Food Quality and Preference 88 (2021) 104074

Contents lists available at ScienceDirect

Food Quality and Preference

journal homepage: www.elsevier.com/locate/foodqual

The influence of acute partial sleep deprivation on liking, choosing and consuming high- and low-energy foods

Jeroen S. Benjamins[a,b], Ignace T.C. Hooge[b], Christian Benedict[c], Paul A.M. Smeets[d,e,f], Laura N. van der Laan[g,*]

[a] Social, Health, and Organisational Psychology, Utrecht University, Utrecht, Netherlands
[b] Experimental Psychology, Helmholtz Institute, Utrecht University, Utrecht, Netherlands
[c] Department of Neuroscience, Uppsala University, Uppsala, Sweden
[d] UMC Utrecht Brain Center, Utrecht University, Utrecht, The Netherlands
[e] Division of Human Nutrition and Health, Wageningen University, Wageningen, The Netherlands
[f] Image Sciences Institute, University Medical Center, Utrecht, Netherlands
[g] Department of Communication and Cognition, Tilburg School of Humanities and Digital Sciences, Tilburg University, Tilburg, Netherlands

ARTICLE INFO

Keywords:
Food choice
Self-control
Sleep-deprivation
Eye-tracking

ABSTRACT

A wealth of cross-sectional studies found a link between sleep deprivation and food-related outcomes like energy intake and BMI. Recent experimental studies suggest that this link is causal. However, the mechanisms through which sleep deprivation influences intake remain unclear. Here, we tested two prevailing hypotheses: that sleep deprivation leads to 1) increased food reward sensitivity and 2) decreased food-related self-control.

In a within-subject study (n = 60 normal-weight females), we compared outcome measures under normal sleep and partial sleep deprivation conditions. Our outcome measures were 1) proxies for food reward sensitivity – liking of high and low energy foods, 2) binary food choices ranging in level of self-control conflict, and 3) intake of high and low energy foods. Eye-movements during food choice were measured with an eye-tracker to gain insights in implicit food choice processes.

Food reward sensitivity outcomes showed a lower liking of low energy foods after partial sleep deprivation. More high energy foods were chosen after partial sleep deprivation independent of the level of self-control conflict. Intake of high energy foods was higher in the partial sleep deprivation condition. Lastly, the number of gaze switches between high and low energy foods, an implicit measure of conflict in choice, was lower in the high-conflict trials after sleep deprivation than after a normal night sleep.

To conclude, the increased intake of high energy foods after sleep deprivation may be driven by a decreased liking of low energy foods, rather than an increased liking of high energy foods. Further, sleep deprivation may affect self-control conflict detection as indicated by a lower number of gaze switches between food options.

1. Introduction

Poor sleep, eating behavior and its consequences seem to be intertwined. According to the National Health Interview Survey involving 324,242 US adults aged ≥18 y, the average number of hours of sleep reported per day was 7.18 in 2012, with 29.2% of the population reporting 6 or less hours of sleep per day (Ford, Cunningham, & Croft, 2015). This means that nearly one-third of the adults sleeps at least an hour less than the minimum hours as recommended for adults by the National Sleep Foundation (https://sleepfoundation.org/press-release/national-sleep-foundation-recommends-new-sleep-times). Similarly in European samples, average sleep duration seems to decline (Kronholm et al., 2008). This sleep loss epidemic is alarming as short sleep duration has been linked to an increased risk of overweight and obesity (Kecklund & Axelsson, 2016; Taheri, 2006; Taheri, Lin, Austin, Young, & Mignot, 2004). In normal-weight healthy subjects, insufficient sleep results in overconsumption of energy-dense foods (Taheri, 2006), selection of unhealthy snacks (Hogenkamp et al., 2013) and increased hunger, food cravings, food reward, and portion sizes (Yang, Schnepp, & Tucker, 2019). This is corroborated in another study where a positive correlation was found between BMI and food intake after sleep deprivation (Lombardo, Ballesio, Gasparrini, & Cerolini, 2019). Analogously,

* Corresponding author at: Tilburg University, Tilburg School of Humanities and Digital Sciences, Department of Communication and Cognition, P.O. Box 90153, 5000 LE Tilburg, Netherlands.
E-mail address: l.n.vdlaan@uvt.nl (L.N. van der Laan).

https://doi.org/10.1016/j.foodqual.2020.104074
Received 19 February 2020; Received in revised form 26 August 2020; Accepted 27 August 2020
Available online 31 August 2020

relationships have been reported between insomnia and eating disorders probed by the Disordered Eating Questionnaire, although BMI did not show a relationship with sleep in this particular study (Lombardo et al., 2014). Conversely, extending sleep decreases sugar intake (Al Khatib et al., 2018). Taken together, (poor) sleep and food intake seem to be closely linked.

A candidate mechanism through which a lack of sleep may promote food intake in humans includes altered brain reward processing of food cues (Gujar, Yoo, Hu, & Walker, 2011; Higgs, Williamson, & Attwood, 2008; Hofmann, Friese, & Roefs, 2009; Lundahl & Nelson, 2015). Acute sleep deprivation is associated with an increased activation of reward-related brain areas in young adults when they view food images (Rihm et al., 2019; St-Onge et al., 2012). An increased reward-related brain response to food has been shown to relate to stronger preferences for high energy foods (van der Laan, Barendse, Viergever, & Smeets, 2016), and may therewith constitute a core mechanism through which habitual short sleep may increase the risk of future weight gain.

A second mechanism that has been proposed to account for the weight gain-promoting effect of sleep loss is that sleep loss leads to unhealthier food choices through a reduction of (executive) inhibitory control and consequently decreased food-related self-control. Already a few hours of sleep loss result in lower executive functioning, as evidenced by impaired concentration, worse performance on tasks that require a cognitive inhibition of pre-potent responses, and disturbances in emotion regulation (Lim & Dinges, 2008; Nilsson et al., 2005; Wassing et al., 2016). If executive functioning is impaired, desires for energy-dense foods may not be cognitively inhibited, leading to an increased likelihood of choosing high energy foods and thereby excess food consumption. Many studies show that weaker inhibitory control relates to a higher food intake (Rollins, Dearing, & Epstein, 2010), especially consumption of energy rich snacks (Allan, Johnston, & Campbell, 2011; Hall, 2012). Further, training inhibitory control may even facilitate healthier food choices (Carbine & Larson, 2019). Supporting the assumption that sleep loss may compromise cognitive control over reward signals triggered by food cues, it has been demonstrated in young men and women that daytime sleepiness correlated with reduced activation in a brain region (ventromedial prefrontal cortex) involved in inhibition and emotional control during viewing high- versus low-calorie food images (Killgore et al., 2013). The observed reduction in prefrontal activation because of sleepiness was also predictive of self-reported difficulty curtailing food intake, although this association was only significant for women. Taken together, a second possible mechanism that explains the relationship between poor sleep and poor food choices lies in a reduction of (executive) inhibitory control and consequently decreased food-related self-control.

In the current study we aimed to investigate effects of partial sleep deprivation on these two potential underlying mechanisms driving sleep-loss induced increases in food intake, namely increased food reward sensitivity and decreased food-related self-control. We did this by measuring proxies of food reward sensitivity (food liking), and of food-related self-control, and food intake. The current study involving 60 young normal-weight women sought to investigate the following sub research questions and hypotheses:

What is the effect of partial sleep deprivation on food reward sensitivity? To our knowledge, no earlier study has assessed the effect of partial sleep deprivation on liking of both high energy (HE) and low energy (LE) food. Therefore, it is unknown if the sleep-loss induced increase in energy intake is due to an increased liking of HE foods or a decreased liking of LE foods. If the food-reward sensitivity hypothesis is true, then we would expect liking for HE foods to increase.

