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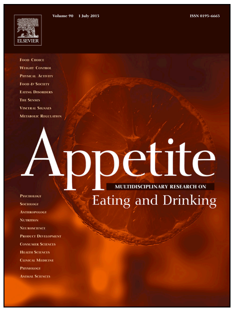

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Ingested but not perceived: response to satiety cues disrupted by perceptual load

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All data are available on the open science framework (osf.io/tvfpq/)

Response to satiety cues disrupted by perceptual load

Abstract

Selective attention research has shown that when perceptual demand is high, unattended sensory information is filtered out at early stages of processing. We investigated for the first time whether the sensory and nutrient cues associated with becoming full (satiety) would be filtered out in a similar manner. One-hundred and twenty participants consumed either a low-satiety (75kcal) or high-satiety (272kcal plus thicker texture) beverage, delivered via an intra-oral infusion device while participants simultaneously completed a task which was either low or high in perceptual demand. Among participants who performed the low perceptual load task, ingestion of the high-satiety beverage increased rated satiety and reduced consumption at a subsequent snack test. However, both effects were eliminated by the high perceptual load task. Therefore, the processing of satiety cues was dependent on the availability of attention, identifying a novel perceptual load mechanism of inattentive eating and supporting more recent cognitive models of appetite control.

Keywords: Attention, Perceptual load, Satiety, Food intake

1. Introduction

Satiation, referring to the process that causes cessation of intake, and satiety, the feeling of fullness after a meal that suppresses further intake, are key components of appetite control (Blundell & Tremblay, 1995). The satiety cascade has outlined a variety of processes involved in generating satiation and satiety, which have tended to be split into early cognitive and sensory influences, and later post-ingestive influences (Bellisle & Blundell, 2013; Blundell & Tremblay, 1995). More recently, stronger cognitive models of eating behaviour have suggested that satiety is partly cognitively constructed and dependent upon memory (Higgs et al., 2017). These models are supported by considerable evidence that reducing memory for a consumed food by interfering with attention at the time of initial consumption (e.g., by watching television or playing games) increases subsequent consumption (Higgs, 2015; Higgs & Woodward, 2009; Mittal, Stevenson, Oaten, & Miller, 2011; Oldham-Cooper, Hardman, Nicoll, Rogers, & Brunstrom, 2010; Robinson et al., 2013).

Several potential mechanisms have been suggested to explain the role of attention and memory in eating behaviour. For example, manipulations of attention have been argued to influence subsequent intake via changes in meal memory (Higgs & Spetter, 2018; Robinson, Kersbergen, & Higgs, 2014). In support of this claim, when food is consumed while distracted, subsequent memory ratings for vividness of the food and accuracy of which food items had been consumed were reduced (Higgs, 2015). Another potential explanation is that memory for recently consumed food increases attention to physiological appetite signals (e.g., hunger and fullness) and therefore allows the individual to adjust subsequent intake accordingly (Higgs, 2005).

However, in both potential explanations the attentional mechanism is implied—it is unknown to what extent the subsequent memory effects are due to lack of attention. In addition, other explanations such as mood cannot be ruled out, as paradigms most commonly compare television (which is known to influence intake via changes in mood, Yeomans & Coughlan, 2009) to a no task control condition (which could induce boredom). One study varied engagement with a computer task by offering a financial reward to the highest performing participant of the week (Higgs, Dolmans, Humphreys, & Rutters, 2015) and found that recall for the serial order of lunch items and memory vividness of the lunch was reduced and subsequent consumption was greater in the high compared to low engagement condition. These results are consistent with an attentional explanation (that greater attention was paid to the distraction task when a reward was offered), however, there is no direct evidence that this is the case.

Furthermore, part of the memory effect on satiety may be explained by factors that act only on post-ingestive aspects of satiety, rather than the processing of satiety information at the time of initial consumption. Brunstrom et al. (2012) used a refilling soup bowl paradigm to manipulate actual intake (300ml vs 500ml) without participant awareness (aware participants were removed) and perceived intake (300ml vs 500ml). Actual food consumption guided appetite ratings immediately after consumption (e.g., the larger portion reduced hunger), suggesting that nutrient-based satiety was controlling appetite despite lack of awareness of amount consumed. Memory for the perceived amount eaten only influenced satiety two hours after the initial consumption (the perceived larger portion reduced hunger and actual intake had no effect). Therefore, memory for amount consumed had a powerful effect on appetite, but only once nutrient-based satiety effects had worn off.

