event-related potentials, energy intake
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Introduction

Obesity is linked to increased rates of mortality [1], in addition to many diseases, such as diabetes mellitus[2], osteoarthritis[3], gallbladder disease[4], cardiovascular disease[5], and some forms of cancer[6]. Worldwide, approximately 205 million men and 297 million women are considered obese [7]. Although nearly 14% of women around the world are obese [7], the prevalence of female obesity in the United States (35.8%) more than doubles the global prevalence[8]. Furthermore, there has been a significant increase in the prevalence of obesity in women over the last 50 years [9].

With high rates of obesity and associated disease risk, especially among American women, it is important to understand the factors influencing this problem. While decreased physical activity and increased energy intake appear to be the main culprits, other components must be considered [10]. One such component is insufficient sleep.

Over the past 50 years, sleep duration in the United States has decreased by 1.5 to 2 hours per night [11]. Many cross-sectional [12-14] and prospective studies[13, 15, 16], in addition to meta-analyses [17, 18], have found a significant relationship between short sleep duration and obesity. Overall, less than 6 hours of sleep per night appears to increase the risk of obesity [19]. Recent studies have found that short sleep duration is associated with decreased levels of the anorexigenic hormone leptin[20-24], increased levels of the orexigenic hormone ghrelin [20, 23] and impaired glucose tolerance, which may promote additional energy intake[25, 26]. Insufficient sleep may also affect appetite [23], hunger [23, 27], and motivation to seek food[28-30].

The reinforcing value of food has been shown to be higher in obese adults compared to normal-weight adults; thus, suggesting that motivation for food may also be different[31, 32]. One way of indexing the motivation for food is through neural correlates of attention, or when a
neural condition is directly related to conscious attention [33]. These neural mechanisms have also been found to be higher in obese adults compared to normal-weight adults [34].

Only recently have scientists begun to experimentally examine the relationship between sleep deprivation and obesity and the potential mechanisms explaining this relationship. Furthermore, no study to date has compared the differences between normal-weight and obese women for food motivation under sleep-deprived conditions. Understanding individual differences in the motivation for food is important as this may predict increased energy intake and obesity. Therefore, the purpose of this study was to compare neural indices of attention related to food motivation, total energy and macronutrient intake, as well as intake trends across the day, in women under acute sleep-deprived and normal sleep conditions. A secondary purpose was to find how these variables differ between normal-weight and obese women. The following outcomes were hypothesized: 1) neural indices of food motivation would be greater under the sleep-deprived condition; 2) energy intake would be greater under the sleep-deprived condition, especially during lunchtime; 3) carbohydrate intake would be greater in the sleep-deprived condition; and 4) the obese women would exhibit overall greater food motivation, energy intake, and dietary carbohydrate intake in contrast to the normal-weight women.

**Methods**

This study used a combined crossover and ex post facto design to compare 18 obese and 22 normal-weight women during two separate free-living sleep conditions. One condition (normal sleep) included obtaining approximately 8 hours of sleep, and the second condition (sleep deprived) involved less than 5 hours of sleep. Participants were assigned in a counterbalanced fashion to either the normal or sleep deprived condition first and completed the other condition second. The sleep conditions were separated by one week, performed on the
same day of the week and same time of morning, and under the same fed state. EEG-related food motivation was determined on the morning following each sleep condition and energy intake data was collected until the participant went to sleep that night.

Subjects

After obtaining approval from BYU’s Institutional Review Board, 18 obese (BMI ≥30 kg/m²) and 22 normal-weight (BMI ≥18.5 kg/m² and <25 kg/m²) women participated in the study. Informed consent was required from every subject in order to participate.

Participants were all female, pre-menopausal, right-handed, and English speaking. Participants either had a BMI of ≥18.5 kg/m² and <25 kg/m² or ≥30 kg/m². Subjects with BMI’s of ≥25 kg/m² or <30 kg/m² were not be included. Subjects were required to have a consistent sleep pattern, including retiring to bed before midnight every night and obtaining at least 6.5 hours of sleep per night for the previous month. Participants who worked night shifts were excluded. In addition, subjects were required to be weight stable (±5 lbs) for the previous month.

Subjects who engaged in vigorous activity on a regular basis (≥3 times per week for the past month) were excluded from the study. Participants were also excluded if they had any type of chronic disease, sleep problems or disturbances, eating disorders, neurological disorders (including head injury), or attention deficit/hyperactivity disorder. Subjects with a diagnosed psychiatric disorder (including depression or anxiety) or tobacco/substance use could not participate, as well as participants who were pregnant, breastfeeding, or dieting. Finally, participants were excluded if they used medication to aid with sleeping.