What is the effect of partial sleep deprivation on food-related self-control? Partial sleep deprivation could have different effects on food choice depending on the level of self-control conflict that the choice set elicits. We expect that people particularly have problems choosing LE foods after partial sleep deprivation when faced with a food choice where the self-control conflict is high, i.e. when a HE product is liked more than a LE product. In these trials, one could argue that *effort* is required to overcome the self-control dilemma and to choose the LE. The capacity to exert self-control *effort*, may be similarly affected by partial sleep deprivation as more general executive functions, as we argued above. Thus, particularly in high-conflict choice sets, we expect the number of LE choices to decrease compared to the same choice after a normal night's sleep. When liking is reversed or products are equally liked there might not be such a problem making the LE choice after partial sleep deprivation.

To gain more in-depth insight into self-control conflict detection, we investigated visual attention in these different types of choices using eye-tracking. It has been shown that increased attention to certain food products can mediate the eventual choice (van der Laan, Papies, Hooge, & Smeets, 2017) and can give insights in the level of conflict as reflected in the number of eye movement switches between choice options (van der Laan et al., 2014). We expect visual attention to follow the choice made and to be highest as reflected in proportionally longer dwell times on the product of choice. Furthermore, we expect the number of switches between choice options to be highest in trials with a high conflict.

Lastly, by measuring actual food intake in a bogus taste test part of the current study we expect to find food intake to parallel the hypothesized changed food choices and/or food liking after partial sleep deprivation; we expect that HE products will be consumed more after partial sleep deprivation.

2. Methods

2.1. Study design

This experimental study had a within-subjects design with two conditions: normal sleep vs. partial sleep deprivation. The order of sessions was counterbalanced across participants. The study was approved by the ethical committee of the Faculty of Social and Behavioral Sciences at Utrecht University (FETC16-099, Benjamins).

2.2. Participants

The study population consisted of 60 females (age in years: M = 21.6, SD = 2.6; BMI in kg/m2: M = 21.7, SD = 2.0). Participants were recruited with poster and flyers on campus, through posts on online university communities and through research participation websites. Participants that expressed their interest in the study were sent an information letter and an inclusion questionnaire, including questions on age, gender, educational level, dietary restraint (DEBQ), weight concerns, and inclusion and exclusion criteria.

Inclusion criteria were being female, having an age between 18 and 40 years, having a Body Mass Index (BMI) between 18.5 and 25 kg/m^2. Only females were included to increase the homogeneity of the population and known differences between males and females in eating behavior and weight-concerns (Neumark-Sztainer, Sherwood, French, & Jeffery, 1999). Exclusion criteria were a by the participant self-reported problematic sleeping pattern (which could be any self-reported complaints in the insomnia, hypersomnia, circadian rhythm disorder or parasomnia domains), drinking > 14 units of alcohol per week, using drugs, smoking, having food allergies or being a vegetarian.

2.3. Procedure

In order to avoid that participants would be aware of the actual goal of the study, they were told that the primary aim of the study was to investigate the effects of partial sleep deprivation on sweet and salty taste perception. To bolster the cover story, at the start of each study session questions on preference for sweet and salty foods were asked and the questions during the bogus taste test included items on sweet and salty taste. This cover story was expected to not affect our outcomes of interest, i.e., liking, choice and intake of HE versus LE products, as both types of product included both sweet and savory items.

In the week prior to the in-lab experimental sessions, participants had to complete a sleep diary every morning. Participants were asked to refrain from eating and drinking, except water, starting at 8:00 P.M. on the evening prior to the experimental day. Participants wore a GeneActive Original actigraph on their non-dominant wrist during the night prior to the lab sessions. To standardize hunger levels on experimental days, participants received a breakfast to be consumed at home exactly 1.5 h prior to the start of the lab session. They received an amount of breakfast cracker (Sultana GoodMorning Golden Syrup) equal to 20% of their basal metabolic rate (which was calculated with the Schofield equation http://www.globalrph.com/schofield_equation_bmr.htm).

After arrival at the lab, participants completed questions about the level of hunger ranging from 1 = No hunger at all to 9 = Very hungry ($M_{sleep\text{-}deprived} = 4.2$, $SD_{sleep\text{-}deprived} = 2.3$; $M_{normal\ sleep} = 3.8$, $SD_{normal\ sleep} = 2.0$; no significant difference between sessions, $T_{(59)} = 1.46$, $p = 0.15$), and tiredness (see section *Subjective and objective manipulation checks)*. Next, they were seated in front of a computer to perform a task in which they rated liking of HE and LE products (Food liking rating task, see below). After completion of the food ratings, subjects had to choose either a HE or a LE product (Food choice task, see below), presented as food pairs on a computer screen, while their eye-movements were concomitantly measured by eye-tracking. After that, they were seated at a table and they engaged in a bogus taste test. The protocol ended with a computerized psychomotor vigilance task as a measure of alertness (see below).

At the end of the second study session, participants filled out questionnaires that were included for a second study that is beyond the scope of this paper and were reimbursed with 50 euro or course credit. The lab sessions had a total duration of approximately 60 min per session. Starting time of lab sessions were planned between 8:00 and 11:00 in the morning such that time of day did not yield effects on eating behavior. A wash-out period between the two lab sessions they were planned 7 days apart if possible (average days between sessions was 7.08 days, SD = 0.51, maximum 10, minimum 6). To account for time-of-day effects on food-related outcomes, the start time of both lab session differed 1 h at most.

2.4. Sleep interventions

In the normal sleep condition, in the night prior to the experimental day, participants were instructed to sleep as usual. For example, if a participant reported to normally go to bed at 10:00 P.M and get up at 6:00 A.M., she was instructed to do so in the night preceding the lab session. In the sleep-deprived condition, participants were instructed to go to bed six hours later as they did in the normal sleep condition. Specifically, if a participant reported to normally go to bed at 10:00 P.M. and get up at 6:00 A.M., in the sleep loss condition she went to bed at 4:00 A.M. and got up at 6:00 A.M. For the sake of being representative of a normal sleep situation, both the sleep deprivation and sleep interventions were performed in the home environment.

In order to check whether our partial sleep deprivation manipulation successfully decreased sleep duration and resulted in decreased alertness and increased tiredness, we collected data on activity levels, alertness, sleep duration and self-reports of tiredness at the start of the lab session. Activity was measured with the 'GENEActiv Original' (ActivInsights Ltd., Kimbolton, UK) activity tracker, which participants wore on their non-dominant hand from 20:00 h in the evening prior to the study session. The Geneactiv recorder was set to record at a frequency of 30 Hz.

2.5. Alertness (Psychomotor Vigilance Task)

Alertness was measured by the Psychomotor Vigilance Task (Van Dongen & Dinges, 2005), in which median reaction times are computed and compared in the normal sleep and sleep-deprived condition. The task consists of a 3-minute period in which a red outlining of a rectangle is continuously shown on a computer screen. A maximum of 48 trials is presented to the participants with an intertrial interval randomly chosen from a uniform distribution of interval times between 2 and 5 s. A trial consists of a yellow milliseconds counter that has to be stopped by the participant as quickly as possible by pressing the space bar.

2.6. Sleep diary

The sleep diary used to assess sleep was the core version of the dNCS (Dutch digital consensus sleep diary) which is derived and translated, by a panel of Dutch sleep experts working with various forms of digital technology, from the original consensus sleep diary (CSD) developed by experts at the Pittsburgh conference (Carney et al., 2012).

2.7. Self-reports of being rested and tired

In the questionnaire at the start of the session we included a question on "How tired are you feeling at this moment?" which could be answered on a scale ranging from 1 = "not tired at all" to 9 = "very tired". Further, we included a question on "How well-rested do you feel at this moment?" which could be answered on a scale ranging from 1 = "not rested at all" to 9 = "very rested".

2.8. Food liking rating task

Similar as in earlier studies (e.g., Davis et al., 2007), food reward sensitivity can be probed and therefore operationalized by liking ratings of product images. In the food liking rating task, participants rated the taste of a total of 80 products, of which 34 were high in energy content (based on nutritional value: > 150 kcal/100 g) and 46 were low in energy content (based on nutritional value: ≤150 kcal/100 g). The images were taken from the Full4Health Image collection (Charbonnier, van Meer, van der Laan, Viergever, & Smeets, 2015). This image set is validated and standardized, which, due to the calories threshold we used, resulted in a few more low energy than high energy products. Participants were instructed to indicate for each food how much they liked the taste of the presented food at this moment on a nine-point scale ranging from 1 = Very untasty to 9 = Very tasty. The mean liking rating for HE and LE products was calculated.

