

# Testing a Load Theory Framework for Food-Related Cognition

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The way we process rewarding stimuli is widely held to play a key role in normal and abnormal behavior. Biased processing of food—arguably the most primal form of reward—has been strongly implicated in the obesity crisis. Paradoxically, however, existing evidence suggests that both too much and too little attention can potentially lead to overeating. Here we sought to explain this contradiction within the framework of the load theory of attention, while also elucidating the relatively understudied role of memory biases. In 3 experiments, we presented food and nonfood images as irrelevant distractors during a letter search task with high and low levels of perceptual load, followed by a forced choice recognition task. As predicted, increasing perceptual load consistently powerfully reduced distraction by food and nonfood images alike. Similarly, food images encountered under high perceptual load were less likely to be recognized in a surprise memory test. Unexpectedly, however, there was a striking absence of attentional bias to food above and beyond salient nonfood stimuli, either within-subjects or in relation to traits implicated in food-biases. By contrast, a food memory bias was consistently observed across participants, and appeared independent of attentional biases. Food memory was consistently heightened in individuals with high levels of trait disinhibition (a measure of opportunistic eating). Our findings suggest that attention and memory for food and nonfood are similarly impacted by perceptual load. We discuss implications of the load theory framework for the wider literature on food-related cognition and for real world eating behaviors.

**Keywords:** attentional bias, memory, perceptual load, food, reward

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Food is one of the most universal and powerful forms of reward, being both critical for survival and a potential source of pleasure. Like other forms of reward, the way we respond to food has a bidirectional relationship with basic cognitive processes such as attention and memory. On one hand, past experience with rewarding stimuli, such as food, can impact future cognitive processing (Anderson, Laurent, & Yantis, 2013). For example, food associated with pleasant tastes are more likely to receive priority in cognitive processing (di Pellegrino, Magarelli, & Mengarelli, 2011; Higgs, 2016). On the other hand, whether an individual overeats is thought to be influenced by the way they attend and react to food cues (Werthmann, Jansen, & Roefs, 2015). While some individuals can maintain a healthy weight, the obesity crisis is a growing concern due to the significant risk it poses to both physical and psychological health: An estimated 2.8 million people die every year due to the adverse consequences of being overweight or obese (World Health Organization, 2017). Given this, an

important application of the rich cognitive psychology literature on attention and memory is to elucidate the mechanisms of overeating and hence inform interventions.

Research on the cognitive mechanisms of overeating has traditionally focused largely on attention, with more recent work also highlighting an important role for memory. However, as we will discuss in the following sections, the application of this large body of evidence to real world scenarios may be limited by seemingly contradictory implications of the literature. Namely, both too much and too little attention have both been suggested to result in overeating (Robinson et al., 2013; Werthmann et al., 2015). This complicates the advice that can be given to those trying to avoid overeating, as it appears desirable to avoid paying any attention to food in some situations, yet also important to give food our full attention in other situations. Here we argue that this contradiction may be explained utilizing theories of attention to clearly differentiate between situations where increased attention can be a help or a hindrance.

## Attentional Processing of Food

Food related attentional bias, the selective preferential processing of food cues, is one important aspect of biased cognition. Simply put, having an attentional bias for food increases the likelihood that you will notice food in the first place. Attentional bias to food has been typically measured by cognitive tasks showing either faster identification of a food target (e.g., an image of a food item) or interference with a task when a food stimulus was presented as the distractor. A multitude of studies have shown

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evidence for the presence of attentional bias for food stimuli (Ahern, Field, Yokum, Bohon, & Stice, 2010; Castellanos et al., 2009; Cunningham & Egeth, 2018; Hollitt, Kemps, Tiggemann, Smeets, & Mills, 2010; Meule, Vögele, & Kübler, 2012; Neimeijer, de Jong, & Roefs, 2013; Nijs, Muris, Euser, & Franken, 2010; Seage & Lee, 2017; Tapper, Pothos, & Lawrence, 2010; Werthmann et al., 2011). There is also some evidence that this bias is heightened in individuals susceptible to overeating, such as those who are overweight (Hendrikse et al., 2015; Werthmann et al., 2011), people with a tendency toward dieting, (restrained eaters: Hollitt et al., 2010), people with a tendency toward uncontrolled eating (disinhibited eaters: Seage & Lee, 2017) and individuals with greater sensitivity to external food cues (external eaters: Brignell, Griffiths, Bradley, & Mogg, 2009; Hou et al., 2011). However, we note that these individual differences findings have not always been replicated (e.g., Ahern et al., 2010; Boon, Vogelzang, & Jansen, 2000; Doolan, Breslin, Hanna, & Gallagher, 2015; Field et al., 2016; Freijy, Mullan, & Sharpe, 2014; Loeber et al., 2012; Nijs et al., 2010; Pothos, Tapper, & Calitri, 2009; Werthmann et al., 2011; Werthmann et al., 2013).

Attentional bias toward food is argued to have been evolutionarily advantageous, in terms of facilitating the seeking and finding of food in our environment (Werthmann et al., 2015). However, in our modern obesogenic environment attentional bias is thought to be maladaptive and has been associated with several aspects of eating behavior such as craving, consumption (Werthmann, Field, Roefs, Nederkoorn, & Jansen, 2014) and weight gain (Yokum, Ng, & Stice, 2011).

While overly attending to food cues is thought to contribute toward overeating, studies examining attention during ingestion find the opposite effect. Inattentive eating is associated with increased consumption (see Robinson et al., 2013 for a recent review). This is typically tested by comparing amount consumed while attention is engaged in a task such as a game, TV, radio, or reading to amount consumed with no task. Several mechanisms have been put forward to explain the inattentive overeating effect including reduced awareness of intake, interoceptive signals, and dietary control (Braude & Stevenson, 2014). It might simply be assumed that the effect of attention to food cues depends on the stage of eating, with attention to food cues prior to ingestion increasing the likelihood of food being consumed; and attention during ingestion decreasing the quantity that is consumed. However, as outlined below, the paradigms that have been used to study attentional bias and inattentive eating also differ in terms of a factor that has been highlighted within the selective attention literature as a powerful determinant of attention: perceptual load.

A large body of evidence in support of the load theory of attention (e.g., Lavie, 2005, 2010) highlights that the extent to which task-irrelevant stimuli are processed depends on whether the current task leaves sufficient spare perceptual capacity. If the perceptual demand (or “load”) of the task is high (e.g., searching for a friend in a crowded restaurant), task-related processing exhausts perceptual capacity with the result that task-irrelevant stimuli are not processed. On the other hand, when demand is low (e.g., searching for a friend in an empty restaurant) sufficient capacity remains to process task-irrelevant stimuli (e.g., a ringing phone, or the drinks at the bar). Importantly, the modulation of attention by perceptual load is argued to occur in a passive and automatic manner.

Applying the load theory framework to eating behavior plausibly accommodates existing evidence and allows more nuanced predictions and recommendations for real world situations. If perceptual load modulates processing of food stimuli in the same manner as other stimuli, it would be expected that attentional biases and inattentive eating would be observed in distinct situations. Vulnerability to attentional biases (and the resulting increased consumption) should be associated primarily with conditions of low perceptual load, when the current task leaves sufficient spare capacity to allow irrelevant food cues to catch our attention. For example, we might be more likely to notice the dessert trolley while searching for our friend in an empty restaurant versus a crowded restaurant. On the other hand, vulnerability to inattentive eating should occur only in conditions of high perceptual load, when attentional capacity is exhausted by the task. Going back to our restaurant example, imagine that we begin eating while still keeping an eye out for our late-arriving friend: The undemanding task of monitoring the empty restaurant would theoretically be beneficial here in terms of leaving sufficient capacity for awareness of interoceptive signals, making it less likely that we would unintentionally overindulge. Consistent with our proposed application of load theory, the majority of evidence for food-related attentional bias rests on perceptually undemanding tasks such as the visual probe, in which only a small amount of information must be processed at any given time, while inattentive eating studies typically use more perceptually demanding tasks such as computer games and TV (Robinson et al., 2013).

Load theory provides a useful framework from which to draw practical recommendations. Rather than advising individuals to simply attempt to ignore food at all times other than when they are eating, which would place high demands on effortful goal maintenance and inhibitory processes, the load theory framework implies that individuals could simply organize their daily tasks in such a way as to passively facilitate beneficial eating behaviors. For example, individuals wishing to avoid overeating might find high perceptual load tasks useful in avoiding temptation in the course of their daily lives but would be advised to engage only in less demanding tasks while they are eating.

Our proposed application of load theory to food-related cognition assumes that perceptual load would modulate food cues in the same manner as nonfood stimuli. However, this key assumption is brought into question by a recent study in which several other categories of rewarding stimuli (happy faces, erotic images, and stimuli associated with money) caused distractor interference even under high perceptual load (Gupta, Hur, & Lavie, 2016), suggesting that rewarding stimuli may be among the “special” stimulus categories immune to perceptual load effects. Hence, a critical first step in applying the load theory framework was to establish whether external food cues would be modulated by load in the same manner as nonfood cues, or whether the rewarding properties of food would render it immune to load effects. Here we tested this possibility by, for the first time, comparing attention to food and nonfood stimuli in situations of high versus low perceptual load. If our account is correct, food stimuli should be more likely to attract attention during low perceptual load conditions. When perceptual load is increased, attentional processing of food stimuli (and hence any attentional bias) should be reduced or even eliminated.