The current research will utilise Load Theory, a key theory from the selective attention literature, to more directly test the role of attention in satiety. Load Theory suggests that the extent to which task-irrelevant stimuli are processed is limited by the availability of attention, which is determined by whether the primary task leaves adequate spare perceptual capacity (Lavie, 2005, 2010). Increasing the perceptual demand in a task (e.g., searching for a friend in a crowded vs. an empty restaurant) exhausts perceptual capacity, resulting in irrelevant stimuli not receiving attentional processing. Crucially, this is a passive process carried out automatically by the perceptual system at an early stage of selection.

A large body of evidence has demonstrated the powerful effects of perceptual load in reducing task-irrelevant processing across a range of paradigms (for reviews see, Lavie, 2005, 2010; Murphy, Groeger, & Greene, 2016). The most widely used manipulation has been the visual search task, where participants search for a target letter among five small o's (low perceptual load) or five non-target letters (high perceptual load) while ignoring irrelevant stimuli (e.g., Forster & Lavie, 2008; Lavie, 1995). Typically, irrelevant stimuli cause distractor interference (measured by slower reaction times to the central task) under low perceptual load, but this is reduced or eliminated under high perceptual load. Importantly, this task isolates the effect of perceptual demand on attention while keeping other types of load constant (e.g., cognitive load, which has been shown to have the opposite effect on attentional processing, Lavie, Hirst, de Fockert, & Viding, 2004).

Further evidence has demonstrated that when attentional capacity is exhausted by a perceptually demanding task, processing of task-irrelevant stimuli is powerfully reduced from the earliest stages of perception (e.g., V1 for visual stimuli) onwards, with the result that higher level processing such as encoding into memory, and awareness, is substantially diminished and may even fail to occur (for review see, Lavie, 2005; 2010). Although such effects are most well-established with respect to visual stimuli, they have more recently been shown to extend across the senses to smell, hearing and touch (Dalton, Lavie, & Spence, 2009; Forster & Spence, 2018; Macdonald & Lavie, 2011).

In a recent paper (Morris, Yeomans & Forster, 2020), we proposed that a Perceptual Load Theory framework could accommodate multiple aspects of eating behaviour, from the response to external food cues, to the experience of appetitive thoughts, to distracted eating. Our initial work in support of this proposal has shown that high perceptual load in this task eliminates distraction by, and reduces memory for, external, highly palatable food stimuli (Morris, Yeomans & Forster, 2020) and reduces internal appetitive-related thoughts (Morris, Ngai, Yeomans & Forster, 2020). Potentially also consistent with this idea, research from the eating behaviour literature has suggested that both taste responsiveness (Duif et al., 2020a) and goal directed behaviour in order to obtain food (Duif et al., 2020b) were disrupted by a perceptually demanding rapid serial visual presentation task. The goal of this study was hence to further test the applicability of Load Theory to the eating behaviour literature. This was examined by testing whether occupying attention during and immediately after ingestion might similarly disrupt the brain’s processing of satiety signals, with the result of eliminating the effect of satiety on later appetite.

Growing evidence that eating while distracted by real-world tasks such as television can affect subsequent intake (Robinson et al., 2013) is initially consistent with this idea, although such findings could also reflect factors such as mood or memory for prior consumption. The current study set out to test a stronger cognitive model, using controlled manipulations of both attention and satiety, which suggests the generation of satiety is dependent on the consumer being able to attend to the satiety signals generated during and after ingestion. This model has particular relevance to intake of snack foods and beverages, where satiety signals may be relatively small and transient, and which have been implicated in overconsumption and a risk of obesity (e.g., Bellisle, 2014, although see Keast, Nicklas & O'Neil, 2010).

2. Methods

2.1. Participants

One hundred and twenty female participants aged between 18 – 35 years (*M* = 20.58, *SD* = 2.53) were recruited to take part in a study advertised as 'The effect of a smoothie drink on cognition'. This cover story was selected to reduce potential demand effects, in line with recommendations on the conduct of appetite studies with human participants (Robinson, Kersbergen, Brunstrom, & Field, 2014). The sample was restricted to female participants only because of the difficulty recruiting an equal number of men and women from a predominantly female cohort of students, and therefore we wanted to avoid potential gender-related intake differences in an uneven sample obscuring experimental effects (Mittal, Stevenson, Oaten, & Miller, 2011). Participants had normal or corrected to normal (e.g., with glasses) vision and were native English speakers or as fluent at both speaking and reading English as a native speaker. Participants were primarily University of Sussex students who received course credits or a nine-pound financial compensation.