Procedures

After recruiting, participants were screened by email or telephone. Email included a short description of the study and questions concerning age, BMI, and availability. Participants who
responded by email and fit the criteria were contacted via telephone to gather data on additional exclusion criteria, including the Pittsburgh Sleep Quality Index (PSQI) and Obstructive Sleep Apnea (Intermountain Healthcare form). The PSQI measured subjective sleep quality, sleep latency, sleep duration, habitual sleep efficiency, sleep disturbances, use of sleeping medication, and daytime dysfunction [35]. Participants with a score of greater than 10 on the PSQI were excluded, similar to the sleep research performed by Nedeltcheva et al. [36]. Screening solely by telephone included all the components of the email and follow-up phone call. Testing began after meeting all the exclusion/inclusion criteria and the informed consent was signed.

For sleep condition one (normal sleep) the participant went to sleep at 10:30 p.m. the night of the intervention and arose at 6:30 a.m. the following morning. Sleep condition two (sleep-deprived) required going to sleep at 1:30 a.m. and arising at 6:30 a.m. Both conditions occurred under free-living circumstances. The sleep conditions were assigned in a counterbalanced manner. Each sleep condition required the participants to avoid vigorous exercise from 8:00p.m. that evening until the laboratory testing the subsequent morning, since exercising before bedtime can alter sleep[10]. Moreover, participants were required to cease eating at 8:00 p.m. the evening of the condition. This was done to standardize satiation across participants due to results from Stockburger et al. who found that reactions to food pictures differed between fasted and fed conditions [37].

The first visit occurred the day before the first sleep condition. The participants went to the Human Performance Laboratory, on the Brigham Young University campus, where the researchers explained the study in detail and answered any questions. After informed consent was signed, testing began. Height was assessed using a digital stadiometer. Participants wore a
standard swimsuit for measuring body weight and composition. Weight was measured using a
digital scale. Body composition was measured using dual-energy X-ray absorptiometry (DXA).

After taking these measurements, participants were given the following materials and
instructions for their uses: a digital food scale and diet record, a breakfast shake, a sleep log that
rates sleep quality and quantity, and wrist accelerometers.

The digital food scale was used to weigh and record all food and beverages (including
water) consumed for the remainder of the day after the sleep condition. Participants were
instructed not to consume energy drinks, sports drinks, or caffeine for the duration of the testing
period, beginning 8:00 p.m. the night of the sleep condition until the day after testing. Caffeine
restriction during the testing period was similar to the studies of Benedict et al. [2011] and Oliver
et al. [2009] whose participants abstained from caffeine before and during the study interventions
[38, 39]. In addition, caffeine has been found to affect EEG readings [40]. The breakfast
shakewas consumed no later than 7:00 a.m. the morning after the sleep condition. Participants
consumed nothing but the breakfast shake (and water as desired) the morning of the testing.
Breakfast shake amount was determined by calculating 10% of total energy needs through the
Harris Benedict equation with an activity factor of 1.3 [41, 42].

In order to assess sleep quality, wrist accelerometers were worn the night of the sleep
condition, beginning when the participant lied down for bed until she arose the following
morning. Data on actual amount of sleep obtained was gathered by visually comparing sleep log
bed time and awake time with wrist accelerometers through use of the ActiLife software.

On the second visit, the morning after the sleep condition, participants reported to the
Clinical Cognitive Neuroscience and Neuropsychology Laboratory on the Brigham Young
University campus. Sleep time and quality were confirmed by verbal response and through
downloading accelerometer data. The following were also checked before continuing with the testing: vigorous exercise was avoided in the morning and previous evening, food and beverage (except water) intake was suspended since 8:00 p.m. the previous evening, and the breakfast shake was consumed before 7:00 a.m. If the conditions were not met, the sleep condition was redone and testing rescheduled.

Next, motivation for food was tested for each participant by using electroencephalogram (EEG) from 128 scalp sites while participants completed a computerized, passive-viewing task. Forty pictures of plated food and forty pictures of flowers were displayed randomly while event-related brain potentials (ERPs) were recorded. Subsequently, each of the eighty pictures was shown to the participants again to obtain the subjective measurements of valence and arousal ratings. The valence rating was a measure of the pleasantness of the picture, with 1 being the most unpleasant and 9 being the most pleasant. The arousal rating was a measure of the engagement toward the picture, with 1 being no engagement and 9 being the most engagement possible. The participants assigned two scores to each picture, one score for the valence rating and a second score for the arousal rating.