## The Role of Memory

The effects of perceptual load have also been found to extend beyond attention, to impede memory for stimuli encountered under high perceptual load (Jenkins, Lavie, & Driver, 2005). This raises the intriguing possibility that perceptual load might impact eating behavior beyond the time point that the stimulus is originally encountered, by modulating the likelihood that a food cue will be later recognized. The mechanism by which attentional biases lead to later consumption necessarily involves memory for the food cue. For example, May, Andrade, Kavanagh, and Hetherington (2012) suggest that once a food cue captures attention it is then more likely to be processed further and remembered, reducing an individual's ability to ignore that craving. Perceptual load could therefore potentially not only reduce the likelihood of food cues capturing attention in the first place, but also disrupt the pathway from capture to craving (and ultimately overeating) by preventing the food cues from being encoded into memory.

The above suggestion implies a benefit of perceptual load-disrupted memory in avoiding overeating. However, as in the case of inattentive eating, a high perceptual load task during ingestion could have the opposite consequence. If, as we predict, perceptual load impedes memory for food-related stimuli this would also imply that engaging in a high perceptual load task while eating might interfere with people's ability to later remember how much they have eaten. This would be undesirable given that memory for previous intake appears to play an important role in eating behavior, as shown by research with amnesic patients who despite consuming multiple meals show no changes in reported hunger (Hebben, Corkin, Eichenbaum, & Shedlack, 1985; Rozin, Dow, Moscovitch, & Rajaram, 1998). In healthy participants, poor memory for a recent meal, usually manipulated by disrupting the encoding of the meal via a secondary task, has been repeatedly shown to increase subsequent intake (Higgs, 2015; Mittal, Stevenson, Oaten, & Miller, 2011; Moray, Fu, Brill, & Mayoral, 2007; Oldham-Cooper, Hardman, Nicoll, Rogers, & Brunstrom, 2011). Notably, as with the inattentive eating literature, the secondary tasks used to demonstrate memory effects on eating behavior are typically rather perceptually demanding tasks such as computer games (Higgs, 2015; Oldham-Cooper et al., 2011) or TV (Higgs, 2015; Moray et al., 2007; Mittal et al., 2011). Our study therefore sought to more directly test the possibility that high perceptual load tasks can interfere with memory for food cues.

Just as the effect of memory on intake parallels the inattentive eating literature, a small number of studies demonstrate memory effects paralleling the attentional bias literature. Biased memory for food has been found using recognition memory tests in hungry participants (Morris & Dolan, 2001) and with free-recall tasks in both hungry (Talmi et al., 2013) and restrained eaters (Soetens, Roets, & Raes, 2014). A significant theoretical question is to what extent the roles of attention and memory on eating behaviors are separable. Are the effects of poor memory on overconsumption and enhanced memory for food stimuli simply a consequence of attentional processes?

It is well established that disrupting attention at the time of encoding is detrimental to subsequent memory performance (Anderson & Craik, 1974; Baddeley, Lewis, Eldridge, & Thomson, 1984; Jenkins et al., 2005). Similarly, the elaboration intrusion theory (May et al., 2012) from the eating literature argues that food

attentional bias leads to cognitive elaboration of food related cues, their consequent presence in working memory should make them easier to remember, hence memory bias reflects the early attention bias. On the other hand, the relationship between attention and memory is bidirectional: Memory has also been found to guide attention. For example, Rutters, Kumar, Higgs, and Humphreys (2015) found with both behavioral and electrophysiological measures that holding food cues in working memory guided attention toward task irrelevant food distractor images. More broadly, it should be noted that memory plays a key role in eating behavior, through the learning of associations between food cues, eating, and its consequences (see Higgs, 2016, for a full review on the role of memory). For example, flavor aversions may be learnt from a previous pairing of the flavor and a negative postingestive consequence (i.e., illness); future food choices and intake is then guided by this learned association (Garcia & Koelling, 1966; Smith & Roll, 1967).

To date only one study has attempted to compare both attention and memory biases to food: Talmi et al. (2013) measured interference from food images on a tone discrimination task, followed by a free recall memory test. Although they found both attention and memory biases in participants under conditions of hunger, but not satiety, these processes did not appear to be linked. This intriguing null result is at odds with the wider attention and memory literature. A secondary aim of our study is therefore to more extensively test the relationship between attention and memory.

## The Current Research

In summary, the current research provides the first test of an application of the load theory framework to understand the influence of basic cognitive processes (attention and memory) on eating behaviors. Across three experiments we conducted a comprehensive investigation of both attention and memory biases across a single paradigm based on the irrelevant distractor task (Forster & Lavie, 2008). This task has previously been adapted, using a well-established manipulation of perceptual load, to replicate the effects of perceptual load on task irrelevant processing (Forster & Lavie, 2008, 2016; Lancaster, Forster, Tabet, & Rusted, 2017; Lunn, Sjoblom, Ward, Soto-Faraco, & Forster, 2019). A version of this task, which did not include a perceptual load manipulation, was also recently used to demonstrate the attentional bias for food cues (Cunningham & Egeth, 2018). The irrelevant distractor task has the advantage that, unlike widely used measures such as the dot-probe, the distractor is presented in an entirely task irrelevant location and as such avoids inadvertently encouraging top down attention to food (for further discussion of this issue see Forster & Lavie, 2008; Lichtenstein-Vidne, Henik, & Safadi, 2007). Hence, distractor interference in this task is analogous to the daily life phenomenon whereby attention is drawn to something entirely irrelevant to what we are currently doing—for example, as we sit on a train reading a book, an advert for a chocolate bar might catch our eye.

Our first aim across all experiments was to establish whether the powerful effects of perceptual load in reducing task irrelevant processing also extend to food stimuli; this would be reflected by slower on reaction times (RTs) on food present trials compared to no distractor trials under low perceptual load but no difference



under high perceptual load. We also tested whether a memory bias exists for food images, which would be demonstrated by higher recognition accuracy of food images compared with nonfood images on a recognition memory task. We expected this memory bias to manifest only under low perceptual load conditions—this was tested directly in our final experiment.

To investigate the extent to which attention and memory biases (and their modulation by perceptual load) are related, we examined the correlation between attention and memory biases in each of our experiments. If a memory bias is a consequence of the attentional bias, it would follow that a stronger attentional bias in an individual would lead to a stronger memory bias. Similarly, if load modulation of memory for food cues reflects the load effect on attention, the degree of the load effect on memory should be greatest for those participants showing the greatest load effect on attention. Finally, we also measured a variety of traits previously shown to influence food related cognition to enable exploratory analyses of potential interactions of trait differences and perceptual load.

## Experiment 1

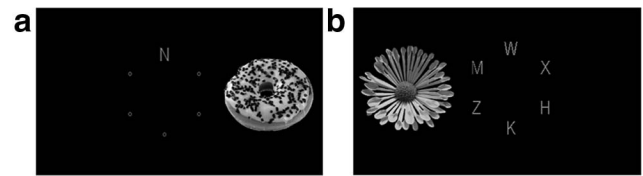
### Method

**Participants.** Sixty female participants were recruited, who were aged between 18 and 35 years ( $M = 21.46$ ,  $SD = 1.68$ ), with normal or corrected to normal (e.g., with glasses) vision, and were either native English speakers or as fluent at both speaking and reading English as a native speaker. Three participants were excluded from analysis as it was later identified they did not meet all the eligibility requirements. Participants were primarily University of Sussex students who received course credit or a five-pound financial compensation.

**Forster and Lavie's (2016) study,** which replicated the load effects on irrelevant distraction in a sample size of 77, found an effect size of .36 for the interaction of load and distractor interference. A more recent study using the irrelevant distractor paradigm, in a very similar design to our study ( $2 \times 3$  within-subjects), found an effect size of .10 for the interaction between load and distractor interference, in a sample size of 52 (Lunn et al., 2019). Our sample size of 60 was selected a priori on the basis of being highly powered (.95) to detect the within subject effects reported by Lunn, Sjoblom, Ward, Soto-Faraco, and Forster (2019) and having 80% power to detect small-medium correlations of .33 (Faul, Erdfelder, Lang, & Buchner, 2007). The study was approved by the University of Sussex Sciences & Technology Cross-Schools Research Ethics Committee and complied fully with BPS ethical standards.

**Stimuli and procedure.** The task was adapted from Forster and Lavie's (2008) irrelevant distractor paradigm. All stimuli were presented using E-prime 2.0 (Schneider, Eschman, & Zuccolotto, 2002) on a 13.5-in. computer screen at a viewing distance of 57 cm. The experiment was presented on a black background and all letter stimuli were gray.

At the start of every trial a fixation point appeared for 500 ms, followed by the stimulus display. When the stimulus display appeared, participants had to search for an "X" or "N" target letter which appeared in a random location within a circle of six letters (see Figure 1). In the high load condition the nontarget letters in



**Figure 1.** Example stimulus displays with: (a) a food distractor presented on a low load trial, (b) a nonfood (nature) distractor presented on a high load trial. Food/nonfood distractors appeared with equal frequency in the high and low load conditions. Participants searched for the target letter (X or N), while ignoring any distractors.

the circle were selected at random from five potential letters: H, K, M, Z, W, V. In the low load condition, the nontarget letters were all lowercase o's. The letter circle had a  $2.4^\circ$  radius (each letter subtending  $1.2^\circ \times 1^\circ$ ) and the small o's were  $0.19^\circ$ . The letter stimuli appeared for 100 ms, but participants had up to 2,000 ms to respond.