The current experiment was closely based on previous research from the Sussex Ingestive Behaviour laboratory, which investigated the effect of energy content and sensory properties in a beverage on satiety (McCrickerd et al., 2014). We used G*Power to calculate our sample size based on effect sizes obtained by McCrickerd et al., (2014), which used the same preload manipulation as the current experiment, and Yeomans, McCrickerd, Brunstrom & Chambers (2014), which used the same between subjects design as the current experiment. Based on effect sizes of *d* = .72 (McCrickerd et al., 2014) and *d* = .65 (Yeomans et al., 2014) for the effect of a preload on appetite ratings, G*Power indicated that a sample size of 25 and 30 would be needed in each condition, respectively. Likewise, to detect the effects of the difference in preload energy on intake, effect sizes of d = .67 (McCrickerd et al., 2014) and d = .87 (Yeomans et al., 2014) indicated a sample size of 29 and 18 in each condition would be needed, again reported respectively. To ensure we could detect effects of preload on both appetite ratings and snack intake, we therefore used a sample of 30 participants in each condition.

The study was approved by the University of Sussex Sciences & Technology Cross-Schools Research Ethics Committee. All participants provided informed consent.

2.2. Design

A between subjects 2x2 design was used to assess the development of satiety (measured by changes in appetite ratings and consumption at a snack intake test) in response to a “preload” (here a beverage: low energy thin texture or high energy thick texture) consumed either while participants performed a low or high perceptual load task.

2.3. Test Beverage and Foods

All participants consumed a standard breakfast in the Sussex Ingestive Behaviour Laboratory, later followed by the test drink and an intake test disguised as a taste test. They received a 500 ml bottle of spring water (Sainsbury’s, UK) to drink in-between breakfast and the main test session. For breakfast, participants were given Crunchy Nut Cornflakes (Kelloggs, UK: 60 g), semi-skimmed milk (Sainsbury’s, UK: 160 g) and orange juice (Sainsbury’s, UK: 200 g), which provided 440 kcal in total.

The recipe for the two test drinks was developed in a previous study (Mccrickerd et al., 2014) using commercially available ingredients. The two test drinks which had the largest contrasting effect on appetite in the previous study (where attention was not manipulated) were used for the current study: a low energy thin texture drink (LE) and a high energy thick texture drink (HE). The thinner low energy drink generates a weak effect on satiety and the slightly thicker textured higher energy drink reliably generates stronger satiety. Previous research has shown that experienced satiety depends upon the combination of congruent sensory and physiological cues (Chambers, Ells & Yeomans, 2013; Yeomans & Chambers, 2011; Camps, Mars, De Graaf, & Smeets, 2016; McCrickerd, Tay, Tang & Forde, 2020), and therefore the thin LE vs. thick HE comparison maximised the potential difference in satiety response.

The drinks were prepared as a 297 g portion, each containing fresh mango, peach and papaya fruit juice (LE and HE = 100 g; Tropicana Products, Inc.), 0.1% fat fromage frais (LE = 55 g, HE = 30 g; Sainsbury's UK), water (LE = 130 g, HE = 100 g) and peach diluting drink (LE and HE = 11 g; 'Robinsons' from Britvic, UK). The HE version of the drink also contained maltodextrin (Cargill, UK: 55 g) and as a result one portion of the HE drink contained 272 kcal while the LE drink contained 75 kcal. Tara gum (Kalys Gastronomie, FR) was added to the HE drink to increase its viscosity (thin LE = 0.2 g; thick HE = 1 g). Aspartame was used in the LE drink to match sweetness to the HE drink (Ajinomoto, Japan: 0.03 g).

Participants also consumed savoury snack foods in a disguised taste test. They received ready salted crisps (Walkers, UK: 40 g), cool tortilla chips (Morrisons, UK: 40 g) and mini poppadums (Morrisons, UK: 30 g). The smaller amount of mini poppadums was to account for their larger volume, so that participants were presented with a visually similar amount of each snack.

2.4. Perceptual load task

All stimuli were presented using Eprime 2.0 (Schneider, Eschman, & Zuccolotto, 2002) on a 13.5-inch computer screen. The experiment was presented on a grey background and all letter stimuli were black.

We adapted the task from Forster and Spence (2018). Participants completed either six low or high perceptual load blocks of a visual search task. Each trial started with a central fixation cross displayed for 500 ms, immediately followed by the letter stimuli, the letters appeared for 100 ms but the response window was 2000 ms. The next trial began after the 2000 ms response window had finished regardless of when a response was given. This was to ensure that participants completing the low load version of the task (where responses are typically quicker) spent the same time carrying out the task as those completing the high load version.