2.9. Food choice task

To measure self-control, the subjects performed a food choice task. Participants were instructed to choose the product that they would prefer to eat at this moment. In each choice trial, two products were presented on the screen, one of the left side and one on the right side. Participants could indicate their choice with the left and right arrow buttons of the keyboard. The choice pair was presented on the screen until a button was pressed. Choice trials were interspersed with a random inter trial interval uniformly distributed between 500 and 1000 ms. In each trial, the choice was always between a HE and a LE product. The location of HE and LE products was counterbalanced across trials of each trial type. The choice pairs were based on the taste ratings participants gave for the 80 foods in the food liking rating task. Three types of choices were presented in the task, varying in the type of (self-control) conflict that it elicits: In the first type of trials, *self-control conflict trials*, a choice pair with a HE product 1–3 points higher in tastiness than the LE product was presented. This type of trials represents a self-control conflict between eating enjoyment and long-term goal of watching weight by a participant. In the second type of trials, *hedonic conflict trials,* a HE and LE product equal in tastiness were presented. Only the hedonic value, the tastiness, in this type of trial is competing rather than having a competition between enjoyment of eating and health goals. Classic models on value-based decision-making posit that decisions between equally liked options are more difficult than decisions in which one of the options is inferior (Krajbich, Armel, & Rangel, 2010; Slovic, 1975; Tversky, Sattath, & Slovic, 1988). So lastly, in the third type of trials, *no conflict trials,* a pair consisting of a HE product 1–3 points lower in tastiness than the LE product was presented. This type of trials does not present participants with any conflict as the healthy option is also the tasty option. The order of the trials was randomized. The pairs for the three trial types were matched with a Matlab script. Since choices were matched on individual liking ratings, the number of choices was not the same for all participants ($M_{normal\ sleep} = 61.1$, $SD_{normal\ sleep} = 12.8$; $M_{sleep\text{-}deprived} = 62.3$, $SD_{sleep\text{-}deprived} = 14.8$). The maximum number of choices per trial category was 30. Stimuli were used maximally one time in each trial category. The percentage of chosen HE products was calculated for each trial type. Eye movements were recorded with an eye tracker during the task.

2.10. Bogus taste test

In line with the cover story, participants were instructed that they would take part in a taste perception test in which they would have to evaluate several attributes, like sweetness and saltiness, of foods. It was told that they could take as much as they wanted as the remainder would be thrown away. They were presented with four bowls, two with HE products (Chips, chocolate) and two with LE products (cherry tomatoes, white grapes). Intake in kcal was assessed by weighting the bowls prior and after the test and multiplying it by the amount of kcal per gram.

2.11. Eye-tracking setup

During the food choice task, eye movements were recorded at 52 Hz using a portable, EyeTech TM3 eye-tracker (Design Interactive, Inc., Oviedo, FL). The recording was binocular and was preceded by a 9-point calibration. Fixation detection was established by marking fixations with an adaptive velocity threshold method (Hooge & Camps, 2013), with 58 ms as lower cut-off for a single fixation duration. Further technical specifications of the setup and the fixation detection algorithm are identical to the procedure in Van der Laan et al. (2015) (Van der Laan, Hooge, de Ridder, Viergever, & Smeets, 2015).

2.12. Eye-tracking measures

To analyze eye-movements, for each trial the screen was divided into three areas of interest (AOI), namely, 'HE product', 'LE product', and 'not'. These AIO are defined as follows: 'HE product', the outline of the HE product; 'LE product', the outline of the LE; and 'not', everywhere else on the screen. For each trial, we calculated total dwell time on the HE and LE product, which is the sum of all fixations on a particular product AOI over the course of a trial (Reisenberg, 2013). Moreover, we look at the number of gaze switches between HE and LE products, which we consider an operationalization of a more unconscious experience of conflict; the more conflict is experienced the more switches will be made between HE and LE products (e.g. (Van der Laan, de Ridder, Charbonnier, Viergever, & Smeets, 2014).

2.13. Statistical analysis

The statistical program R was used to perform statistical analyses. Eye-tracking data were pre-processed with custom scripts using Matlab and further processed using IBM Statistics SPSS 22. All analyses such as ANOVA's, *t*-tests and a Wilcoxon signed rank test are tested against a signifcance level of $\alpha = 0.05$, two-tailed where applicable.

3. Results

3.1. Objective and subjective manipulation checks of sleep manipulation: Activity measures

GENEActiv data of 50 participants (the remaining subjects did not comply in wearing the device as instructed) was extracted to text files using the manufacturer software. Average activity (resampled to 1 min bouts) over the 12 h before 8:00 AM of each testing day in the lab was calculated. The activity ratio between normal sleep and sleep-deprived conditions was then calculated, where a ratio above one indicates more activity in the sleep-deprived condition and a ratio of one indicates no difference between conditions. A one-sample Wilcoxon signed rank test indicates the average ratio of 1.304 to be above a null hypothesis value of 1.000 with $p = 0.049$ indicating people were indeed more active in the sleep-deprived condition.

3.2. Measures of alertness (Paramotor Vigilance Task)

Mean median reaction time in the psychomotor vigilance task, a general measure of alertness, was significantly higher in the sleep deprived condition ($M_{normal\ sleep} = 310.70$ ms, $SD_{normal\ sleep} = 19.13$ ms; $M_{sleep\text{-}deprived} = 330.42$ ms, $SD_{sleep\text{-}deprived} = 33.30$ ms; $t_{(59)} = 3.891$, $p = 0.0003$). Also the number of attention lapses (errors of omission) were significantly higher in the sleep deprived condition ($M_{normal\ sleep} = 0.617$ $SD_{normal\ sleep} = 0.958$; $M_{sleep\text{-}deprived} = 1.600$ $SD_{sleep\text{-}deprived} = 3.258$; $t_{(59)} = 2.276$, $p = 0.0256$).

3.3. Self-reports of being rested and tired and self-report diary data

A paired *t*-test corroborated that participants felt significantly less rested and more tired in the sleep-deprived compared to the normal sleep condition (Table 1). Secondly, analysis of 56 participants' CSD data was used (4 participants failed to comply filling out the CSD) to calculate average total sleep time (TST) for nights that did not precede days in the lab (baseline TST), which was compared to TST of the nights of normal sleep and partial sleep-deprivation preceding days in the lab. Average $TST_{baseline}$ was 7.695 h, average $TST_{normal\ sleep}$ was 7.360 h and $TST_{sleep\text{-}deprived}$ was 2.378 h, which multiple comparisons, after one-way ANOVA analysis, showed to be a significant difference between $TST_{sleep\text{-}deprived}$ and $TST_{baseline}$ and between $TST_{sleep\text{-}deprived}$ and $TST_{normal\ sleep}$ (both $p < 0.000$), but not between $TST_{baseline}$ and $TST_{normal\ sleep}$, $p = 0.172$. This further confirms the partial sleep deprivation manipulation worked.

Taken the above objective activity and alertness measures and the

Table 1
Mean (and SD) of manipulation check measures.

	Normal sleep	Sleep-deprived	Test for difference
Self-report of being rested[a]	6.6 (1.4)	2.9 (1.5)	$T_{(59)} = 14.1$, $p < 0.001$
Self-report of being tired[a]	3.6 (1.7)	6.6 (1.8)	$T_{(59)} = -10.5$, $p < 0.001$
PVT (RT in ms)	310.70 (19.13)	330.42 (33.30)	$T_{(59)} = 3.891p < 0.001$
PVT (number of omission errors)	0.617 (0.958)	1.600 (3.258)	$T_{(59)} = 2.276$, $p = 0.0256$

[a]Answered on a 9-point scale ranging from 1 = "not rested/tired at all" to 9 = "very rested/tired".

subjective diary measures together we can safely assume our partial sleep deprivation manipulation at the participant's homes was successful[1].