After EEG testing, participants continued their day as normal with a few exceptions. First, the participants weighed and recorded all food, beverages, and water consumed until waking up the next morning. Second, participants did not take naps at any time during the day. Participants were not advised on physical activity/exercise, amount or type of food to consume, or on the time to go to sleep that night or awake the next morning. The following morning each participant recorded sleep time and quality.

The third visit was the day after the completion of testing. Participants again reported to the Human Performance Laboratory in order to return all equipment, and the following were
validated: no energy drinks, sports drink, or caffeine were consumed, and no naps were taken the previous day. The sleep and food logs were also checked for completion and detail.

The fourth visit was separated by at least one week from the initial visit, and the sleep condition was completed on the same day of the week. Visit four was the same as visit one except informed consent, body composition, and waist measurements were not taken again. Participants received the same instruction and equipment as in the first visit, except the second sleep condition was explained and performed.

Visits five and six were equivalent to visits two and three, respectively.

Measurements

Biometric Data. Height was measured using a digital stadiometer (Seca Corp., Chino, CA) with accuracy to the nearest 0.01 centimeter. Body weight was assessed using a digital scale (Tanita Corp., Tokyo, Japan), for accuracy to the nearest 0.01 kilogram. Fat mass and fat free mass were determined using DXA (GE Healthcare, Waukesha, WI). Through very low-dose X-ray [43], DXA measures bone mineral content, lean mass, and fat mass to determine total body composition [44]. DXA has been shown to have high precision. For instance, Hind, Oldroyd, and Truscott [2010] found in their study of 52 men and women that DXA had a coefficient of variation of less than 1% for most of the body composition measurements [45]. In addition, Toussirot et al. [2007] found coefficients of variation of 0.63% for percent body fat, 0.59% for fat mass, and 0.45% for lean mass in their evaluation of DXA [46].

Energy Intake. Energy intake and macronutrient data were collected for 24-hours for each sleep condition. Participants were given a food record to chart time of day the food was eaten, description and amount of the food, and special characteristics of the food such as brand name, nutrition labels, or recipes. To increase accuracy of food amount, each participant was given a
food scale (Ohaus Corp., Parsippany, NJ) and encouraged to weigh every food or beverage she consumed. During the third and sixth visits to the laboratory, food logs were reviewed by the researchers with each participant. Weighing food intake may have a behavioral effect on participants, so that they change their eating habits or underreport [47]; however, weighing all food and beverages consumed increases accuracy of the data [48]. Energy intake and macronutrient data was inputted and analyzed by The Food Processor SQL nutrition software, version 10.9.1 (ESHA Research, Salem, OR). The researcher inputting the data was blinded to the sleep condition to which the data belonged.

**Food Motivation.** For both sleep conditions, participants’ food motivation was measured using ERPs. The protocol was similar to the study on food cue processing and ERPs performed by Stockburger et al. [2009], and identical to Hanlon et al. [2012], who used ERPs to test food motivation in normal-weight and obese women after exercise [37, 49]. The task consisted of three blocks of 80 pictures per block (240 total trials). Each block comprised 40 pictures of plated meals and 40 pictures of flowers. With one exception (single picture of noodles), all pictures of food contained multiple foods per plate. However, a broad breakdown of the pictures of food include: salads (6 pictures), fruits (2 pictures), meat-based meals (15 pictures), sandwiches (5 pictures), pizza/tacos/nachos (3 pictures), dessert (3 pictures), pasta-based meals (5 pictures), and pancakes (1 picture). Food and flower pictures were chosen due to the similarity of flowers in picture composition to plated foods and because they were used in previous research on neural correlates of food motivation [37]. Pictures were presented randomly, were matched on contrast, intensity, and brightness levels, and were presented for 2000ms followed by a 500ms inter-trial on a 17-inch computer monitor approximately 20 inches from the participant’s head. The task was identical (same stimuli) for both sessions.
**ERP and EEG Data.** Electroencephalogram (EEG) data was recorded from 128 scalp sites using a geodesic sensor net and Electrical Geodesics, Inc., (EGI; Eugene, Oregon) amplifier system (20K gain, nominal bandpass=.10-100Hz). Through electrodes placed on the scalp, EEG records electrical activity in the brain [50]. The recordings are thought to be the summation of excitatory and inhibitory post-synaptic potentials [51]. Specifically, neural activity time-locked to a stimulus or a response are described as ERPs, which directly measure electrical activity [50]. ERPs are categorized based on “their timing, morphology, scalp topography, and response to experimental manipulations” [50]. For example, the P300 part of the ERP manifests as a positive peak 300 to 500 milliseconds after the presentation of a stimulus. The ERP that typically follows the P300 is known as the late positive potential (LPP), which occurs 450 to 600 milliseconds after a stimulus. Both the P300 and the LPP are larger with unpleasant or pleasant pictures when compared to neutral pictures, and pictures of desired objects elicit greater LPPs [50]. In addition, P300s reveal initial increased attention to specific stimuli, while LPPs measure continued attention to stimuli [50]. Amplitudes of ERPs can be measured and statistically compared to find their differences under opposing stimuli.