Example stimulus displays are shown in Figure 1. Each stimulus display comprised a circle of 6 letters, participants searched for a target letter within the circle, either an X or an N, and responded with the corresponding key. Perceptual load was manipulated by varying the set-size of the letter circle. The letter circle had a 2.4 degree radius (each letter subtending 1.2 by 1 degree). In the high-load condition, the non-target letters in the circle (selected at random from H, K, M, Z, W, V) were placed randomly around the circle. In the low load the small 0's were 0.19 degrees.

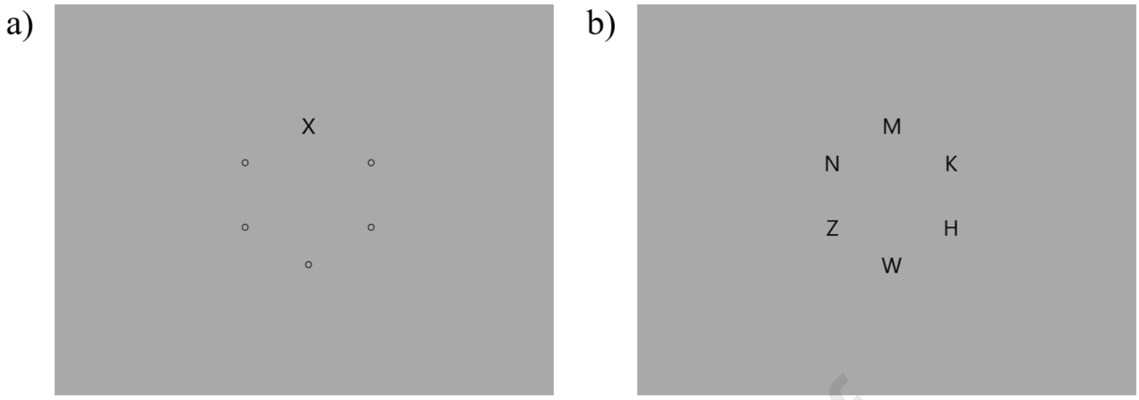

Figure 1. Example stimulus displays showing: (a) low load trial, (b) high load trial.

2.5. Procedure

Figure 2 provides a summary of the test day procedure. Participants arrived for breakfast in the laboratory between 8:15 and 10 am having consumed nothing except water from 23:00pm the evening before. Participants could then leave the laboratory for one hour, then returned for their main test session. They were instructed to consume only water in this time and were given a 500 ml bottle of water to take with them. Upon their return to the laboratory, participants were seated in a testing cubicle where they completed a set of visual analogue ratings run on Eprime 2.0.

Experienced satiety and mood were measured using a 0-100 visual analogue scale (VAS). A composite measure of experienced satiety was created from four ratings: hunger, fullness, desire to eat and ‘how much’ could participants eat. There were five mood ratings: calm, tired, headachy, clearheaded and energetic. Each VAS scale was presented as a 100 mm horizontal line on the computer screen. Each 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 show their current state. All VAS ratings were presented in a randomised order.

Next participants completed three slowed down example trials of the perceptual load task and twenty-four normal speed practice trials for the level of load in their condition.

The preload beverage was delivered via an intra-oral infusion device (TasteBud: Vi, Arthur, & Obrist, 2018), which allowed us to control the time of delivery, remove as many pre-ingestive cues as possible (e.g., visual cues, motor actions associated with ingestion) and ensure participants consumed the preload while fully distracted by the perceptual load task. The Tastebud delivery system used a peristaltic pump to push the beverage through a plastic tube and into the participant's mouth – similar delivery systems have been used in previous research (e.g., Zijlstra et al., 2008, 2009; Bolhuis et al., 2011). The tube was attached to a disposable plastic straw that participants held in their mouth. The liquid was delivered at a slow constant rate (37g per minute) with no need for participants to use their hands to consume the liquid.

Once participants pressed a key to start the task the delivery of the beverage began automatically. The delivery of the beverage lasted nine minutes. The perceptual load task continued for this length of time. After delivery of the beverage had finished participants were instructed to put the straw to the side and continue with the perceptual load task.

Participants then completed six blocks of the perceptual load task during the inter-meal interval, which lasted for a total of 32.5 minutes (intervals of 30 – 120 minutes have been previously suggested to maximise potential energy compensation, Almiron-Roig et al., 2013). Each block continued for five minutes. After each block participants were given a thirty-second break where they were asked to focus on the strategies they had used in the previous block, and how they could improve in the next block.

Upon completing the perceptual load task, participants repeated the visual analogue ratings measuring hunger and mood.