3.4. Effects of partial sleep deprivation on food liking

A 2-way within-subjects ANOVA with Condition (normal sleep vs. sleep-deprived) and Product type (HE vs. LE) as independent variables and self-reported tastiness as a measure of liking as dependent variable revealed a main effect of Product Type ($F_{(1,\ 59)} = 77.6$, $p < 0.002$). Liking was higher for LE products ($M = 5.3$, $SD = 1.2$) than for HE products ($M = 3.8$, $SD = 1.3$). In contrast, no significant main effect of sleep condition was found ($F_{(1,\ 59)} = 1.5$, $p = 0.22$). The interaction between Condition and Product Type was significant ($F_{(1,\ 59)} = 9.0$, $p < 0.001$). Subsequent within subject one-way ANOVA's with Condition (normal sleep vs. sleep-deprived) as independent variable showed that liking for HE products did not significantly differ between the normal sleep and sleep-deprived conditions ($F_{(1,\ 59)} = 0.6$, $p = 0.45$, $M_{sleep\text{-}deprived} = 3.9$, $SD_{sleep\text{-}deprived} = 1.6$, $M_{normal\ sleep} = 3.8$, $SD_{normal\ sleep} = 1.2$). In contrast, liking for LE products was significantly lower in the sleep-deprived compared to the normal sleep condition ($F_{(1,\ 59)} = 6.7$, $p = 0.01$, $M_{sleep\text{-}deprived} = 5.1$, $SD_{sleep\text{-}deprived} = 1.5$, $M_{normal\ sleep} = 5.5$, $SD_{normal\ sleep} = 1.2$) as can be seen in Fig. 1.

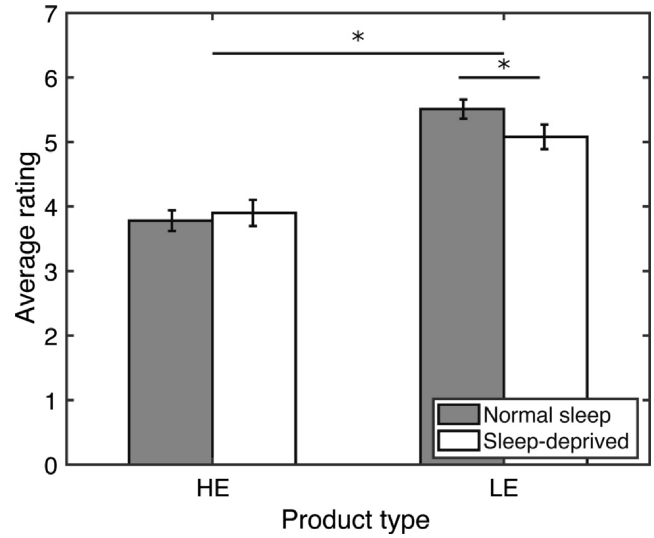

Fig. 1. Rating for HE and LE product types per sleep condition. The rating has a range between 1(very untasty) and 9 (very tasty). Error bars indicate standard deviations. Significant differences are indicated by lines with an asterisk.

3.5. Effects of partial sleep deprivation on food choice

A 2-way within-subjects ANOVA with Condition (normal sleep vs. sleep-deprived) and Conflict Type (self-control conflict (HE tastier than LE) vs. hedonic conflict (HE and LE equally tasty) vs. no conflict (LE tastier than HE) as independent variables and percentage of chosen HE products as dependent variable was performed[2]. This ANOVA showed a significant main effect of Condition ($F_{(1,56)} = 4.5$, $p = 0.04$) and Conflict Type($F_{(2,112)} = 478.3$, $p < 0.001$). The percentage of choices in which a HE product was chosen was higher in the sleep-deprived ($M = 43.5$, $SD = 17.7$) than in the normal sleep condition ($M = 38.6$, $SD = 13.2$). The percentage of HE choices was significantly higher in the self-control conflict condition ($M = 67.7$, $SD = 18.5$) compared to the hedonic conflict condition ($M = 46.1$, $SD = 17.7$. $T(56)_{self\text{-}control\ vs.\ hedonic\ conflict} = 15.0$, $p < 0.001$), where in turn the percentage of HE choices was higher than in the no conflict condition ($M = 19.1$, $SD = 15.0$, $T(56)_{hedonic\ vs.\ no\ conflict} = 18.5$, $p < 0.001$) as can be seen in Fig. 2. There was no significant interaction between Condition and Conflict Type ($F_{(2,112)} = 1.8$, $p = 0.17$).

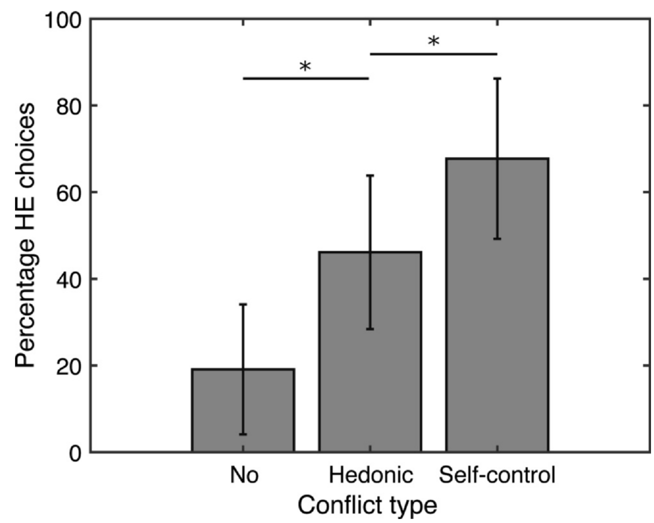

Fig. 2. Percentage of HE product choices in different conflict type conditions. Error bars indicate standard deviations. Significant differences are indicated by lines with an asterisk.

3.6. Effects of partial sleep-deprivation on attention during food choice: Total dwell time

There were significant effects when considering Conflict Type, Product Type and Condition (3 × 2 × 2) and an interaction of those factors when looking at total dwell time[3]. On average the total dwell time on HE products was 45.83 ms shorter than that on LE products ($F_{(1,54)} = 21.640$, $p < 0.001$). On average the total dwell time differed significantly ($F_{(2,108)} = 11.518$, $p < 0.001$) in different conflicts as well: in self-control conflicts average dwell time was 638.55 ms, in no-conflicts 598.74 ms, and 676.99 ms in hedonic conflicts. The interaction between Conflict type and Product type was also significant ($F_{(2,108)} = 21.887$, $p < 0.001$), which is mostly due to the fact that in the no conflict and hedonic conflict conditions the dwell time on HE products seems to be lower (see Fig. 3). No interactions with the sleep condition, nor a main effect of sleep condition on total dwell time is significant.

[1] Note that we also have measured chronotype of our participants using the MCTQ, as we know chronotype might effect eating behavior as it does in adolescents (Beebe, Zhou, Rausch, NOE, & Simon, 2015) and it might affect sleeping schedule. Chronotype did not vary much towards extremes in our population (median MSF 4.8, SD = 0.96). Moreover, the MSF of our tested population stayed in the average range for almost our entire population, with a minimum MSF of 3, which above the threshold for early chronotype (MSF < 2) and two participants with an MSF (both 7.5) just above the late chronotype threshold (MSF > 7). In a separate not-reported sensitivity analysis we ran the manipulation checks again on activity, PVT measures and TST again without the two participants with late chronotypes: activity ratio, PVT RT and omission error differences and differences in TST all stayed significant in the same manner. We therefore report all further analyses with the inclusion of these two late chronotypes in our sample as we do not think these late chronotypes affected our data.

[2] Due to technical issues, for three participants data of the food choices in either the sleep-deprived or normal sleep condition were not collected properly.

[3] Five participants are not in the analysis of eye movements measures as they could not be calibrated properly, and thus no eye-tracking data was recorded for these participants.