**Measurement of Sleep.** Sleep amount was assessed using self-report sleep logs and verified using Actigraph wrist accelerometers (Pensacola, FL). Sleep logs were given to each participant in order to record sleep initiation time and wake up time. The sleep logs were then compared to accelerometer data to validate amount and quality of sleep. Accelerometers are devices that measure movement and accelerations, and can be used to detect activity frequency and intensity [52]. Accelerometers have been found to be reliable and valid measures of sleep-wake patterns [53, 54]. In fact, Morgenthaler et al. [2007] performed a review to determine guidelines for the American Sleep Disorders Association and found that the use of
accelerometers is valid in the measurement of sleep patterns in normal healthy adults [55]. More specifically, wrist actigraphy is highly correlated with polysomnography[56, 57].

The accelerometers, set at 60 s epochs, were worn starting when the participant went to bed the night of both sleep conditions and were removed when the participant arose the following morning. Participants wore the wrist accelerometers on the right wrist.

After completing each sleep condition, accelerometer data was downloaded onto a computer for further analysis using ActiLife Data Analysis Software (version 6.0, Pensacola, FL). Through this software, the following can be determined from the sleep logs plus the accelerometer data: sleep onset, total sleep time, wake after sleep onset (WASO; total minutes the subject was awake after sleep onset occurred), frequency of awakenings, average length of awakenings, total actigraphy counts, and percent sleep efficiency (ratio of total sleep time to time in bed).

Data Analysis

The statistical software, PC-SAS (version 9.3, SAS Institute, Inc., Cary, NC), was used to test significance at the p<0.05 level. A 2-Group (normal-weight vs. obese) x 2-Sleep Condition (normal sleep vs. sleep deprived) x 2-Picture Type (food vs. flower) repeated measures analysis of variance (ANOVA) was used to determine the interaction of sleep and BMI on ERP amplitudes in response to picture type. Mixed models were utilized to determine within group changes in energy and macronutrient intake patterns, as well as group*sleep condition interactions in energy and macronutrient intake patterns. To identify patterns of energy and macronutrient intake across the testing days, the following dietary categories were established based upon time of day energy was consumed: lunch (energy consumed after EEG testing until 1:30 p.m.); afternoon snack (energy consumed from 1:30 p.m.—4:59 p.m.); dinner (energy
consumed from 5:00 p.m.—6:59 p.m.); and evening snack (7:00 p.m. until 6:00 a.m. the following morning).

Results

Table 1 presents descriptive characteristics of the 40 participants included in the analysis. Of the subjects who completed the study, 95% were Caucasian and 5% were Pacific Islander. Average BMI was 22.0±1.6kg/m² for the normal-weight group and 36.4±5.3kg/m² for the obese group (P<0.0001). Age between the groups was not statistically different (P=0.615). Additionally, there was no baseline difference in the Pittsburgh Sleep Quality Index (PSQI) between the two groups (P=0.12) (No participants were excluded based on a PSQI score greater than 10). Two participants were regular caffeine consumers (approximately 1-2 cans of soda per day), and the remaining participants did not consume caffeine on a regular basis.