Next, participants were given a disguised snack intake test, intended to assess satiety (via calorie consumption of the snacks). The experimenter presented participants with a tray of savoury snacks (three varieties of crisps) in bowls labelled with a three-digit number. Participants were instructed they had five minutes to taste the snacks and complete the ratings that appeared on the screen. They were told they could eat as much of the snack foods as they wanted, as they would be thrown away after. Participants made ratings on how pleasant, salty and sweet they thought the snacks were (these ratings received no further analysis).

Participants completed a set of questionnaires measuring individual difference characteristics related to eating behaviour. Using a between-groups design raised the risk that difference between conditions could be affected by group differences in body-size or in traits known to affect satiety responses. For example, dietary restraint and disinhibition have both been specifically linked to an altered response (counter-regulation) to preload consumption (Westenhoefer, Broeckmann, Münch, & Pudel, 1994). In addition, both over-reliance on external cues (Ogden & Wardle, 1990) and sensitivity to reward have been linked to over-eating (Franken & Muris, 2005). Therefore, we collected individual difference data to ensure each experimental group consisted of similar samples, which have been reported in Table S1. The four groups did not differ on any individual difference characteristics related to eating behaviour, all *ps* > .200.

After the questionnaires, participants rated the smoothie beverages on how ‘creamy’, ‘sweet’ and ‘pleasant’ and ‘filling’ they remembered them being. Finally, the researcher measured the participant’s height and weight at the end of the experiment using a stadiometer with an integrated height measure, before thanking and debriefing them.

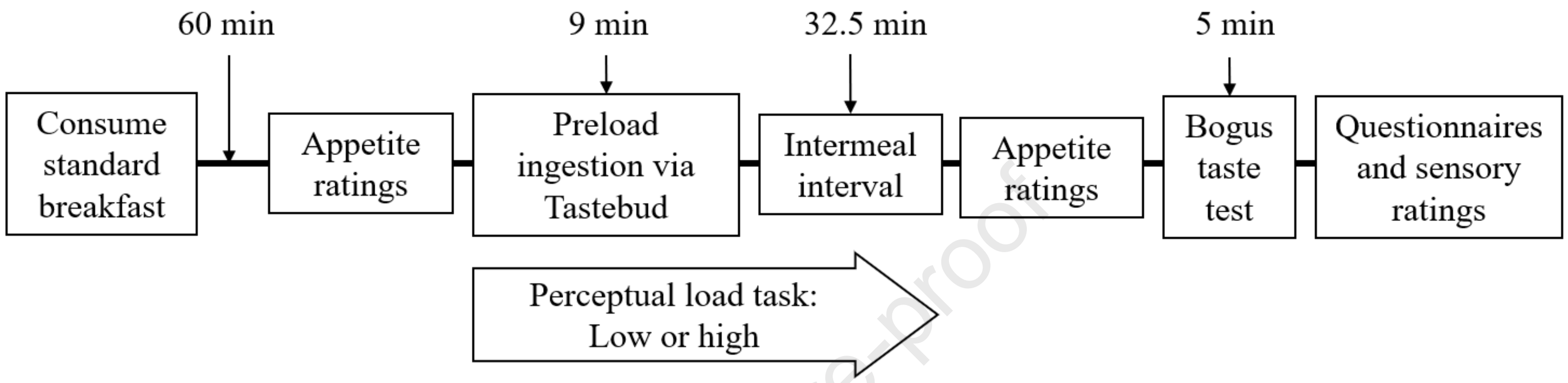

Figure 2. Schematic summary of the test day procedure (note that the preload ingestion via Tastebud took nine minutes in total – split into eight minutes for the preload delivery and a further one minute where the perceptual load task continued, to avoid an abrupt end of preload delivery).

2.6. Questionnaire measures

2.6.1. Three Factor Eating Questionnaire (Stunkard & Messick, 1985). The 51 item TFEQ is divided into three factors: restraint, disinhibition and hunger.

2.6.2. Dutch Eating Behaviour Questionnaire (van Strien, Frijters, Bergers, & Defares, 1986). Only the 10 item external eating subscale of the DEBQ was used in this experiment.

2.6.3. Sensitivity to punishment and reward Questionnaire (Torrubia, Ávila, Moltó, & Caseras, 2001). This 48-item questionnaire comprises two subscales. Sensitivity to reward which reflects behavioural activation, and the sensitivity to punishment which reflects behavioural inhibition.