The majority of trials did not contain a distractor (80%); the remaining trials contained a distractor image. On 10% of trials a randomly selected image of a sweet food item was presented (six food stimuli were used: doughnut, chocolate bar, chocolate cake, muffins, ice cream, or a cookie). On another 10% of trials a randomly selected nonfood item was presented (six nonfood stimuli were used: pink flower, yellow flower, white flower, red leaf, orange leaf, or green leaf). Each stimulus was presented once in each block and a total of eight times throughout the visual search task. Distractor stimuli were presented at a peripheral location, left or right of the letter circle. Distractor stimuli subtended  $3.4^\circ$  to  $4.9^\circ$  vertically by  $3.2^\circ$  to  $4.9^\circ$  horizontally. The center of the distractor was  $4.6^\circ$  from fixation and between  $0.6^\circ$  and  $1^\circ$  edge to edge from the nearest stimulus. The distractor was equally likely to appear in either of these locations. The distractor remained on screen until response or timeout at 2,000 ms. Both food and nonfood stimuli were selected from the online image database FoodPics (Blechert, Meule, Busch, & Ohla, 2014)—each image in this database has been rated by 1,988 people on a range of visual and affective features. The six food images and six nonfood images that we selected did not differ on measures of valence, arousal, brightness, contrast, complexity, or familiarity (all  $ps > .127$ , see Table S1 for means). Food images were chosen based on those which had high palatability and craving ratings.

Participants completed three slow example trials (stimuli appeared for 2,000 ms) and 12 practice trials for both low and high load displays. No distractors appeared during the practice trials. Participants then completed eight experimental blocks, four low load and four high load, each block contained 60 trials. As in Forster and Lavie's (2008) experiments, blocks were counterbalanced across participants in the following order: LHHLLHLL or HLLHHLLH. Within each block, all combinations of load, target position, target identity, distractor condition, and distractor identity were counterbalanced. Distractor images did not appear on the first three trials in each block and these trials were excluded from analysis.

Following the visual search portion of the experiment participants completed a surprise memory test for the distractor images used in the task. Each distractor image was presented alongside two novel but similar images of the same item (i.e., cookie);

participants made a forced choice of which image they had previously seen in the experiment (see Figure 2). Location of correct image and corresponding correct keyboard response were randomized.

Following the memory test, participants completed several ratings. Hunger was measured using a 0–100 visual analogue scale (VAS), embedded within nine other irrelevant mood ratings. We were interested in hunger as it had previously been linked to attentional bias for food stimuli (Castellanos et al., 2009; Nijs et al., 2010; Tapper et al., 2010): The nine other ratings were intended to disguise the hunger rating and received no further analysis. Each VAS scale was presented as a 100-mm horizontal line on the computer screen. Each mood question appeared above the line with a lower end anchor of *not at all* and an upper end anchor of *extremely*. Participants dragged the cursor from the midpoint of the scale to indicate their current mood. Sussex Ingestion Pattern Monitor (SIPM; University of Sussex; Yeomans, 2000) was used to collect these ratings. Hunger was not explicitly manipulated, instead participants were tested between 10:00 a.m.–12:00 p.m. and 3:00 p.m.–5:00 p.m. All testing was carried out in experimental cubicles at the University of Sussex Ingestive Behavior Laboratory.

Finally, participants completed a set of questionnaires measuring individual difference characteristics. The researcher also measured participant's height and weight at the end of the experiment using a stadiometer with an integrated height measure, before thanking and debriefing them. Height and weight were used to calculate body mass index (BMI).

**Questionnaire measures.** We conducted a search of the attentional bias literature to identify questionnaire measures thought to measure separate constructs and which would be predicted to influence attention to food stimuli. Individual difference measures were chosen based on their relevance to eating behavior and frequency of use within attentional bias studies.

#### Measures of eating attitude.

**Three Factor Eating Questionnaire (TFEQ; Stunkard & Messick, 1985).** The 51-item TFEQ is divided into three factors; restraint, disinhibition, and hunger. Several studies have linked both restraint (Ahern et al., 2010; Castellanos et al., 2009; Hollitt et al., 2010; Neimeijer et al., 2013) and disinhibition (Castellanos et al., 2009; Seage & Lee, 2017) with biased attention toward food stimuli. However, it should be noted the relationship between

TFEQ and attention to food is not always observed, particularly on RT measures (Werthmann et al., 2013).

**Dutch Eating Behavior Questionnaire (DEBQ; Van Strien, Frijters, Bergers, & Defares, 1986).** Only the 10-item external eating subscale of the DEBQ was used in this experiment, as it is thought to be the most directly relevant to attentional bias (Brignell et al., 2009; Hou et al., 2011). With some exceptions on RT measures (Nijs et al., 2010), external eating has been linked to biased attention for food stimuli (Brignell et al., 2009; Hou et al., 2011).

#### Measures of impulsiveness.

**Barratt Impulsiveness Scale (BIS 11; Patton, Stanford, & Barratt, 1995).** The 30-item BIS 11 measures three dimensions of impulsivity: attentional, motor, and nonplanning. The BIS 11 has been found to correlate with attentional bias to food (Lattimore & Mead, 2015; Meule & Platte, 2016), even after controlling for external eating (Hou et al., 2011).

**Sensitivity to Punishment and Reward Questionnaire (SPSRQ; Torrubia, Avila, Moltó, & Caseras, 2001).** This 48-item questionnaire comprised of two subscales, sensitivity to reward (SR) which reflects behavioral activation and the sensitivity to punishment which reflects behavioral inhibition. Sensitivity to reward has been associated with greater attention to food (Hennegan, Loxton, & Mattar, 2013).

## Results

Traditional analyses for all three experiments were conducted using IBM SPSS Statistics 24. Data for all experiments can be downloaded from the Open Science Framework (<https://osf.io/srehg/>).

**Reaction times.** To test whether attention to food was modulated by load, we calculated mean RTs on correct response trials only, and then contrasted these as a function of load (low, high) and distractor condition (food, nonfood, absent) using a  $2 \times 3$  within-subject ANOVA. Table 1 presents mean RTs, accuracy, and distractor costs across different conditions. Distractor costs were calculated by subtracting the RT when no distractor was present from the RT when a distractor was present: This demonstrates the cost to RT when a particular distractor is present. We used distractor costs as our measure of attentional processing (as in Forster & Lavie, 2008). The difference between food and nonfood distractor costs is our measure of attentional bias.

As predicted, RTs were slower overall on high than low load trials,  $F(1, 56) = 294.77, p < .001, N_p^2 = .84$ , confirming that the load manipulation increased task difficulty. There was a significant main effect of distractor type,  $F(1.70, 95.33) = 3.57, p = .039, N_p^2 = .06$ , with Greenhouse-Geisser correction applied as Mauchly's test suggests sphericity was violated for the interaction,  $\chi^2(2) = 10.57, p = .005$ . Critically, the interaction between load and distractor was also significant,  $F(1.62, 90.42) = 3.71, p = .037, N_p^2 = .06$ , Greenhouse-Geisser correction applied for violated sphericity,  $\chi^2(2) = 14.99, p < .001$ . The significant interaction reflects that the distractor costs from both food and nonfood stimuli were observed under low load, but not under high load (see Table 1).

To investigate the significant interaction, we conducted planned contrasts on two separate one way ANOVA's; one for the three distractor conditions under low load and another for the same

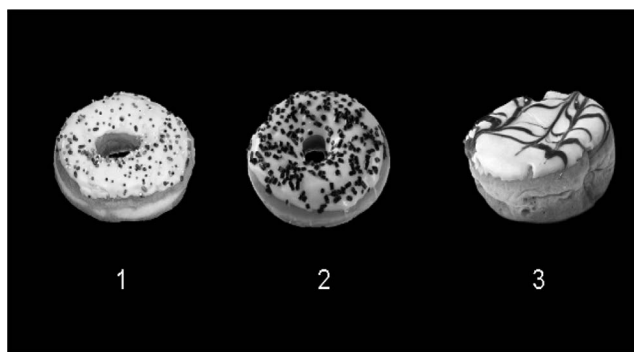


Figure 2. Forced choice memory test. Participants were asked to identify the stimulus presented during the visual search task.

Table 1

Mean RT's (SE in Parentheses) and Percentage Accuracy Rates Across Different Distractor Conditions Under Low and High Load in Experiment 1

Response type & condition	Distractor condition			Distractor costs	
	F	NF	ND	F-ND	NF-ND
Low load					
RT (ms)	491 (9)	494 (8)	474 (8)	17	20
% error	15	16	16		
High load					
RT (ms)	701 (15)	709 (16)	706 (16)	-5	3
% error	28	31	28		

Note. F = food distractor; NF = non-food distractor; ND = no distractor; F-ND = food distractor cost; NF-ND = non-food distractor cost.

variables under high load. There was a significant effect of distractor under low load,  $F(1, 56) = 7.59, p = .008, N_p^2 = .12$ , but not under high load,  $F(1, 56) = .44, p = .511, N_p^2 = .01$ .