Participants averaged 4.7±0.4 hours and 7.7±0.3 hours of sleep during the sleep-restricted condition and during the recommended sleep condition, respectively (Table 2). Main effects by sleep condition were significant for total sleep time (F=1057.02; P<0.0001), sleep efficiency (F=6.23; P=0.0172), awakenings (F=71.95; P<0.0001), WASO (F=47.05; P<0.0001), and sleep latency (F=8.14; P=0.007). Total sleep time, awakenings, WASO, and sleep latency were higher in the normal sleep condition, and sleep efficiency was higher in the sleep-deprived condition. Differences in average awake time were not significant (F=0.42; P=0.5158). Also, main effects by group (normal-weight vs. obese) were significant for sleep efficiency (F=6.25; P=0.0169) and WASO (F=7.24; P=0.0105), with the obese women having lower sleep efficiency and increased WASO. Total sleep time (F=0.06; P=0.8042), awakenings (F=1.64; P=0.2074), average awake (F=1.28; P=0.2465), and sleep latency (F=0.04; P=0.8499) were not significant. Main effects by condition or group did not significantly change when order or condition and age were controlled.
There was not a significant group*condition*picture effect for neither the P300 nor the LPP, as shown in Table 3. Additionally, there were no main effects by group or condition for the P300 or the LPP. There was, however, a significant main effect of picture type for the P300 (F=42.31; P<0.001) as well as the LPP (F=43.845; P<.001), with the food pictures having significantly higher amplitude when compared with the flower pictures.

When measuring self-reported picture valence ratings, or the pleasantness of the pictures, there was a significant group*picture interaction (F=9.37; P=0.004), with the obese subjects rating the flower pictures higher than the food pictures. There were no significant main effects by sleep condition, group, or picture with valence ratings.

When measuring self-reported picture arousal, or how engaging subjects found the pictures, there was a significant picture*group interaction (F=5.468; P=0.025), with the normal-weight women rating the food pictures higher than the flower pictures. There was a significant condition*picture*group interaction (F=5.526; P=0.024), with the obese subjects rating the flower pictures as more arousing while under the sleep-deprived condition. Additionally, there was a significant main effect of sleep condition (F=6.993; P=0.012) with the combined pictures being rated as more arousing under the sleep-deprived condition. There was also a significant main effect by picture type (F=4.224; P=0.047), with the food pictures being rated as more arousing than the flower pictures, matching the findings of the P300 and LPP results.

There was no condition*group interaction for total energy intake (F=1.81; P=0.187, Table 4). There was, however, a significant condition*group interaction for protein intake (F=6.17; P=0.0175). Significance did not change when order of condition, caffeine consumption, and age were controlled. Two participants consumed caffeine regularly; results did not change
significance after excluding these participants individually or collectively. There was no main effect by group or condition with total energy or macronutrient intake (P>0.05).

When energy intake was analyzed during the lunch period (following testing to 1:30pm) there was a significant group*condition interaction (F=6.12; P=0.018, Table 5). The obese women ate significantly more at lunchtime (~300 kcal) during the sleep-deprived condition compared to the regular sleep condition, whereas the normal-weight women did not. Additional intake came from fat (F=5.70; P=0.0221) and protein (F=7.01; P=0.0117). These results did not change after controlling for order, caffeine consumption, and age, and excluding the two participants who regularly consumed caffeine. There was no main effect by group or condition with lunchtime energy or macronutrient intake (P>0.05).

Discussion

The present study, with 22 normal-weight and 18 obese women, examined the relationship between sleep deprivation, attentional response to pictures of food, and energy intake. Our hypothesis was supported in that the results showed lunchtime energy intake was significantly higher in the obese women under the sleep-deprived condition when compared with the recommended sleep condition, while there was no such relationship among the normal-weight women. Overall, however, our hypotheses on food motivation, total energy intake, and carbohydrate intake were not supported, as these factors were not higher in the obese women or under the sleep-deprived condition.

The obese participants exhibited decreased sleep efficiency and increased WASO when compared with the normal-weight participants. This was unexpected since initial PSQI scores were not significantly different between the two groups. Interestingly, Kilkus et al. found in their study of subjects at risk for type 2 diabetes, that sleep quality, not quantity, was correlated with
negative eating patterns such as increased hunger, uncontrolled eating, emotional eating, and increased cognitive restraint [58]. Thus, our results may be affected by decreased sleep quality during both sleep conditions by the obese subjects.

During the EEG testing, food pictures elicited greater amplitudes for the P300 and LPP when compared with the flower pictures when pooled across groups. This supports the theory that the brain is highly receptive to food stimuli [59]. Nevertheless, we did not find a difference in food motivation between the normal-weight and obese subjects.

Valence and arousal ratings of the food and flower pictures revealed interesting results. The obese subjects rated the flower pictures as more pleasant than the food pictures overall, and as more engaging under the sleep-deprived condition. These ratings suggest a possible reactive behavioral effect and social desirability aspect [60], and do not coincide with the ERP results or with the obese participants’ lunchtime energy intake during the sleep-deprived condition.