2.7. Data Analysis

Firstly, manipulation checks were carried out to ensure the perceptual load task had the intended effect. 2 x 2 between subjects ANOVA's were carried out using the factors of perceptual load (low, high) and preload (LE, HE) on reaction time and accuracy data. The same factors were used in a 2 x 2 ANCOVA on change in mood ratings (post task mood rating – baseline mood rating), while controlling for the equivalent baseline mood rating. The following mood ratings were evaluated: calm, clearheaded, energetic, headache, tired.

The key research questions were regarding the impact of perceptual load on the typical preload effect expected in this design. On intake, a 2 x 2 ANCOVA was performed with the factors of perceptual load (low, high) and preload (LE, HE). To identify meaningful individual difference covariates, an exploratory ANCOVA was first carried out with all potential individual difference variables (restraint, disinhibition, sensitivity to reward, external eating and BMI) – this was done to avoid the loss of power associated with including numerous non-significant covariates in the model (Kahan, Jairath, Dore & Morris, 2014). Significant covariates were included in all subsequent analyses. To investigate significant interactions between perceptual load and preload, follow up ANCOVA's testing the effect of preload on intake were performed under each level of perceptual load.

The same analysis process was carried out on change in experienced satiety data (post task satiety – baseline satiety). However, baseline satiety was included as an additional covariate (as suggested by Blundell et al., 2010).

Unadjusted means and models (without individual difference covariates) for the effect of perceptual load and preload on intake (Table S2 and Figure S1) and experienced satiety (Table S3 and Figure S2) have been reported in supplementary materials. Adjusting for covariates did not change the interpretation of any of our results.

As we expected to find non-significant effects of preload under high perceptual load, Bayes factors were calculated for these effects on intake and experienced satiety. 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.

Finally, we calculated 2 x 2 ANOVA's (with the factors of perceptual load and preload) to test for group differences on sensory ratings collected after the experiment (pleasant, filling, sweet and creamy).

3. Results

All traditional analyses were conducted using IBM SPSS Statistics 24. Dienes (2008) online calculator was used to calculate Bayes factors for key non-significant results important to our interpretation.

3.1. Manipulation check

Only trials to which a correct response was made were included in reaction time analyses. All reaction times are reported in milliseconds. Slower reaction times (low perceptual load: *M* = 513, *SE* = 10; high perceptual load: *M* = 751, *SE* = 15), $F(1, 116) = 178.99$, $p < .001$, $N_P^2 = .61$, and lower accuracy rate, (low perceptual load: *M* = .94, *SE* = .00; high perceptual load: *M* = .84, *SE* = .01) $F(1, 116) = 60.15$, $p < .001$, $N_P^2 = .34$, under high compared to low perceptual load confirmed the expected increase in task difficulty. No other task performance effects were significant, all *ps* > .531.

Mood ratings were collected before and after the perceptual load task. The change in mood ratings (post task rating-baseline rating) are reported in Table 1. Due to outliers, headache data were removed for two participants. Change in mood ratings did not differ significantly based on perceptual load condition, all *ps* > .256. No other effects (the effects of preload and its interaction with perceptual load) were significant, all *ps* > .125.

Table 1

Change in mood (post task rating-baseline rating) in low and high perceptual load conditions (SE in parentheses). Data are estimated marginal means.

	Low perceptual load	High perceptual load
Calm	-5.58 (3.01)	-3.16 (3.01)
Clearheaded	-19.57 (2.73)	-17.07 (2.73)
Energetic	-22.69 (2.82)	-18.10 (2.82)
Headache	20.21 (3.50)	16.72 (3.50)
Tired	20.54 (3.22)	21.64 (3.22)

3.2. Effect of perceptual load on snack intake

Intake is presented in Figure 3. A between-subjects analysis of covariance (ANCOVA) was carried out, testing the effect of preload (LE, HE) and level of perceptual load (low, high) on crisp intake (calories). Exploratory analysis identified that the following covariates were significantly related to intake and therefore they were included in the main ANCOVA: sensitivity to reward, p = .042, and DEBQ external eating, p = .008. There were no other significant effects of covariates, all *ps* > .482.

There was a significant effect of sensitivity to reward, $F(1, 114) = 4.44$, $p = .037$, $N_P^2 = .04$, and DEBQ external eating, $F(1, 114) = 10.61$, $p = .001$, $N_P^2 = .09$, on intake. After controlling for the selected covariates, the ANCOVA showed that intake was significantly higher overall after consumption of the LE compared to the HE preload, $F(1,114) = 9.44$, $p = .003$, $N_P^2 = .08$. Perceptual load had no overall effect on intake,

F(1,114) = .08, p = .782, N_P^2 = .00. Crucially, there was a significant interaction between preload and perceptual load, F(1,114) = 13.78, p < .001, N_P^2 = .11.