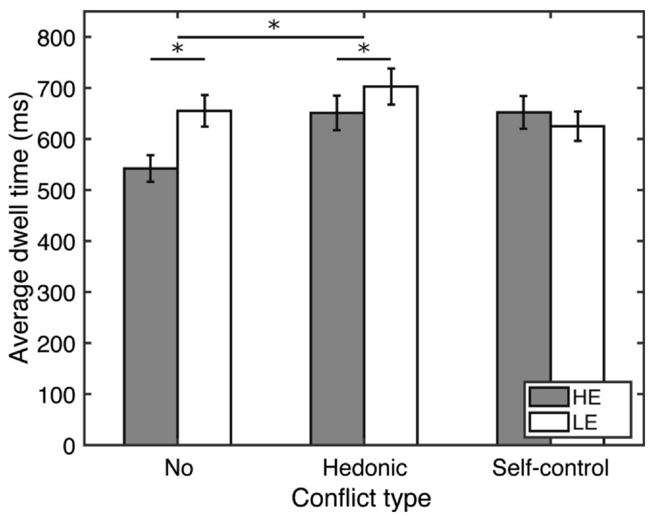

Fig. 3. Average dwell time (ms) on high (HE) and low (LE) energy products in different conflict conditions. Error bars indicate standard errors. Significant difference are indicated by lines with an asterisk.

3.7. *Effects of partial sleep deprivation on conflict perception during food choice: Number of gaze switches between HE and LE foods*

As an operationalization of a more unconscious experience of conflict we investigated the number of switches between HE and LE AOIs. In this measure we find a main effect of Conflict type ($F_{(2,108)} = 13.421$, $p < 0.001$), where in conflict conditions a higher number of switches between HE an LE AOIs is present. A significant interaction ($F_{(2,108)} = 4.671$, $p = 0.010$) between Conflict type and the normal and sleep-deprived condition seems to indicate that this number of switches seems to level out after partial sleep deprivation (see Fig. 4), suggesting that the unconscious perception of conflict decreases after partial sleep deprivation. Separate repeated measure ANOVAs for the normal sleep and sleep-deprived condition on the number of gaze switches show that indeed a main effect of conflict type ($F_{(1,54)} = 16.904$, $p < 0.001$) exists, with Bonferroni-corrected pairwise comparisons indicating the no conflict condition to significantly differ from self-control conflict and hedonic conflict. In the sleep-deprived condition this main effect is no longer significant ($F_{(1,54)} = 2.584$, $p = 0.08$).

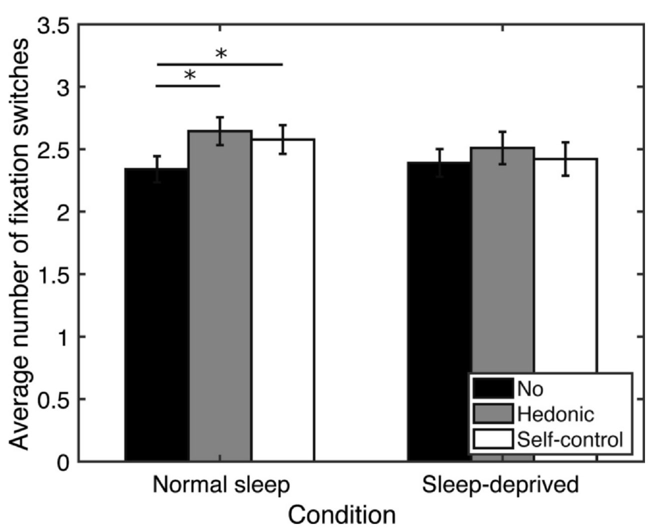

Fig. 4. Number of fixation switches between HE-LE products per sleep and conflict condition. Error bars indicated standard deviations. Significant difference are indicated by lines with an asterisk.

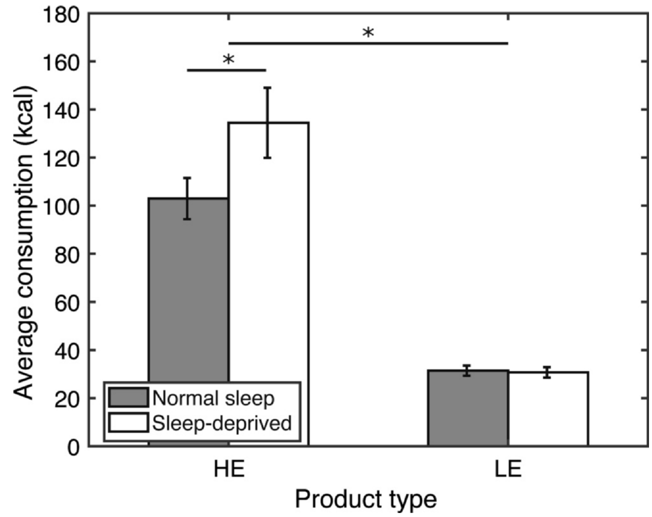

Fig. 5. Mean and standard deviation of consumption of HE and LE products (in kcal) in the two sleep conditions.

3.8. *Effects of partial sleep deprivation on food intake*

A 2-way within-subjects ANOVA with Condition (normal sleep vs. sleep-deprived) and Product Type (HE vs. LE) as independent variables and intake expressed in kcal as dependent variable showed a significant main effect of Condition ($F_{(1,59)} = 5.94$, $p = 0.018$). Energy intake was higher in the sleep-deprived ($M = 82.6$, $SD = 59.9$) than in the sleep condition ($M = 67.2$, $SD = 36.3$). Also, a significant main effect of Product Type ($F_{(1,59)} = 82.0$, $p < 0.001$) was found. Energy intake in kcal from HE products ($M = 118.7$, $SD = 79.3$) was higher than from LE products ($M = 31.1$, $SD = 15.3$). Further, the interaction between Condition and Product type was significant ($F_{(1,59)} = 6.89$, $p = 0.01$). We performed two separate one-way ANOVA's with as independent variable Condition: one with intake in kcal from HE products as dependent variable and one with intake in kcal from LE products as dependent variable. These ANOVA's showed that energy intake from HE products was higher in the sleep-deprived ($M_{sleep\text{-}deprived} = 134.5$, $SD_{sleep\text{-}deprived} = 112.9$) compared to the normal sleep condition ($F_{(1,59)} = 6.50$, $p = 0.01$, $M_{normal\ sleep} = 102.9$, $SD_{normal\ sleep} = 66.4$) but that there was no significant effect of sleep condition on kcal of LE products eaten ($F(_{1,59}) = 0.22$, $p = 0.64$), see Fig. 5. Thus, our hypothesis, that intake from HE compared to LE products is higher in the sleep-deprived than in the normal sleep condition, was confirmed.

3.9. *Additional analyses*

To investigate whether changes in liking caused by partial sleep deprivation are actually translated into changes in intake, we calculated the correlation between the difference in mean liking rating for HE products in the normal sleep versus the partial sleep deprivation condition and the mean difference in intake (kcal) between the normal sleep and the sleep-deprived condition. A significant relation between these difference scores was found ($r_{(58)} = 0.30$, $t = 2.34$, $p = 0.02$). This analysis was repeated for the LE foods and again a significant positive relation was found ($r_{(58)} = 0.20$, $t = 2.14$, $p = 0.04$). This suggests that changes in liking are indeed related to changes in intake.

4. Discussion

We investigated the effects of acute partial sleep deprivation on two potential underlying mechanisms driving sleep-loss induced increases in food intake, namely increased food reward sensitivity, operationalized as self-reported food liking, and decreased food-related self-control, operationalized as food choices ranging in level of self-control conflict.