Similar to our results, Nijs, Franken, and Muris found no difference in food cues as assessed by event-related potentials between normal-weight and obese adults, suggesting that obese women may not have an increased response to food stimuli [61]. Both our study and the study by Nijs et al. [61] contradict the findings of several studies that reported abnormal responses to food (e.g., decreased response to enlarged food images, increased attention to food images, increased initial attention to food-related words) in obese subjects as compared to normal-weight subjects [62-64]. However, none of these studies were performed under sleep-deprived conditions.

In regards to sleep deprivation, St-Onge et al. and Benedict et al. found increased neuronal activity in response to food stimuli using fMRI in normal-weight subjects [29, 30]. Both of these studies differed significantly on either length or completeness of sleep
deprivation when compared with the present study. St-Onge et al. required six days of 4 hours of sleep per night and a separate six days of 9 hours of sleep per night [29]. Benedict et al. employed a single night of total sleep deprivation and a separate night of 7 hours of sleep [30]. In contrast, the present study required a single night of less than 5 hours of sleep and a separate night of approximately 8 hours of sleep. While this sleep deprivation was not as drastic as the other two studies addressed, the present study was under free-living circumstances, increasing real-world application. In summary of the food motivation data, although a few studies have looked at attentional processing of food stimuli with either 1) obese vs. normal-weight subjects or 2) under sleep-deprived conditions, none of these studies combined these two variables, creating a need for the present study.

In concordance with the food motivation testing, there was no difference in total energy or carbohydrate intake by BMI group or sleep condition (although there was a significant increase in fiber intake for the obese participants under the sleep-deprived condition). These results confirm the findings of Schmid et al. who found that after two nights of sleep restriction, total energy intake did not increase [65]. In contrast, Brondel et al. and Bosy-Westphal found an increase in total energy intake with either one night of sleep restriction or four nights of increasing sleep curtailment [21, 27].

There is one possible mechanism that may explain why we did not find differences in total energy intake by neither the BMI groups nor the sleep conditions. Our participants were provided with a food record and scale. Weighing food intake may have a reactive behavioral effect on participants, so that they change their eating habits or underreport [47], and obese women have been found to under-report more than normal-weight women [66]. However, food
logs were reviewed with each participant for completeness and accuracy; therefore, we are confident in the accuracy of the data reported.

Although total energy intake did not differ by group or sleep condition, there was a significant condition*group effect with protein. The normal-weight subjects consumed more protein under the normal sleep condition than while under the sleep-deprived condition. In contrast, the obese subjects consumed more protein under the sleep-deprived condition than while under the normal sleep condition. The driving force behind this finding is unclear, as many studies show changes in carbohydrate intake and not protein intake [23, 36].

Lunchtime energy intake showed a significant caloric difference. Under the sleep-deprived condition, the obese subjects ate ~300 more calories than with the normal-sleep condition, whereas the normal-weight subjects showed no such relationship. More specifically, the obese subjects consumed approximately 60% more calories under the sleep-deprived condition than under the normal sleep condition. Also, the obese subjects under the sleep-deprived condition consumed approximately 22% and 50% more calories than the normal weight subjects under the normal sleep and sleep-deprived conditions, respectively.

These lunchtime energy intake findings are similar to Nedeltcheva et al. who found that under a two-week stint of 5.5 hours per night of sleep restriction, participants showed an increase in calories from snacks, but not increased total energy intake when compared with the normal sleep condition[36]. Both this study from Nedeltcheva et al. and the present study found that while total energy intake remained the same under a sleep-deprived condition, distribution of intake changed.

This increase in lunchtime energy intake supports the theory that lack of sleep can disrupt energy balance [67], even if for a short amount of time. Although the increase in energy intake
did not continue throughout the rest of the day, it is an important trend in obese subjects, especially with only one night of sleep restriction in a free-living environment (with lunchtime being the first free-living exposure to food that day). In contrast, the normal weight women did not have an increase in energy intake, regardless of time of day. This comparison shows possible underlying differences between normal-weight and obese women under sleep-deprived circumstances, and that obese women may be more susceptible to changes in energy intake patterns under sleep deprivation than normal-weight women.

There are many strengths to the present study. This is the first study to compare normal-weight and obese women under sleep-deprived conditions. We also used a cross-over design so that each subject served as her own control for the sleep conditions. In addition, subjects were tested in a free-living environment, increasing generalizability of the study. Lastly, sleep time and quality were validated using a sleep log as well as wrist accelerometers.