To follow up the significant interaction between preload and perceptual load, one way ANCOVA's were carried out under each level of perceptual load, while controlling for DEBQ external eating and sensitivity to reward. The DEBQ external eating subscale was significantly related to intake under both low, F(1, 56) = 6.89, p = .011, N_P^2 = .11, and high perceptual load conditions, F(1, 56) = 3.94, p = .052, N_P^2 = .07. There was no significant effect of sensitivity to reward, all *ps* > .094. After controlling for covariates, there was a significant effect of preload under low perceptual load: participants who consumed the HE preload consumed 45% fewer crisps than participants who consumed the LE preload, F(1, 56) = 25.85, p < .001, N_P^2 = .32, confirming a satiety response. Critically, there was no equivalent difference in intake under high perceptual load, F(1, 56) = .19, p = .665, N_P^2 = .00, with near identical intake after LE and HE versions.

In addition, a Bayes factor was calculated for the non-significant effect of preload on subsequent intake under high perceptual load, using a prior of 60 (calories) obtained from McCrickerd et al, (2014). The resulting Bayes factor was .20, suggesting that the lack of satiety response under high perceptual load was a sensitive non-significant result. Therefore, participants showed no evidence of reduced intake in response to the HE compared to LE preload when engaged in the high perceptual load task, showing for the first time that inattention can mask responses to satiety cues.

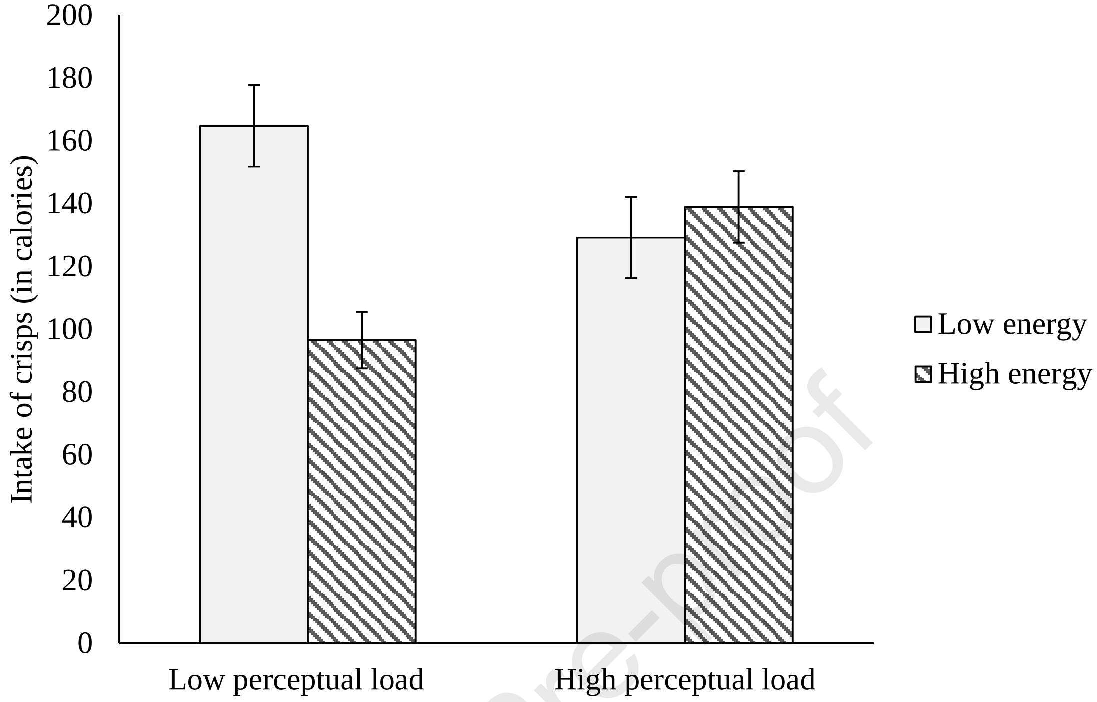

Figure 3. Mean calorie intake (± SEM) of crisps after consumption of LE or HE preload under low or high perceptual load.