In contrast to some earlier findings (e.g., McNeil et al., 2017), partial sleep deprivation did not lead to higher liking of HE foods. Rather, liking of LE foods was lower after partial sleep deprivation. The popular hypothesis, that sleep deprivation increases food liking in general and particularly that for HE foods, suggesting a higher sensitivity to food reward, was thus not supported. Several studies have shown that intake of HE foods or snacks is higher in a sleep deprived condition (e.g., Bosy-Westphal et al., 2008; Brondel, Romer, Nougues, Touyarou, & Davenne, 2010; Hogenkamp et al., 2013; Nedeltcheva et al., 2009; St-Onge et al., 2012) and this is used to argue that liking of HE foods is higher and that sleep deprivation increases reward sensitivity. However, only few studies actually assessed the effect of sleep deprivation on liking of HE foods specifically and to our knowledge the current study is the first to explicitly assess the effect of partial sleep deprivation on liking of LE foods. The study of McNeil et al. (2017) showed that liking of high- relative to low-fat foods was higher after partial sleep deprivation compared to normal sleep. However, as their measurement of liking of high fat food was relative to low fat options, it may be that their effects were driven by sleep loss-induced lower liking for LE foods, similar to the current study. Moreover, their results, which were only found when sleep deprivation was in a later part of the night, are based on participants that did not ate any breakfast, which we know from literature could have affected liking differently (Pender, Stevenson, Francis, & Oaten, 2019; Stevenson, Francis, Attuquayefio, & Ockert, 2017). Our participants did receive a breakfast that was matched to their basic metabolic rate to avoid that results were driven by a (confounding) effect of stronger energy expenditure in the sleep deprived (compared to the normal sleep) state. A study of Dweck et al. (2014) found no relation between sleep duration and liking, though in their study sleep duration was not manipulated. In sum, the current study raises the novel hypothesis that the effect of partial sleep deprivation on unhealthy food intake may not be caused by an increased liking of HE foods but rather by decreased liking of LE foods. Some indirect evidence in line with this hypothesis is that of a recent study (Alkozei et al., 2018) showing that three weeks of 4 h sleep deprivation resulted in lower implicit liking for LE foods, as measured by an implicit association task (though only in men). Another possible explanation for our results may lie in a study that showed cravings for certain food types in terms of taste changes after sleep deprivation. Umami and sour taste sensations intensified when being more sleepy (Lv, Finlayson, & Dando, 2018). Perhaps the imagined taste of our LE products were influenced by these effects of sleep deprivation and therefore liked less. As participants in our experiment did not actually tasted the products in the food choice task, this should be subject of further study.

We found that partial sleep deprivation led to a higher likelihood of choosing HE over LE foods, irrespective of whether the choice entails a self-control conflict, a hedonic conflict or no conflict. We hypothesized, based on research on effects of sleep loss on (inhibitory) control (Lim & Dinges, 2008; Nilsson et al., 2005) that partial sleep deprivation would steer food choices towards HE options particularly when faced with a food choice where the self-control conflict is high, i.e. when a HE product is liked more than a LE product, and thus control is needed to choose an LE over a HE product. Our study does not support this hypothesis. This effect was also absent for participants higher in dietary restraint (results not presented). Thus, in our data there is no support for the hypothesis that partial sleep deprivation results in lower food-related self-control. Rather, our findings suggest that partial sleep deprivation increases relative liking of HE over LE foods in general, or, in line with our findings for food liking, decreases liking of LE foods.

Note however, there was a difference between the different types of conflict in choice in the eye-tracking measures and that this was influenced by partial sleep deprivation: participants looked back and forth more often between HE and LE foods in the conflict conditions, but this leveled out after partial sleep deprivation. This could be a reflection of what in the literature has been described as a two-stage model of self-control where a conflict first needs to be identified before restraint can be exerted (Myrseth, Fishbach, & Trope, 2009; Van der Laan et al., 2014); in the current study the number of gaze switches could be a measure of experienced conflict which stays below a level of awareness to yield conflict identification. In line with an earlier finding that self-control failure can result from a lack of conflict perception (Van der Laan et al., 2014), it could be because of this failed conflict identification that we do not observe effects of partial sleep deprivation on how type of conflict affects the food choices in the current study. Whether these eye-tracking findings truly reflect subconscious conflict needs further investigation.

We found that intake of HE foods was higher in the partially sleep deprived than in the normal sleep condition. This is in line with several earlier studies linking sleep duration to food intake (Beebe et al., 2013; Dweck et al., 2014; Martinez et al., 2017; Nedeltcheva et al., 2009). However, there are also studies which did not find an effect of sleep deprivation on intake (McNeil et al., 2017; Tajiri, Yoshimura, Hatamoto, Tanaka, & Shimoda, 2018) and these contrasting findings may be explained by the type of food offered in the measure of intake. For instance, the study by McNeil et al. (2017) employed intake of meal items (*an ad libitum lunch*) instead of tempting HE snacks like the foods in the bogus taste task of our study. Tajiri and colleagues (2018) also found no effect of sleep deprivation on intake. In their study they measured which foods (including meals, and all other daily food items) participants bought (and ate) during a three-night sleep restriction period. Contrarily, some other studies did find that low sleep duration related to a higher intake of food. For example, a cross sectional study of Martinez et al. (2017) found that individuals with a lower sleep duration had a higher intake of high carbohydrate foods. An experimental study found that, after a night of total sleep deprivation compared to a normal night's sleep, subjects chose larger snack portions, whereas the selection of meal items did not differ between the sleep interventions (Hogenkamp et al., 2013). Though we found that liking of LE foods was lower in the partially sleep deprived condition, intake of LE foods was not affected. To summarize, it may be that sleep loss primarily affects intake of snack-like foods high in energy (or carbohydrates).

4.1. Limitations and strengths

Studies on (partial) sleep deprivation typically have investigated the effects of 4 h (e.g., sleeping 4 h less than normal) deprivation or of total sleep deprivation. In partial sleep deprivation studies this amount of sleep deprivation is used to spare either the early or late phase of sleep to investigate contributions of different types of sleep that occur at these two stages (e.g. more slow wave sleep during the early phase and more REM sleep during the late phase). In the current study we used a partial sleep deprivation in which people sleep for 2 h covering both early and late phases of sleep while still maintaining some sleep. This is not unlike many real-world scenarios, people can periodically suffer from extreme short sleep duration, as employed in the present study (eg physicians on call-duty; parents of toddlers). Whether our results can be applied to mild short sleep duration (e.g. 6 h of sleep per night) warrants, however, further investigation in future studies.

Another consideration is that our sample consisted of young, highly educated, and healthy females. An advantage of this population is that they are more likely to diet (Wardle et al., 2004) and generally score higher on dietary restraint and thus enabled us to study self-control (conflict). A score on the restraint eating scale of the DEBQ of 2.8 or higher indicates actively restraining eating behavior with weight goals in mind. (van Strien, Frijters, Bergers, & Defares, 1986). The median for that score in our population was 2.7. Furthermore, our participants indicated having weight concerns on a 9 point scale, where higher score indicate more concerns. The median for that scores was 6, which suggests our population was weight-concerned. A disadvantage is that the population is not representative for the general population. Though effects of sleep deprivation on eating behavior or preference have been shown for both genders (e.g., in men: (Brondel et al., 2010; Hogenkamp et al., 2013), in females: (Bosy-Westphal et al., 2008); and in mixed populations: (Nedeltcheva et al., 2009; St-Onge et al., 2012)), it has been shown that some enzymatic activity (DPP-4) may be differentially altered by sleep loss in men and women (Rångtell et al., 2018). It is unknown whether effects of sleep deprivation depend on educational level or age. Future research should establish whether the present findings also hold for males and more diverse populations in terms of age and education level. A strength of the study is that we assessed liking and choice for a broad range of HE and LE products instead of only one or a handful, as earlier studies did. This reduces the risk that findings are specific to any specific HE or LE food. Moreover, participants were faced with choices based on their personal liking of food items ensuring proper levels of conflict for each participant.

To conclude, this study suggests that increased energy intake and relative liking for HE foods after partial sleep deprivation may not be caused by an increased attractiveness of the HE alternatives but rather by decreased attractiveness of the LE alternatives. Further, conflict detection, as indexed by the amount of gaze switches between HE and LE foods during choice, was lower in the partially sleep deprived condition, though this did not translate into the selection of LE foods. Thus, it may be that sleep-loss induced increases in intake are not because of increased reward sensitivity or decreased self-control ability but rather a combination of lower conflict detection ability and lower attractiveness of low energy alternatives.