Although there were important strengths to the study, there were also limitations. The sleep conditions and subsequent testing were limited to a 24-hour period, and the sleep restriction period limited sleeping to five hours or less. This time frame may not have been long enough or restricted enough to measure changes in energy intake. Moreover, weighing and recording energy intake may alter the amount and type of food consumed[47], making it difficult to accurately assess energy intake. However, given the design of the study, we assume that any reactivity to weighed food records was consistent on both sleep conditions for each participant. Finally, this study was limited to relatively healthy women, excluding obese women with co-morbid conditions.

In conclusion, a single night of sleep deprivation increases lunchtime energy intake in obese women, without increasing total energy intake. Normal-weight women showed no
difference in energy intake, regardless of time of day, between a night of normal sleep compared
to a night of sleep restriction. Neither the obese nor the normal-weight group showed an increase
in food motivation, as measured by EEG. Through these research findings, it is difficult to
conclude that short sleep duration is a correlate of obesity. Further research comparing obese and
normal-weight women under sleep-deprived circumstances is warranted.
References


66. Weber, J.L., et al., *Validity of self-reported energy intake in lean and obese young women, using two nutrient databases, compared with total energy expenditure assessed*

Table 1 Participant characteristics

<table>
<thead>
<tr>
<th></th>
<th>Normal-Weight Group n=22</th>
<th>Obese Group n=18</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>30.9±9.5</td>
<td>29.7±10.7</td>
<td>0.51</td>
<td>0.615</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>166.2±5.5</td>
<td>164.4±6.0</td>
<td>1.43</td>
<td>0.158</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>60.9±6.4</td>
<td>98.8±18.2</td>
<td>11.92</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>22.0±1.6</td>
<td>36.4±5.3</td>
<td>17.21</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Body Fat (%)</td>
<td>31.1±4.8</td>
<td>47.0±2.9</td>
<td>18.24</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Waist Circumference (cm)</td>
<td>75.1±6.2</td>
<td>102.0±8.8</td>
<td>14.04</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Hip Circumference (cm)</td>
<td>95.7±4.4</td>
<td>124±26.5</td>
<td>6.19</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>PSQI</td>
<td>2.9±2.1</td>
<td>3.6±1.9</td>
<td>1.57</td>
<td>0.120</td>
</tr>
</tbody>
</table>

Values represented are mean±SD.

F and P values represent differences between normal-weight and obese groups.

BMI = Body Mass Index.

PSQI = Pittsburgh Sleep Quality Index.
Table 2  Sleep characteristics by group and sleep condition

<table>
<thead>
<tr>
<th></th>
<th>Normal-Weight Group</th>
<th>Obese Group</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n=21*</td>
<td>n=18</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TST (hrs)</td>
<td>7.9±0.7</td>
<td>4.9±0.3</td>
<td>1.64</td>
<td>0.2086</td>
</tr>
<tr>
<td>Sleep Efficiency (%)</td>
<td>89.8±5.1</td>
<td>90.8±3.5</td>
<td>2.62</td>
<td>0.1143</td>
</tr>
<tr>
<td>Awakenings</td>
<td>18.5±7.2</td>
<td>11.1±4.8</td>
<td>4.33</td>
<td>0.0447†</td>
</tr>
<tr>
<td>WASO (min)</td>
<td>41.9±22.4</td>
<td>23.0±11.5</td>
<td>5.80</td>
<td>0.0213</td>
</tr>
<tr>
<td>Avg Awake (min)</td>
<td>2.7±0.9</td>
<td>2.7±1.4</td>
<td>0.29</td>
<td>0.5916</td>
</tr>
<tr>
<td>Sleep Latency (min)</td>
<td>6.9±5.2</td>
<td>4.2±3.9</td>
<td>0.41</td>
<td>0.5258</td>
</tr>
</tbody>
</table>

Values represented are mean±SD with data from wrist accelerometers.

*Data from one subject was unusable.

†Controlling for order and age caused Awakenings to become borderline non-significant (P=0.0503).

F and P = group*condition interaction.

TST = Total Sleep Time; the total amount of time scored as “asleep”.

Sleep Efficiency = Minutes of sleep divided by total number minutes subject was in bed.

Awakenings = Count of awakening episodes as scored by the Cole-Kripke algorithm.

WASO = Wake After Sleep Onset; total time subject was awake after sleep onset occurred.

Avg Awake = Average length of all awakening episodes.