As there was a significant effect of distractor under low load, we conducted follow-up  $t$  tests. Under low load RTs were significantly slower when a food distractor was present,  $t(56) = 3.66, p = .001, d = .28$ , and when a nonfood distractor was present,  $t(56) = 5.49, p < .001, d = .33$ , compared with when no distractor was present. Unexpectedly, across all participants, under low load there was no evidence of attentional bias to food distractors: RT did not differ in the presence of food versus nonfood distractors,  $t(56) = .43, p = .672, d = .04$ .

**Error rates.** While RT is the primary measure of interest, a  $2 \times 3$  within subject ANOVA was applied to the equivalent percentage error data (error referring to a missed or incorrect keyboard response to the letter search task). There was a significant main effect of load,  $F(1, 56) = 83.13, p < .001, N_p^2 = .60$ , reflecting higher error rates under high load compared with low load. Neither the main effect of distractor nor the load by distractor interaction reached significance (all  $ps > .2$ ).

**Recognition accuracy for images.** A within subjects  $t$  test was used to compare the number of food and nonfood images recognized on the memory test. Despite no attentional bias to food images being observed, a significant memory bias was found: As can be seen (see Figure 3), the mean percentage recognition accuracy was greater for food images than nonfood images,  $t(56) = 2.43, p = .019, d = .45$ .

**Individual differences in food-related attention and memory.** We also examined whether individual differences in recognition accuracy of food items was related to the extent to which people were distracted by these stimuli during the visual search task. Increased memory for the distractor stimuli was not associated with an increased distractor cost for the corresponding stimuli for both food,  $r(55) = -.02, p = .437, 95\% \text{ CI} [-.28, .21]$ , and nonfood categories,  $r(55) = .16, p = .124, 95\% \text{ CI} [-.10, .35]$ . In addition, attentional bias for food stimuli was not correlated with memory bias for food,  $r(55) = -.03, p = .409, 95\% \text{ CI} [-.34, .22]$ . Therefore, the memory bias did not appear to be dependent on attention.

**Exploratory analysis of individual differences.** We also conducted a range of exploratory correlations to analyze individual differences in Experiment 1 due to the variety of measures used in

the literature. For the full set of correlations see Table S2 in the online supplemental material. Following the advice of Field (2012), Bonferroni corrections have not been applied, instead correlations have been reported with their bootstrapped confidence intervals.

Only one significant correlation was found between the effect of the presence of distracting images on performance on the visual search task and any of the questionnaire measures of eating and impulsivity: participants scoring highly on the TFEQ restraint scale were more distracted by food,  $r(55) = .29, p = .014, 95\% \text{ CI} [-.02, .51]$ , but not nonfood stimuli,  $r(55) = .16, p = .124, 95\% \text{ CI} [-.09, .42]$ , under low load, although the difference for food versus nonfood distraction (i.e., the attentional bias) did not reach significance,  $r(55) = .15, p = .136, 95\% \text{ CI} [-.16, .40]$ . In addition, none of the questionnaire measures correlated with the load modulation (distraction under low load—distraction under high load) of distraction by food images, all  $ps > .1$ .

On the other hand, recognition accuracy for food correlated with a set of measures relating to the tendency to overeat: higher trait TFEQ disinhibition,  $r(55) = .25, p = .033, 95\% \text{ CI} [-.08, .52]$ , and BMI,  $r(55) = .33, p = .006, 95\% \text{ CI} [-.15, .53]$ , positively predicted the number of food images recognized in the memory test, with self-rated hunger showing a similar but marginally significant relationship,  $r(55) = .21, p = .060, 95\% \text{ CI} [-.09, .48]$ . None of these measures were associated with recognition of nonfood images, all  $ps > .13$ . Unlike disinhibition and BMI, all  $ps > .11$ , self-rated hunger also correlated significantly with memory bias for food images (i.e., the degree of increased recognition accuracy for food vs. nonfood images),  $r(55) = .25, p = .031, 95\% \text{ CI} [-.06, .52]$ .

## Discussion

The key finding from Experiment 1 is that distraction by food stimuli was eliminated in the high load condition, thus supporting our prediction that food cues can be modulated by perceptual load in the same manner as nonfood stimuli. Therefore, contrary to studies which have suggested that positive stimuli may be immune to the effects of perceptual load (Gupta et al., 2016), food does not constitute a “special” load-resistant stimulus category. An unexpected finding of Experiment 1 was the absence of heightened

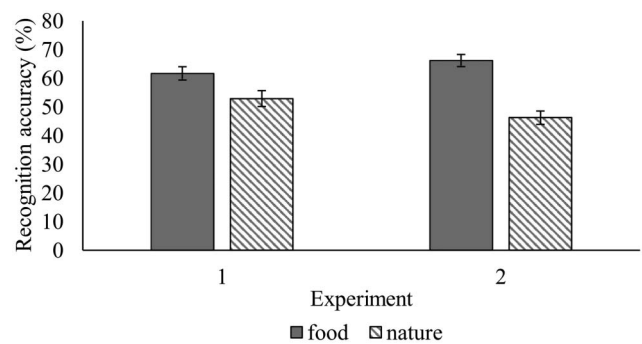


Figure 3. Mean recognition accuracy for food and nonfood images across Experiments 1 (left) and 2 (right). Experiments 1 and 2 were identical, with the exception of stimuli location (Experiment 1: periphery; Experiment 2: fixation).



distraction for food versus nonfood stimuli (i.e., attentional bias). As such, our results suggest cannot speak to the issue of how load would affect any such bias. Nevertheless, our findings are compatible with our proposed application of the load theory framework to cognitive processing of food, in terms of implying that the likelihood of external food cues catching our attention, potentially triggering overeating, is substantially greater in situations of low perceptual load.

Despite not finding an attentional bias, we did find a clear memory bias for food. This is the first demonstration, to our knowledge, of a general memory bias for food across individuals. The presence of this bias in the absence of any attentional bias, in addition to the lack of correlation between attentional and memory biases, is intriguing in suggesting that food cues may receive prioritized processing at some stage of memory independently of attention.

Regarding our exploratory analysis, perhaps the most striking result was the absence of any correlation between attentional bias and the trait measures that have been previously linked to eating behaviors. In the light of this finding, it appears unlikely that the lack of overall bias could be explained by the trait composition of our sample. While a small number of potentially intriguing correlations were observed, particularly with respect to memory, given the high risk of false positives due to overtesting we sought to determine whether these could be replicated in subsequent experiments.

## Experiment 2

Experiment 1 demonstrated that food stimuli are modulated by perceptual load to the same extent as nonfood stimuli, thereby providing initial support for our proposal that load theory can be applied to food-related cognition. We also found evidence of a memory bias which did not appear to be linked to attention. Unexpectedly, however, no attentional bias to food stimuli was observed in either load condition. We reasoned that one potential explanation for the lack of attentional bias could be our presentation of food stimuli in entirely task-irrelevant locations. As mentioned in our introduction, previous evidence for attentional food bias has almost exclusively been found using paradigms such as the dot probe, in which the distractor location must be attended (although see Cunningham & Egeth, 2018, for a recent exception published after we had collected this data). To explore this possibility, Experiment 2 repeated the methods of Experiment 1 using distractors presented at fixation. This also afforded an opportunity to internally replicate our findings regarding load modulation of food distractors and a memory bias to food images.

An additional aim of Experiment 2 was to test whether the correlations revealed in the exploratory analysis of Experiment 1 would replicate. In particular we wanted to test whether significant relationships would be found, as in Experiment 1, between memory of food and a cluster of traits linked to overeating: disinhibition, hunger, BMI.

## Method

**Participants.** One-hundred and two female participants were recruited, who were aged between 18 and 35 years ( $M = 21.09$ ,  $SD = 3.26$ ). All other participant details were identical to Exper-

iment 1. For Experiment 2 and 3 we increased the sample size to 100 (two extra participants were recruited due to scheduling issues) to detect smaller correlations. According to G\*Power, this sample size allowed us to detect a correlation of .25 with 80% power (Faul et al., 2007).

**Stimuli and procedure.** All stimuli and procedure were identical to Experiment 1, except for the distractor stimuli location and size. All distractor stimuli were presented at fixation, at the center of the letter circle. Due to better retinal acuity at central locations, the distractor images were reduced to ensure their cortical representation was equivalent to those in Experiment 1. We used the cortical magnification equation provided by Rousselet, Husk, Bennett, and Sekuler (2005) to obtain a scaling factor of 2.43. After using the scaling factor to reduce the size of distractor stimuli, they subtended 1.4° to 2° vertically by 1.3° to 2° horizontally.

## Results

**Reaction times.** As in Experiment 1, to test the primary hypothesis that load would modulate distraction by food stimuli, RTs (correct responses only) were entered into a  $2 \times 3$  within-subject ANOVA, with the factors of load (low, high) and distractor type (food, nonfood, absent). Table 2 presents mean RTs, accuracy, and distractor costs across different conditions.