CRediT authorship contribution statement

Jeroen S. Benjamins: Conceptualization, Methodology, Software, Formal analysis, Data curation, Supervision, Writing - original draft, Writing - review & editing. **Ignace T.C. Hooge:** Conceptualization, Methodology, Software, Writing - review & editing. **Christian Benedict:** Conceptualization, Writing - review & editing. **Paul A.M. Smeets:** Conceptualization, Writing - review & editing. **Laura N. van der Laan:** Conceptualization, Methodology, Software, Formal analysis, Data curation, Supervision, Writing - original draft, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors express their gratitude to Iris van Hooijdonk and Madhronica Sardjoe for assisting in data collection.

Disclosure statement

Financial disclosure: This study was financially supported by a Food Future Utrecht grant of Utrecht University.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodqual.2020.104074.

References

Al Khatib, H. K., Hall, W. L., Creedon, A., Ooi, E., Masri, T., McGowan, L., ... Pot, G. K. (2018). Sleep extension is a feasible lifestyle intervention in free-living adults who are habitually short sleepers: A potential strategy for decreasing intake of free sugars? A randomized controlled pilot study. *American Journal of Clinical Nutrition, 107*(1), 43–53. https://doi.org/10.1093/ajcn/nqx030.

Alkozei, A., Killgore, W. D. S., Smith, R., Dailey, N. S., Bajaj, S., Raikes, A. C., & Haack, M. (2018). Chronic sleep restriction differentially affects implicit biases toward food among men and women: Preliminary evidence. *Journal of Sleep Research*. https://doi.org/10.1111/jsr.12629.

Allan, J. L., Johnston, M., & Campbell, N. (2011). Missed by an inch or a mile? Predicting the size of intention-behaviour gap from measures of executive control. *Psychol Health, 26*(6), 635–650. https://doi.org/10.1080/08870441003681307.

Beebe, D. W., Simon, S., Summer, S., Hemmer, S., Strotman, D., & Dolan, L. M. (2013). Dietary intake following experimentally restricted sleep in adolescents. *Sleep*. https://doi.org/10.5665/sleep.2704.

Beebe, D. W., Zhou, A., Rausch, J., Noe, O., & Simon, S. L. (2015). The impact of early bedtimes on adolescent caloric intake varies by chronotype. *Journal of Adolescent Health*. https://doi.org/10.1016/j.jadohealth.2015.02.017.

Bosy-Westphal, A., Hinrichs, S., Jauch-Chara, K., Hitze, B., Later, W., Wilms, B., ... Müller, M. J. (2008). Influence of partial sleep deprivation on energy balance and insulin sensitivity in healthy women. *Obesity Facts*. https://doi.org/10.1159/000158874.

Brondel, L., Romer, M. A., Nougues, P. M., Touyarou, P., & Davenne, D. (2010). Acute partial sleep deprivation increases food intake in healthy men. *American Journal of Clinical Nutrition*. https://doi.org/10.3945/ajcn.2009.28523.

Carbine, K. A., & Larson, M. J. (2019). Quantifying the presence of evidential value and selective reporting in food-related inhibitory control training: A p-curve analysis. *Health Psychology Review*. https://doi.org/10.1080/17437199.2019.1622144.

Carney, C. E., Buysse, D. J., Ancoli-Israel, S., Edinger, J. D., Krystal, A. D., Lichstein, K. L., & Morin, C. M. (2012). The consensus sleep diary: Standardizing prospective sleep self-monitoring. *Sleep, 35*(2), 287–302. https://doi.org/10.5665/sleep.1642.

Charbonnier, L., van Meer, F., van der Laan, L. N., Viergever, M. A., & Smeets, P. A. M. (2015). Standardized food images: A photographing protocol and image database. *Appetite*. https://doi.org/10.1016/j.appet.2015.08.041.

Davis, C., Patte, K., Levitan, R., Reid, C., Tweed, S., & Curtis, C. (2007). From motivation to behaviour: A model of reward sensitivity, overeating, and food preferences in the risk profile for obesity. *Appetite*. https://doi.org/10.1016/j.appet.2006.05.016.

Dweck, J. S., Jenkins, S. M., & Nolan, L. J. (2014). The role of emotional eating and stress in the influence of short sleep on food consumption. *Appetite*. https://doi.org/10.1016/j.appet.2013.10.001.

Ford, E. S., Cunningham, T. J., & Croft, J. B. (2015). Trends in self-reported sleep duration among US Adults from 1985 to 2012. *Sleep, 38*(5), 829–832. https://doi.org/10.5665/sleep.4684.

Gujar, N., Yoo, S. S., Hu, P., & Walker, M. P. (2011). Sleep deprivation amplifies reactivity of brain reward networks, biasing the appraisal of positive emotional experiences. *Journal of Neuroscience*. https://doi.org/10.1523/JNEUROSCI.3220-10.2011.

Hall, P. A. (2012). Executive control resources and frequency of fatty food consumption: Findings from an age-stratified community sample. *Health Psychology, 31*(2), 235–241. https://doi.org/10.1037/a0025407.

Higgs, S., Williamson, A. C., & Attwood, A. S. (2008). Recall of recent lunch and its effect on subsequent snack intake. *Physiology & Behavior, 94*(3), 454–462. https://doi.org/10.1016/j.physbeh.2008.02.011.

Hofmann, W., Friese, M., & Roefs, A. (2009). Three ways to resist temptation: The independent contributions of executive attention, inhibitory control, and affect regulation to the impulse control of eating behavior. *Journal of Experimental Social Psychology, 45*(2), 431–435. https://doi.org/10.1016/j.jesp.2008.09.013.

Hogenkamp, P. S., Nilsson, E., Nilsson, V. C., Chapman, C. D., Vogel, H., Lundberg, L. S., ... Schioth, H. B. (2013). Acute sleep deprivation increases portion size and affects food choice in young men. *Psychoneuroendocrinology, 38*(9), 1668–1674. https://doi.org/10.1016/j.psyneuen.2013.01.012.

Hooge, I. T. C., & Camps, G. (2013). Scan path entropy and arrow plots: Capturing scanning behavior of multiple observers. *Frontiers in Psychology, 4*, 996. https://doi.org/10.3389/fpsyg.2013.00996.

Kecklund, G., & Axelsson, J. (2016). Health consequences of shift work and insufficient sleep. *BMJ, 355*, Article i5210. https://doi.org/10.1136/bmj.i5210.

Killgore, W. D. S., Schwab, Z. J., Weber, M., Kipman, M., DelDonno, S. R., Weiner, M. R., & Rauch, S. L. (2013). Daytime sleepiness affects prefrontal regulation of food intake. *NeuroImage*. https://doi.org/10.1016/j.neuroimage.2013.01.018.

Krajbich, I., Armel, C., & Rangel, A. (2010). Visual fixations and the computation and comparison of value in simple choice. *Nature Neuroscience*. https://doi.org/10.1038/nn.2635.

Kronholm, E., Partonen, T., Laatikainen, T., Peltonen, M., Härmä, M., Hublin, C., ... Sutela, H. (2008). Trends in self-reported sleep duration and insomnia-related symptoms in Finland from 1972 to 2005: A comparative review and re-analysis of Finnish population samples. *Journal of Sleep Research*. https://doi.org/10.1111/j.1365-2869.2008.00627.x.

Lim, J., & Dinges, D. F. (2008). Sleep deprivation and vigilant attention. *Annals of the New York Academy of Sciences, 1129*, 305–322. https://doi.org/10.1196/annals.1417.002.

Lombardo, C., Ballesio, A., Gasparrini, G., & Cerolini, S. (2019). Effects of acute and chronic sleep deprivation on eating behaviour. *Clinical Psychologist*. https://doi.org/10.1111/cp.12189.

Lombardo, C., Battagliese, G., Baglioni, C., David, M., Violani, C., & Riemann, D. (2014). Severity of insomnia, disordered eating symptoms, and depression in female university students. *Clinical Psychologist*. https://doi.org/10.1111/cp.12023.