Sleep Latency = Time elapsed between “in-bed time” and “asleep” per Cole-Kripke algorithm.
Table 3 Event-related potentials by group, sleep condition, and picture

<table>
<thead>
<tr>
<th></th>
<th>Normal-Weight Group</th>
<th>Obese Group</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n=21*</td>
<td>n=18</td>
</tr>
<tr>
<td></td>
<td>Normal Sleep</td>
<td>Sleep Deprived</td>
</tr>
<tr>
<td>P300†</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flower (µV)</td>
<td>5.5±2.9</td>
<td>5.2±3.9</td>
</tr>
<tr>
<td>Food (µV)</td>
<td>6.5±3.4</td>
<td>6.1±4.4</td>
</tr>
<tr>
<td>LPP‡</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flower (µV)</td>
<td>1.9±1.9</td>
<td>2.1±2.3</td>
</tr>
<tr>
<td>Food (µV)</td>
<td>2.8±2.3</td>
<td>2.6±2.8</td>
</tr>
</tbody>
</table>

*Data from one subject was unusable.

µV = microvolts.

LPP = Late Positive Potential.

†F<2.90, P>0.097

‡F<2.97, P>0.093

There was not a significant group*condition*picture effect for neither the P300 nor the LPP (P>0.05).

There was a significant main effect of picture type, with the food pictures having significantly higher amplitude than the flower pictures for the P300 (F=42.31; P<0.001) and the LPP (F=43.85; P<0.001).

There were no significant main effects by group or condition for the P300 or the LPP (P>0.05).
Table 4 Total dietary intake by group and sleep condition

<table>
<thead>
<tr>
<th></th>
<th>Normal-Weight Group</th>
<th>Obese Group</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n=22</td>
<td>n=18</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normal Sleep</td>
<td>Energy Intake (kcal)</td>
<td>1968±718.7</td>
<td>1816±421.6</td>
<td>1.81</td>
</tr>
<tr>
<td>Sleep Deprived</td>
<td>CHO (g)</td>
<td>263.0±101.6</td>
<td>254.9±72.8</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>Fat (g)</td>
<td>70.8±32.7</td>
<td>62.4±23.1</td>
<td>2.43</td>
</tr>
<tr>
<td></td>
<td>Protein (g)</td>
<td>77.5±24.5</td>
<td>66.5±18.1</td>
<td>6.17</td>
</tr>
<tr>
<td></td>
<td>Fiber (g)</td>
<td>18.4±7.1</td>
<td>15.3±5.6</td>
<td>7.61</td>
</tr>
<tr>
<td>Sleep Deprived</td>
<td>Energy Intake (kcal)</td>
<td>1898±662.2</td>
<td>2102±723.4</td>
<td>1.81</td>
</tr>
<tr>
<td></td>
<td>CHO (g)</td>
<td>272.7±110.0</td>
<td>278.6±102.4</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>Fat (g)</td>
<td>64.6±27.5</td>
<td>78.6±42.9</td>
<td>2.43</td>
</tr>
<tr>
<td></td>
<td>Protein (g)</td>
<td>65.6±22.1</td>
<td>78.5±30.9</td>
<td>6.17</td>
</tr>
<tr>
<td></td>
<td>Fiber (g)</td>
<td>16.7±7.5</td>
<td>22.0±13.9</td>
<td>7.61</td>
</tr>
</tbody>
</table>

Values represented are mean±SD.

F and P = group*condition interaction.

There were no significant main effects by group or condition for total energy and macronutrient intake (P>0.05).
Table 5 Lunchtime dietary intake by group and sleep condition

<table>
<thead>
<tr>
<th></th>
<th>Normal-Weight Group</th>
<th>Obese Group</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n=22</td>
<td>n=18</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy Intake (kcal)</td>
<td>Normal Sleep</td>
<td>Sleep Deprived</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>654.9±364.1</td>
<td>521.9±224.9</td>
<td>6.12</td>
<td>0.0180</td>
</tr>
<tr>
<td>CHO (g)</td>
<td>90.3±54.1</td>
<td>76.3±37.3</td>
<td>2.87</td>
<td>0.0983</td>
</tr>
<tr>
<td>Fat (g)</td>
<td>23.4±16.0</td>
<td>16.9±11.1</td>
<td>5.70</td>
<td>0.0221</td>
</tr>
<tr>
<td>Protein (g)</td>
<td>24.3±20.9</td>
<td>19.1±11.3</td>
<td>7.01</td>
<td>0.0117</td>
</tr>
<tr>
<td>Fiber (g)</td>
<td>7.1±4.7</td>
<td>5.5±3.1</td>
<td>4.33</td>
<td>0.0443</td>
</tr>
</tbody>
</table>

Values represented are mean±SD.

F and P = group*condition interaction.

There were no significant main effects by group or condition for lunchtime energy and macronutrient intake (P>0.05).