The main effects of load, distractor, and the Load  $\times$  Distractor interaction were replicated from Experiment 1. The Load  $\times$  Distractor type ANOVA showed a significant main effect of load,  $F(1, 101) = 587.99$ ,  $p < .001$ ,  $N_p^2 = .85$ : RTs were longer in the high load than in the low load conditions, confirming that the load manipulation increased the task difficulty. There was also a significant main effect of distractor type,  $F(2, 202) = 5.10$ ,  $p = .007$ ,  $N_p^2 = .05$ : RTs were slower for both food and nonfood distractor present trials compared to no distractor trials. Finally, there was a significant Load  $\times$  Distractor interaction,  $F(1.71, 173.07) = 24.00$ ,  $p < .001$ ,  $N_p^2 = .19$ . Greenhouse-Geisser correction was applied as Mauchly's test suggested sphericity was violated for this interaction,  $\chi^2(2) = 18.29$ ,  $p < .001$ .

As in Experiment 1, we investigated the significant interaction with planned contrasts on distractor type under each level of load. Under low load there was a significant effect of distractor,  $F(1, 101) = 33.27$ ,  $p < .001$ ,  $N_p^2 = .25$ , but not under high load,  $F(1, 101) = 1.86$ ,  $p = .175$ ,  $N_p^2 = .02$ . This suggests that high load eliminated distractor interference.

Table 2

*Mean RTs (SE in Parentheses) and Percentage Accuracy Rates Across Different Distractor Conditions Under Low and High Load in Experiment 2*

Response type & condition	Distractor condition			Distractor costs	
	F	NF	ND	F-ND	NF-ND
Low load					
RT (ms)	560 (8)	563 (8)	528 (7)	31	35
% error	12	13	10		
High load					
RT (ms)	785 (12)	781 (12)	794 (12)	-10	-14
% error	26	27	22		

*Note.* F = food distractor; NF = non-food distractor; ND = no distractor; F-ND = food distractor cost; NF-ND = non-food distractor cost.

Follow-up *t* tests suggest under low load RT's were significantly slower both when a food distractor was present,  $t(101) = 8.38, p < .001, d = .40$ , and when a nonfood distractor was present,  $t(101) = 9.70, p < .001, d = .46$ , versus the no distractor baseline. However, critically, as in our previous experiment there was no significant difference on RT between food and nonfood distractors,  $t(101) = .84, p = .401, d = .04$ . Hence, even when presented at fixation food distractors did not appear to differentially capture attention.

**Error rates.** A  $2 \times 3$  within subject ANOVA was applied to the equivalent error data. There was a significant main effect of load,  $F(1, 101) = 198.94, p < .001, N_p^2 = .66$ , again showing higher error rates under high compared to low load. Unlike Experiment 1, there was also a significant main effect of distractor,  $F(1.71, 172.25) = 14.89, p < .001, N_p^2 = .13$ , reflecting higher error rates on both food and control distractor present trials compared with distractor absent trials. Greenhouse-Geisser was applied due to violated sphericity  $\chi^2(2) = 18.96, p < .001$ . The interaction was not significant  $p > .2$ .

**Recognition accuracy for images.** Mean number of images recognized are presented in Figure 3. As in Experiment 1, a within subjects *t* test showed that participants recognized significantly more food images than nonfood images,  $t(101) = 7.50, p < .001, d = .89$ . This finding suggests participants displayed a memory bias toward food stimuli.

**Individual differences in food-related attention and memory.** Increased recognition accuracy for the distractor stimuli was not associated with an increased distractor cost for the corresponding stimulus for both food,  $r(100) = -.05, p = .309, 95\% \text{ CI } [-.22, .11]$ , and nonfood categories,  $r(100) = .15, p = .068, 95\% \text{ CI } [-.04, .33]$ . In addition, the correlation between attentional and memory bias for food stimuli was not significant,  $r(100) = -.14, p = .078, 95\% \text{ CI } [-.31, .03]$ . This is in line with the null findings from Experiment 1 and does not support any link between attention and memory biases in this context.

**The role of individual differences.** The full set of correlations between attention, memory, and individual differences are presented in Table S3 of the online supplementary materials. The correlations previously observed between recognition accuracy of food stimuli and disinhibition, hunger, and BMI were replicated in Experiment 2: disinhibition,  $r(100) = .18, p = .036, 95\% \text{ CI } [-.02, .35]$ ; hunger,  $r(100) = .20, p = .023, 95\% \text{ CI } [-.01, .40]$ ; and BMI,  $r(100) = .24, p = .008, 95\% \text{ CI } [.06, .41]$ . Specifically, all three measures significantly and positively predicted the number of food images recognized in the memory test, but not the number of nonfood images recognized, all  $ps > .17$ . In Experiment 1, hunger was also associated with a memory bias for food, but this correlation did not reach significance in Experiment 2,  $r(100) = .11, p = .127, 95\% \text{ CI } [-.08, .30]$ .

The exploratory finding of a correlation between restraint and food-related distraction under low load did not replicate in Experiment 2,  $r(100) = .01, p = .48, 95\% \text{ CI } [-.21, .21]$ , suggesting that it may have been a false positive.

## Discussion

Experiment 2 replicated our key finding that the processing of food cues can be modulated by perceptual load in the same manner as nonfood stimuli. Indeed, it was striking that perceptual load

completely eliminated any interference from food and nonfood distractors alike, even when these were presented at fixation. We also replicated the memory bias for food across participants, as well as our exploratory finding of enhanced memory for food among individuals with high levels of food disinhibition, hunger, and BMI. However, as in Experiment 1, memory for food did not appear related to any attention measure.

Despite our presentation of the distractors at fixation, no attentional bias for food stimuli was observed—rather, food and nonfood stimuli were equally distracting. In both Experiments 1 and 2 we used natural stimuli (flowers and leaves) as the nonfood control category, they were matched to the food stimuli in both valence and arousal. We chose a positively valenced control category so that any potential “special” attention grabbing properties of food could be attributed specifically to food and not to just positive stimuli in general. Previous attentional bias research, while controlling for low level visual differences, does not usually control for valence and arousal differences between their food and control stimulus sets. The lack of attentional bias in Experiments 1 and 2 might therefore be explained by our choice of control stimuli. For this reason, our final experiment used a neutral control category more consistent with prior literature; we chose office equipment as they have been frequently used as a control category in previous studies investigating cognitive processing (Hume, Howells, Rauch, Kroff, & Lambert, 2015; Nijs, Franken, & Muris, 2008; Nijs et al., 2010; Svaldi et al., 2015; Velázquez-Martínez, Toscano-Zapién, & Velázquez-López, 2013).

Using office equipment as distractors also allowed us to address an issue relating to the food memory bias revealed in Experiments 1 and 2. Our food and nonfood distractor stimuli were matched on several variables (valence, arousal, brightness, contrast, and complexity) and were selected to be visually distinctive from other distractors in the same condition (e.g., the flower stimuli consisted of a pink, yellow, and a white flower). However, the food category consisted of six nameable stimuli, whereas the nonfood category consisted of only two. It is not clear what effect this might have on memory. On one hand it could be argued that the ability to name all six food stimuli made them more distinctive. On the other hand, as the memory test involved identifying the distractor images among other items from same category (e.g., a doughnut among other doughnuts), the use of multiple exemplars from the same category might have highlighted within category visual differences and hence facilitated memory for the nonfood images. In order to rule out any potential influence of namability, the office stimuli chosen for Experiment 3 were distinct items that could be easily named.

## Experiment 3

Experiments 1 and 2 provide strong evidence to suggest that perceptual load can modulate the extent to which food cues are processed, to the extent that they do not produce RT interference even when directly fixated. In this respect, the effects of perceptual load on food cues were similar to those observed for nonfood cues. This evidence is compatible with our application of a load theory framework to food-related attentional processing. In our previous experiments, as the food images were presented in both load conditions, it was not possible to test for perceptual load effects on memory (this design decision was taken in order to remove the



need for between-subjects counterbalancing that might reduce sensitivity to find individual differences). To test whether the effects of perceptual load on food-related cognition also extend to memory, Experiment 3 repeated the paradigm of Experiment 2 with the change that different images were presented under low and high perceptual load. This also afforded the opportunity to test whether the enhanced food-related memory linked to food disinhibition, hunger, and BMI, as observed across both Experiments 1 and 2, would be found in both load conditions. In addition, to correct for the possibility that our failure to detect food-related attentional biases in prior experiments was due to our use of affectively matched nonfood distractors (flowers and leaves), these were replaced with neutral office stimuli. This change in stimulus category also allowed us to generalize the food memory bias beyond the specific nonfood stimulus set used in Experiments 1 and 2.

## Method

**Participants.** One-hundred female participants were recruited, who were aged between 18 and 35 years ( $M = 19.48$ ,  $SD = .17$ ). All other details were the same as in Experiment 1 and 2. One participant was excluded from the analysis due to incomplete data.

**Stimuli and procedure.** The stimuli and procedure were identical to Experiment 2, with the following exceptions. To correct for the possibility that the nonfood distractors were too pleasant as a control category, they were changed to office stimuli (e.g., stapler, files, and calculator). Twelve office stimuli and an additional six food stimuli (combined with the original six food stimuli used in Experiments 1 and 2) were selected from the FoodPics database. Images were matched on the key visual features of brightness, contrast, and familiarity (all  $ps > .110$ , see Table S1 for means). Food images were rated as significantly more positive in valence and higher in arousal than office images, as we wanted to maximize the possibility of observing attentional bias.