Lundahl, A., & Nelson, T. D. (2015). Sleep and food intake: A multisystem review of mechanisms in children and adults. *Journal of Health Psychology*. https://doi.org/10.1177/1359105315573427.

Lv, W., Finlayson, G., & Dando, R. (2018). Sleep, food cravings and taste. *Appetite*. https://doi.org/10.1016/j.appet.2018.02.013.

Martinez, S. M., Tschann, J. M., Butte, N. F., Gregorich, S. E., Penilla, C., Flores, E., ... Deardorff, J. (2017). Short sleep duration is associated with eating more

carbohydrates and less dietary fat in mexican American children. *Sleep*. https://doi.org/10.1093/sleep/zsw057.
McNeil, J., Forest, G., Hintze, L. J., Brunet, J. F., Finlayson, G., Blundell, J. E., & Doucet, É. (2017). The effects of partial sleep restriction and altered sleep timing on appetite and food reward. *Appetite*. https://doi.org/10.1016/j.appet.2016.11.020.
Myrseth, K. O. R., Fishbach, A., & Trope, Y. (2009). Counteractive self-control: When making temptation available makes temptation less tempting. *Psychological Science*. https://doi.org/10.1111/j.1467-9280.2009.02268.x.
Nedeltcheva, A. V., Kilkus, J. M., Imperial, J., Kasza, K., Schoeller, D. A., & Penev, P. D. (2009). Sleep curtailment is accompanied by increased intake of calories from snacks. *American Journal of Clinical Nutrition*. https://doi.org/10.3945/ajcn.2008.26574.
Neumark-Sztainer, D., Sherwood, N. E., French, S. A., & Jeffery, R. W. (1999). Weight control behaviors among adult men and women: cause for concern? Obes Res, 7(2), 179–188. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/10102255.
Nilsson, J. P., Soderstrom, M., Karlsson, A. U., Lekander, M., Akerstedt, T., Lindroth, N. E., & Axelsson, J. (2005). Less effective executive functioning after one night's sleep deprivation. *Journal of Sleep Research, 14*(1), 1–6. https://doi.org/10.1111/j.1365-2869.2005.00442.x.
Pender, S., Stevenson, R. J., Francis, H. M., & Oaten, M. J. (2019). Wanting and liking for sugar sweetened beverages and snacks differ following depletion and repletion with energy and fluids. *Appetite*. https://doi.org/10.1016/j.appet.2019.02.014.
Rångtell, F. H., Schmidt, F., Würfel, J., Karamchedu, S., Andersson, P., Vogel, H., & Benedict, C. (2018). Morning enzymatic activity of DPP-4 is differentially altered by sleep loss in women and men. *Diabetes Care*. https://doi.org/10.2337/dc17-1762.
D. Reisenberg The Oxford handbook of cognitive psychology. In Choice Reviews Online 50 2013 pp. 50–7051-50–7051) 10.5860/choice.50-7051.
Rihm, J. S., Menz, M. M., Schultz, H., Bruder, L., Schilbach, L., Schmid, S. M., & Peters, J. (2019). Sleep deprivation selectively upregulates an amygdala–hypothalamic circuit involved in food reward. *Journal of Neuroscience*. https://doi.org/10.1523/JNEUROSCI.0250-18.2018.
Rollins, B. Y., Dearing, K. K., & Epstein, L. H. (2010). Delay discounting moderates the effect of food reinforcement on energy intake among non-obese women. *Appetite, 55*(3), 420–425. https://doi.org/10.1016/j.appet.2010.07.014.
Slovic, P. (1975). Choice between equally valued alternatives. *Journal of Experimental Psychology: Human Perception and Performance.*. https://doi.org/10.1037/0096-1523.1.3.280.
St-Onge, M. P., McReynolds, A., Trivedi, Z. B., Roberts, A. L., Sy, M., & Hirsch, J. (2012). Sleep restriction leads to increased activation of brain regions sensitive to food stimuli. *American Journal of Clinical Nutrition, 95*(4), 818–824. https://doi.org/10.3945/ajcn.111.027383.
Stevenson, R. J., Francis, H. M., Attuquayefio, T., & Ockert, C. (2017). Explicit wanting and liking for palatable snacks are differentially affected by change in physiological state, and differentially related to salivation and hunger. *Physiology and Behavior*. https://doi.org/10.1016/j.physbeh.2017.10.007.
Taheri, S. (2006). The link between short sleep duration and obesity: We should recommend more sleep to prevent obesity. *Archives of Disease in Childhood, 91*(11), 881–884. https://doi.org/10.1136/adc.2005.093013.
Taheri, S., Lin, L., Austin, D., Young, T., & Mignot, E. (2004). Short sleep duration is associated with reduced leptin, elevated ghrelin, and increased body mass index. *PLoS Medicine, 1*(3), Article e62. https://doi.org/10.1371/journal.pmed.0010062.
Tajiri, E., Yoshimura, E., Hatamoto, Y., Tanaka, H., & Shimoda, S. (2018). Effect of sleep curtailment on dietary behavior and physical activity: A randomized crossover trial. *Physiology and Behavior*. https://doi.org/10.1016/j.physbeh.2017.11.008.
Tversky, A., Sattath, S., & Slovic, P. (1988). Contingent weighting in judgment and choice. *Psychological Review*. https://doi.org/10.1037/0033-295X.95.3.371.
van der Laan, L. N., Barendse, M. E. A., Viergever, M. A., & Smeets, P. A. M. (2016). Subtypes of trait impulsivity differentially correlate with neural responses to food choices. *Behavioural Brain Research, 296*, 442–450. https://doi.org/10.1016/j.bbr.2015.09.026.
van der Laan, L. N., Hooge, I. T. C., de Ridder, D. T. D., Viergever, M. A., & Smeets, P. A. M. (2015). Do you like what you see? The role of first fixation and total fixation duration in consumer choice. *Food Quality and Preference, 39*, 46–55. https://doi.org/10.1016/j.foodqual.2014.06.015.
van der Laan, L. N., Papies, E. K., Hooge, I. T., & Smeets, P. A. (2017). Goal-directed visual attention drives health goal priming: An eye-tracking experiment. *Health Psychology, 36*(1), 82–90. https://doi.org/10.1037/hea0000410.
L.N. van der Laan D.T.D. de Ridder L. Charbonnier M.A. Viergever P.A.M. Smeets Sweet lies: Neural, visual, and behavioral measures reveal a lack of self-control conflict during food choice in weight-concerned women Frontiers in Behavioral Neuroscience 8 MAY 2014 10.3389/fnbeh.2014.00184.
Van Dongen, H. P., & Dinges, D. F. (2005). Sleep, circadian rhythms, and psychomotor vigilance. Clin Sports Med, 24(2), 237–249, vii–viii. https://doi.org/10.1016/j.csm.2004.12.007.
van Strien, T., Frijters, J. E. R., Bergers, G. P. A., & Defares, P. B. (1986). The Dutch Eating Behavior Questionnaire (DEBQ) for assessment of restrained, emotional, and external eating behavior. International Journal of Eating Disorders. https://doi.org/10.1002/1098-108X(198602)5:2 < 295::AID-EAT2260050209 > 3.0.CO;2-T.
Wardle, J., Haase, A. M., Steptoe, A., Nillapun, M., Jonwutiwes, K., & Bellisle, F. (2004). Gender differences in food choice: The contribution of health beliefs and dieting. *Annals of Behavioral Medicine*. https://doi.org/10.1207/s15324796abm2702_5.
Wassing, R., Benjamins, J. S., Dekker, K., Moens, S., Spiegelhalder, K., Feige, B., ... Van Someren, E. J. (2016). Slow dissolving of emotional distress contributes to hyperarousal. *Proceedings of the National Academy of Sciences of the United States of America, 113*(9), 2538–2543. https://doi.org/10.1073/pnas.1522520113.
Yang, C. L., Schnepp, J., & Tucker, R. M. (2019). Increased hunger, food cravings, food reward, and portion size selection after sleep curtailment in women without obesity. *Nutrients*. https://doi.org/10.3390/nu11030663.