In order to test for load effects on memory, different distractor sets were presented in low and high load blocks. For example, Food Distractors 1–6 and Nonfood Distractors 7–12 were presented in low load blocks; Food Distractors 13–18 and Nonfood Distractors 19–24 were presented in high load blocks. We ran a pilot study ( $N = 12$ ) to obtain individual distractor costs for each stimulus and create sets that were equally distracting. In addition, distractor sets were counterbalanced between subjects so that each distractor image was equally represented in the high and low load conditions. Participants in the two counterbalancing groups did not differ in terms of disinhibition, hunger, or BMI (all  $ps > .47$ ).

The extra distractor images were added to the memory test; no other changes to the stimuli were made. For practical reasons we changed to online rather than in person data collection. Experiment 3 was run as an online experiment using *Inquisit 5* (2016) software. Several changes to the task and procedure were made to adapt the experiment for online use. First, as lighting and screen brightness could not be controlled for, the screen background was changed to gray and the letter stimuli changed to black. This was because the gray screen was less susceptible to glare and the black letter stimuli less affected by brightness.

Second, the size and locations were kept constant across different screens by using a calibration procedure. Participants were

required to change the length of a line on the screen to match the length of a standard sized bank card. This was then used to calibrate the pixels to millimeter ratio on that screen and generate stimuli in the same sizes and locations as in Experiment 2.

Finally, to ensure participants had understood the instructions without the experimenter being present, they had to correctly answer an example trial to show their understanding. The number of practice trials was increased to 24 under both levels of load and they had to achieve 60% accuracy under both low and high load. Any participants who attempted the practice blocks more than five times were not allowed to complete the rest of the experiment.

## Results

**Reaction times.** The effect of load on distraction by food stimuli was tested using an ANOVA as in Experiments 1 and 2. RTs (correct responses only) were entered into a  $2 \times 3$  within subject ANOVA, with the factors of load (low, high) and distractor type (food, office, absent). Table 3 presents mean RTs, accuracy, and distractor costs across different conditions.

The main effects of load, distractor, and the Load  $\times$  Distractor interaction were replicated from the previous two experiments. The Load  $\times$  Distractor type ANOVA showed a significant main effect of load,  $F(1, 98) = 359.66$ ,  $p < .001$ ,  $N_p^2 = .79$ . RTs were longer in the high load than in the low load conditions, again confirming that the load manipulation was effective in increasing the task difficulty. There was a significant main effect of distractor type,  $F(1.66, 162.88) = 5.28$ ,  $p = .009$ ,  $N_p^2 = .05$ , with Greenhouse-Geisser correction applied as Mauchly's test suggests sphericity was violated,  $\chi^2(2) = 22.05$ ,  $p < .001$ . The interaction between Load  $\times$  Distractor was also significant,  $F(1.81, 176.94) = 17.76$ ,  $p < .001$ ,  $N_p^2 = .15$ , Greenhouse-Geisser correction applied as Mauchly's test suggests sphericity was violated for the interaction,  $\chi^2(2) = 11.06$ ,  $p = .004$ .

Planned contrasts were conducted on distractor costs under low and high load, to investigate the significant interaction. Under low load there was a significant effect of distractor,  $F(1, 98) = 14.54$ ,  $p < .001$ ,  $N_p^2 = .13$ , but not under high load,  $F(1, 98) = 1.69$ ,  $p = .197$ ,  $N_p^2 = .02$ . This once again replicates the finding that distractor interference was eliminated by high load.

Follow-up  $t$  tests suggest that under low load RT's were significantly slowed when a food distractor was present,  $t(98) = 9.06$ ,

Table 3  
Mean RTs (*SE* in Parentheses) and Percentage Accuracy Rates Across Different Distractor Conditions Under Low and High Load in Experiment 3

Response type & condition	Distractor condition			Distractor costs	
	F	NF	ND	F-ND	NF-ND
Low load					
RT (ms)	532 (6)	534 (7)	501 (5)	31	33
% error	14	14	12		
High load					
RT (ms)	704 (14)	699 (12)	711 (13)	−7	−12
% error	28	30	25		

Note. F = food distractor; NF = non-food distractor; ND = no distractor; F-ND = food distractor cost; NF-ND = non-food distractor cost.

$p < .001$ ,  $d = .54$ , and when a nonfood distractor was present,  $t(98) = 7.44$ ,  $p < .001$ ,  $d = .55$ . However, there was no significant difference on RT between food and nonfood distractors,  $t(98) = .35$ ,  $p = .730$ ,  $d = .03$ . Hence, there is no evidence for attentional bias even after changing the nonfood category to neutral office stimuli.

As our final experiment again found no evidence of attentional bias, we conducted Bayesian analyses in order to establish the extent to which the data provided evidence for the null hypotheses. We calculated Bayes factors for nonsignificant results important to our interpretation: the difference between food and nonfood distraction under low load; and both food and nonfood distraction under high load. Using the benchmarks provided by Dienes (2014), a Bayes factor of less than a third is evidence for the null hypothesis, more than three is evidence for the alternative hypothesis and any value in between reflects insensitivity. A half normal distribution was used, as all predictions were directional. Bayesian analyses were conducted using the Dienes (2008) online Bayes calculator.

To calculate a Bayes factor (B) for the difference between food and nonfood distractor RT under low load (our measure of food-related attentional bias), a prior of 10.5 was obtained from averaging previous research that found a significant food related RT bias across participants (Ahern et al., 2010; Deluchi, Costa, Friedman, Gonçalves, & Bizarro, 2017; Kakoschke, Kemps, & Tigge-mann, 2015; Werthmann, Jansen, & Roefs, 2016). The resulting Bayes factors were: Experiment 1,  $B = .43$ ; Experiment 2,  $B = .25$ ; Experiment 3,  $B = .38$ . Therefore, in Experiments 1 and 3, the Bayes factors narrowly missed the .3 threshold for sensitivity. In Experiment 2, we obtained a sensitive Bayes factor, suggesting that food did not preferentially capture attention in this experiment.

To calculate the Bayes factors for the nonsignificant effect of distraction by food and nonfood stimuli under high load in Experiment 1, a prior of 60 was used from Forster and Lavie's (2008) previous research. As we obtained significant effects of distraction by food and nonfood stimuli in Experiment 1, we were able to use these as priors for the Bayesian analyses in Experiment 2. It was preferable to use priors from Experiment 1 over previous perceptual load experiments as Experiment 1 specifically tested the research questions of interest in an almost identical design to Experiment 2, therefore, the priors were more informative. Furthermore, as the distractor effects were smaller than those from Forster and Lavie's (2008) study, using these as priors gave a more conservative estimate of sensitivity. To calculate the Bayes factors for the nonsignificant effect of distraction by food and nonfood stimuli under high load in Experiment 2, priors of 17 and 20 (respectively) were used from Experiment 1. Lastly, in Experiment 3, a prior of 31 was used for food, and a prior of 35 was used for nonfood from Experiment 2.

Bayes factors for distraction by food and nonfood under high load are reported in their respective order (i.e., food then nonfood): Experiment 1,  $B = .05$  and  $B = .15$ ; Experiment 2,  $B = .12$  and  $B = .11$ ; Experiment 3,  $B = .08$  and  $B = .07$ . Therefore, Bayesian analyses suggested a sensitive null effect of distraction from both food and nonfood stimuli under high load across all three experiments.

**Error rates.** There was a significant main effect of load,  $F(1, 98) = 213.19$ ,  $p < .001$ ,  $N_p^2 = .69$ , error rates were higher under high load than low load. There was also a significant main effect

of distractor,  $F(1.54, 150.97) = 10.36$ ,  $p < .001$ ,  $N_p^2 = .10$ , again this reflected slightly higher error rates on food and control distractor present trials compared with distractor absent, Greenhouse-Geisser correction was used,  $\chi^2(2) = 34.36$ ,  $p < .001$ . Finally, there was a nonsignificant interaction,  $p > .3$ .

**Recognition accuracy for images.** The mean percentage of food and nonfood images recognized in each load condition are presented in Figure 4. To test the effect of load on memory for food and nonfood images, recognition accuracy rates were entered into a within subjects  $2 \times 2$  ANOVA, with the factors of load (low, high) and image type (food, office).

The ANOVA revealed a main effect of load,  $F(1, 98) = 5.29$ ,  $p = .024$ ,  $N_p^2 = .05$ . Recognition accuracy was higher for images presented under low load than high load. In addition, there was a highly significant main effect of distractor,  $F(1, 98) = 19.30$ ,  $p < .001$ ,  $N_p^2 = .17$ . As in previous experiments, recognition accuracy was higher for food images than for nonfood images. There was a nonsignificant Load  $\times$  Memory Stimulus interaction,  $F(1, 98) = .56$ ,  $p = .455$ ,  $N_p^2 = .01$ , implying a similar food memory bias regardless of load. To confirm the presence of a food memory bias under both levels of load, follow-up within subject  $t$  tests were conducted comparing the difference in recognition accuracy between food and nonfood images under low and then high load. The  $t$  tests showed that participants recognized significantly more food images than nonfood images under both low load,  $t(98) = 3.57$ ,  $p = .001$ ,  $d = .42$ , and high load,  $t(98) = 2.84$ ,  $p = .005$ ,  $d = .31$ .

**Individual differences in food-related attention and memory.** Correlations between food and nonfood distractor costs and their corresponding memory recognition accuracy, split by load, are presented in Table 4. As in Experiments 1 and 2, the correlations between attention and memory were not significant, meaning that increased distraction by food and nonfood stimuli was not associated with better recognition accuracy for those images. Attention and memory biases for food were not associated under low load, as in Experiment 1 and 2. However, under high load, a positive correlation between attention and memory bias narrowly missed significance,  $p = .054$ . The extent to which load modulated distraction by food images was unrelated to the extent to which it modulated recognition accuracy of those food images,  $r(98) = .11$ ,  $p = .132$ , 95% CI  $[-.08, .30]$ .

**The role of individual differences.** The full set of correlations between attention, memory, and individual difference traits

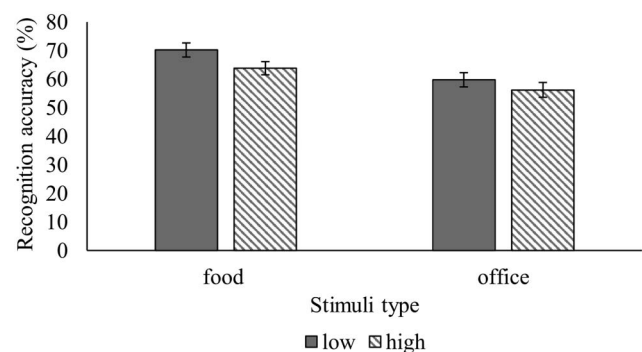


Figure 4. Mean recognition accuracy of food and office images presented under low and high perceptual load.

Table 4

One Tailed Pearson *R* Correlations and 95% Bootstrapped Confidence Intervals Between Attention and Memory Measures in Experiment 3

Recognition accuracy	Distractor cost (ms)				Bias scores (food–nonfood)	
	Low load		High load		Low load attentional bias	High load attentional bias
	Food	Office	Food	Office		
Low load food recognition accuracy	.03 [–.18, .25]	—	—	—	—	—
Low load nonfood recognition accuracy	—	0.16 [–.02, .32]	—	—	—	—
High load food recognition accuracy	—	—	.02 [–.16, .19]	—	—	—
High load nonfood recognition accuracy	—	—	—	.01 [–.18, .20]	—	—
Low load memory bias	—	—	—	—	.02 [–.16, .21]	—
High load memory bias	—	—	—	—	—	.16 [–.08, .38]

Note. Memory bias = number of food images recognized – number of nonfood images recognized.

are presented in Table S4 and S5 of the online supplementary materials. As in both of our previous experiments, disinhibition positively predicted the number of food images recognized in the memory test—however, this relationship was confined to the high load condition,  $r(97) = .18$ ,  $p = .034$ , 95% CI [.01, .35]. There was no relationship between disinhibition and recognition accuracy under low load,  $r(97) = .06$ ,  $p = .268$ , 95% CI [–.15, .25]. Disinhibition was, as in previous experiments, not associated with the number of nonfood images recognized under low,  $r(97) = .05$ ,  $p = .325$ , 95% CI [–.16, .25], or high load,  $r(97) = .09$ ,  $p = .183$ , 95% CI [–.11, .29]. Hunger again correlated with recognition accuracy of food images, both under low,  $r(97) = .25$ ,  $p = .006$ , 95% CI [.03, .46], and high load,  $r(97) = .22$ ,  $p = .016$ , 95% CI [.02, .42]. However, in contrast to previous experiments, hunger also predicted improved recognition accuracy of the nonfood images under both low,  $r(97) = .18$ ,  $p = .021$ , 95% CI [–.01, .36], and high load,  $r(97) = .20$ ,  $p = .037$ , 95% CI [–.03, .42]. There was no relationship between BMI and recognition accuracy of food images presented under low load,  $r(97) = .03$ ,  $p = .379$ , 95% CI [–.24, .17]; however, for food images presented under high load there was a trend in keeping with previous experiments, but this did not reach significance,  $r(97) = .14$ ,  $p = .087$ , 95% CI [–.03, .29]. There was no evidence of correlations between BMI and recognition accuracy of nonfood images under low,  $r(97) = .00$ ,  $p = .482$ , 95% CI [–.16, .15], or high load,  $r(97) = .02$ ,  $p = .409$ , 95% CI [–.14, .18].

Our finding linking hunger to enhanced memory for food replicates two prior findings (Morris & Dolan, 2001; Talmi et al., 2013). We further examined whether hunger might play an underlying role in the observed new correlations between recognition accuracy and both disinhibition and BMI, which were observed in each of our three experiments, with the exception of BMI and recognition accuracy in Experiment 3. This did not appear to be the case. Neither disinhibition nor BMI correlated with hunger in any of the three experiments, all  $ps > .177$ . Furthermore, correlations between disinhibition, BMI, and recognition accuracy of food stimuli remained significant after controlling for hunger, across all experiments. Experiment 1: disinhibition,  $r(55) = .23$ ,  $p = .044$ , 95% CI [–.054, .499], and BMI,  $r(55) = .31$ ,  $p = .009$ , 95% CI [.126, .515]. Experiment 2: disinhibition,  $r(100) = .18$ ,  $p = .036$ , 95% CI [–.03, .38], and BMI,  $r(100) = .25$ ,  $p = .005$ , 95% CI [–.09, .41]. Experiment 3: disinhibition and recognition accuracy

for food stimuli under high load only,  $r(97) = .18$ ,  $p = .036$ , 95% CI [–.01, .36].

## Discussion

Experiment 3 once again replicated our key finding that perceptual load eliminates distraction from both food and nonfood stimuli alike. As in our previous experiments, but in contrast to prior evidence, food stimuli did not cause any distraction above and beyond nonfood stimuli (i.e., attentional bias). Most importantly, Experiment 3 also demonstrated that the effects of perceptual load on food-related cognition extend to memory: Recognition accuracy for both food and nonfood images was reduced under high perceptual load. To our knowledge this is the first experiment to simultaneously examine load effects on both distraction and recognition memory for the same stimuli. An intriguing feature of our results is that despite distractor interference being eliminated in the high load condition, participants were able to recognize the distractor images used in this condition with accuracy well above chance.<sup>1</sup> This implies that processing of the images was attenuated rather than entirely eliminated in the high load condition (cf. Treisman, 1969). This attenuated processing appears to have been sufficient to allow above chance recognition of the distractor images, although as we did not include confidence ratings it is unclear whether this memory performance reflected explicit recognition as opposed to more implicit familiarity judgments. On the other hand, the attenuated processing was not of sufficient strength to cause distractor interference.

Finally, Experiment 3 replicated the previous experiments' finding of a memory bias, which was observed here in both load conditions, as well as the relationship of disinhibition and hunger to food recognition accuracy. As in Experiments 1 and 2, disinhibition was still correlated with food recognition accuracy even when controlling for hunger. Overall the pattern of results was very similar to previous experiments despite the change to online testing—to our knowledge this is the first online replication of perceptual load effects on any form of distractor interference. The one way in which the online presentation appeared to reduce sensitivity was with respect to BMI, which was measured with a

<sup>1</sup> We thank Juan Lupiáñez for bringing this important point to our attention.



stadiometer with an integrated height measure in previous experiments but based on self-report here; this change appears likely to explain the reduction in the strength of the correlation between BMI and food recognition accuracy.

### General Discussion

Across our three highly powered experiments, our findings establish for the first time that two key aspects of cognitive processing of food stimuli—attention and memory—can be powerfully modulated by perceptual load. The ability of food images to cause distractor interference was consistently eliminated under high load, and recognition accuracy for food images was also reduced in the high load condition. Indeed, our results imply that food stimuli are subject to perceptual load modulation to the same degree as nonfood stimuli: Each of our experiments revealed a similar magnitude of load effects for food versus nonfood.

Prior research has demonstrated that although perceptual load modulates the overwhelming majority of stimuli, a small number of “special” stimulus categories, such as faces, have been highlighted as having immunity to perceptual load effects (e.g., Murphy, Groeger, & Greene, 2016, for review). Interestingly, one prior study by Gupta, Hur, and Lavie (2016), found that several classes of rewarding stimuli (erotic photographs, happy faces, and stimuli that had been experimentally associated with financial reward) were unaffected by perceptual load. Our research clarifies that, despite their association with reward, food cues do not hold any special attentional status with respect to perceptual load modulation.

Our findings hence support our proposal that load theory can be usefully applied as a framework from which to understand the role of attention and memory in eating behaviors, accommodating prior findings with respect to both cognitive bias research and inattentive eating. To recap, under low perceptual load, attentional capacity is available to process irrelevant stimuli, with the result that irrelevant food cues may attract attention, potentially triggering food cravings (and, ultimately, consumption). However, under high perceptual load, attentional capacity is fully exhausted by the task, meaning that irrelevant food cues cannot attract attention.

Our results demonstrate that high perceptual load not only reduces attentional capture by food cues during the task, but also reduces subsequent memory for these food cues. While the direct link between food memory bias and consumption has not yet been tested, the pathway between attention to food cues and later consumption necessarily depends on memory processes (May et al., 2012; Werthmann et al., 2014). As such, our findings suggest that engaging in high perceptual load tasks could not only reduce temptation from external food cues during the task but may also reduce cravings associated with these cues even after the task is completed.

One useful direction for future research would be to directly test the effect of perceptual load on cravings. In keeping with our proposed application of load theory, prior research has demonstrated that cravings can be reduced by real world tasks which are high in perceptual load. For example, the visually demanding game Tetris has been shown to reduce craving for food (Skorka-Brown, Andrade, & May, 2014). However, as these prior studies compare to a no task baseline, rather than using a controlled manipulation of perceptual load, it remains to be clarified whether

these prior demonstrations can be attributed to perceptual load effects as opposed to other task demands (e.g., motor demands).

We have highlighted above some potentially beneficial effects of perceptual load in preventing external food cues from producing unwanted cravings. On the other hand, our suggested application of load theory predicts that high perceptual load tasks may have a negative (in contexts where increased consumption is undesirable to the individual) impact once eating commences. In this context, perceptual load would theoretically reduce processing of the food being consumed, with the potential consequences of reducing awareness of important satiety signals and disrupting memory of intake.

Such effects would depend on the perceptual load effects established here applying not only to visual food cues, as in the present study, but to olfactory and gustatory food cues and interoceptive satiety cues. Two sources of existing evidence support this possibility. First, the effects of perceptual load (typically operationalized as visual load) have already been established to extend cross-modally to the auditory, olfactory, and tactile domains (Dalton, Lavie, & Spence, 2009; Forster & Spence, 2018; Macdonald & Lavie, 2011), as well as to internally generated stimuli (task-unrelated thoughts, Forster & Lavie, 2009). Second, prior demonstrations of inattentive eating effects (in terms of both immediate effects and subsequent memory-mediated effects on intake) have tended to use tasks that are high in perceptual load, such as TV or computer games (Higgs, 2015; Robinson et al., 2013). An important next step in applying load theory to food-related cognition would be to integrate controlled manipulations of perceptual load, as used in the present study, into investigations of inattentive eating and memory. Such work is currently being conducted in our lab.

Our proposed application of load theory to food-related cognition has focused on the role of perceptual load. However, load theory also discusses another type of load: load on cognitive control processes such as working memory (WM). Contrary to the effect of perceptual load, high WM load in a task is argued to increase vulnerability to distraction by taxing the executive resources necessary for efficient distractor rejection (Lavie, 2005, 2010). In contrast to the effect of perceptual load, high working memory load should therefore increase unwanted distraction by irrelevant food stimuli. This carries the real world implication that while perceptual load may help people to avoid attention to tempting food cues, high levels of WM load might be especially problematic for people attempting to ignore food (i.e., if they are on a diet) and may counterproductively increase the risk of noticing the food stimulus.

An exciting recent line of research by van Dillen and colleagues might initially seem to conflict with these latter predictions of load theory. Van Dillen, Papies, and Hofmann (2013), found reduced rather than increased attentional bias to food under high WM load. More recently, van Dillen and van Steenbergen (2018) demonstrated a reduced neural response to food images under high, versus low, WM load. These results are compelling in suggesting that higher level processes also play a key role in processing the rewarding value of food stimuli, yet might initially seem at odds with the predictions of load theory regarding WM load. However, it is important to note that neither of these studies presented food cues as irrelevant distractors. Rather, the food cues appeared as targets requiring some task response, meaning that not only was it

necessary to attend to the food cues in order to perform the task (e.g., to identify their location or classify them as edible or nonedible), but doing so quickly would in fact benefit, rather than disrupt, performance. As there was no reason for participants to recruit executive resources to suppress attention to the food, this study does not directly test the predictions of load theory regarding WM load, and differs somewhat from real world situations in which people may wish to ignore entirely irrelevant food cues as they go about their daily tasks. Establishing the effects of WM load on the ability to ignore entirely irrelevant food cues is hence an important direction for future research. In particular, clarifying whether WM load may in some cases increase attention to food will enable more accurate recommendations regarding task-based management of eating behavior.

Moving away from load theory, an unexpected yet striking result of our study was the lack of any clear evidence for biased attention toward food versus nonfood stimuli, either across participants or in relation to any of a range of traits previously implicated in food-related cognition. In all three experiments food images captured attention to the same extent as nonfood images despite being high-fat, high-sugar, rated highly on VAS measures of palatability and craving in the FoodPics database (Blechert et al., 2014). Attentional bias was not observed even in Experiment 3 where we used office-based control stimuli pre-rated to be less positive and lower in arousal than the food stimuli. This finding conflicts with some previous studies that have found attentional bias for food (Werthmann et al., 2015), including one study using a similar task and food stimuli from the same database (Cunningham & Egeth, 2018). On the other hand, as noted in our introduction, there is inconsistency in the existing evidence for attentional bias in regard to individual differences. In addition, several reviews have highlighted contradictory study evidence for the presence of a general attentional bias (for reviews see Doolan et al., 2015; Nijs & Franken, 2012; Werthmann et al., 2015). Taking these prior inconsistencies together with the complete absence of any bias effects across our three experiments, we speculate that attentional bias for food cues may be either less robust than sometimes assumed, or dependent upon some hidden moderator. Understanding of attentional bias, and in particular trait differences in food-related cognition, would benefit from future research including more internal replication and preregistered replication of existing findings.

The lack of attentional bias is all the more striking in the light of our finding of a consistent and robust memory bias for food, across all three experiments. In contrast to previous memory bias studies (Morris & Dolan, 2001; Soetens et al., 2014; Talmi et al., 2013), a general memory bias for food was found across individuals, with participants recognizing on average approximately 20% more food versus nonfood images across experiments. Across all three experiments, recognition accuracy for food was also consistently enhanced among individuals reporting high levels of hunger, as well as those high in trait tendency toward uncontrolled eating (disinhibition). Objectively measured BMI also significantly predicted food recognition accuracy in both Experiments 1 and 2 (with Experiment 3, which used the less reliable self-report measure of BMI, showing a similar trend).

The relation of hunger to food recognition accuracy replicates the prior findings of Morris and Dolan (2001) and Talmi et al. (2013). Interestingly, our novel findings of enhanced memory in

individuals high in disinhibition and BMI were not simply driven by hunger: Hunger was unrelated to disinhibition and BMI in all three experiments, and all correlations between disinhibition, BMI, and recognition accuracy of food images were maintained even when controlling for hunger. In other words, individuals with a high BMI or a tendency toward uncontrolled eating had improved memory for food regardless of their level of hunger. A promising direction for future research would be to clarify whether these intriguing individual differences relationships reflect a role of memory in conferring vulnerability to overeating, or conversely might reflect an effect of habitual overeating on memory (e.g., perhaps driven by enhanced familiarity or reward associations for the food stimuli).

Another key question for further research is at what stage the enhanced processing underlying the food memory bias occurred. For example, it could be that food stimuli receive enhanced processing during encoding, that food-related memories are more easily consolidated, or that food-related memories are more accessible to be retrieved. For now we note one clue: The fact that the bias itself (i.e., the difference between food vs. nonfood recognition accuracy, rather than recognition accuracy per se) did not appear to be modulated by perceptual load, along with the lack of correlation between any attention and memory biases, is clearly inconsistent with any view of memory biases as being simply a consequence of increased attention to the food cues. Rather, these biases appear to reflect an aspect of memory independent of attention.

Returning to our key aim of applying load theory to food-related cognition, it is important to note that regardless whether a bias was observed (as in the case of memory) or not (as in the case of attention), perceptual load nevertheless modulated cognitive processing of food and nonfood stimuli alike. Hence, the lack of attentional bias in our dataset does not undermine our key conclusions regarding the ability of perceptual load to modulate attention to food cues. Nevertheless, it should be noted that the magnitude of the food memory bias itself (i.e., difference in accuracy for food vs. nonfood) was not altered by load. Given this, it remains unclear how a food attentional bias, where observed, would be influenced by load. In cases where attentional effects are fully eliminated as in the present study, floor effects make any attentional bias appear unlikely. On the other hand, in cases where food-related attentional effects were reduced rather than eliminated, biased attention to food versus nonfood might still be observed, following the pattern seen in the memory biases. Future research should clarify this issue. For now we conclude that, critically, the impact of any such attentional biases would be substantially mitigated by the general load-related reduction in attention to food (as well as nonfood) stimuli. In other words, a chocolate bar stuffed vending machine is far less likely to catch our eye, potentially leading to temptation, in situations of high versus low load.

To summarize, across our three experiments we demonstrate that perceptual load modulates both attention (Experiments 1–3) and memory (Experiment 3) of food cues. In real-world terms, our findings imply that vulnerability to the multitude of food cues in our obesogenic environment (e.g., posters and billboards) would be greatest when attention is engaged in a perceptually simple task. More broadly, our findings provide initial support for the use of load theory as a framework for understanding food-related cognition. The unexpected lack of evidence for attentional bias and

consistent individual differences questions the generalizability of these biases. Our research also highlights the overlooked area of memory biases for food, which may prove to be an interesting avenue for further study, particularly the bidirectional relationship between attention and memory and the influence of individual differences.

### Context of the Research

This research was conducted as part of the PhD research of J.M., and represents the first step in an application of Lavie's load theory, drawn from the field of selective attention, to the field of eating behavior. The findings will be used to further inform a load theory framework of both food-related cognition and consumption. Several further articles are currently in preparation that build on the present research by testing load theory's predictions in relation to appetitive thoughts and consumption.

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