3.3. Effect of perceptual load on experienced satiety

To test effects on the experience of satiety, participants completed visual analogue ratings of hunger, fullness, desire to eat and the amount they thought they could eat. There were no group differences on any of these ratings at baseline (at the start of the experiment), all *ps* >. 393. We calculated change in satiety by subtracting baseline from post-task ratings and, as in previous studies (Deighton, Karra, Batterham, & Stensel, 2013; Harrold, Breslin, Walsh, Halford, & Pelkman, 2014; Perrigue, Drewnowski, Wang, & Neuhouser, 2016), combined these ratings into a single overall satiety index using the formula *((hunger + amount + desire to eat) – (fullness))/4*. These satiety index data were contrasted using a 2 x 2 ANCOVA with preload and perceptual load, while controlling for the baseline satiety index score and DEBQ external eating (which was identified as a marginally significant covariate in exploratory analyses, p = .057). Satiety index data are presented in Figure 4.

There was a significant effect of baseline satiety, $F(1, 114) = 19.36$, $p < .001$, $N_P^2 = .15$, and a marginally significant effect of DEBQ external eating on experienced satiety, $F(1, 114) = 3.32$, $p = .071$, $N_P^2 = .03$. There was no overall statistically significant effect of preload, $F(1, 114) = .76$, $p = .387$, $N_P^2 = .01$, or perceptual load, $F(1, 114) = .29$, $p = .590$, $N_P^2 = .01$. However, there was a significant interaction, $F(1, 114) = 7.94$, $p = .006$, $N_P^2 = .07$.

To follow up the significant interaction between preload and perceptual load, one way ANCOVA's were carried out under each level of perceptual load, while controlling for Baseline satiety and DEBQ external eating. Baseline satiety was significantly related to change in satiety under both low, $F(1,56) = 7.07$, $p = .010$, $N_P^2 = .11$, and high perceptual load conditions, $F(1,56) = 12.37$, $p = .001$, $N_P^2 = .18$. There was no effect of DEBQ external eating, all *ps* > .174. After controlling for covariates, under low perceptual load, there was a greater reduction in experienced satiety from participants who consumed the HE compared to the LE drink, $F(1, 56) = 6.89$, $p = .011$, $N_P^2 = .11$. Again, there were no significant difference under high perceptual load, $F(1,56) = 1.73$, $p = .194$, $N_P^2 = .03$. Thus, changes in snack intake were mirrored by no evidence of any change in experienced satiety after the HE preload under high perceptual load.

Finally, a Bayes factor was calculated for the non-significant effect of preload on experienced satiety, using a prior of 3.54 (change in satiety index) obtained from previous unpublished research in the Sussex Ingestive Behaviour Laboratory. The resulting Bayes factor was .40, narrowly missing the .33 threshold for sensitivity.

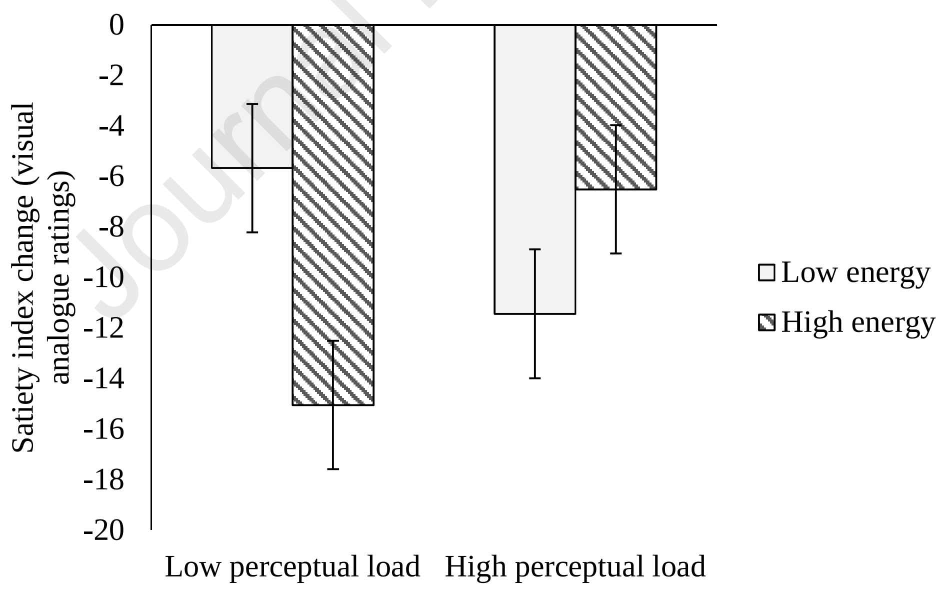

Figure 4. Overall satiety index change after consumption of LE or HE preload under low or high perceptual load. A larger negative score reflects a greater increase in experienced satiety.

3.4. Effect of perceptual load on sensory memory ratings

In addition, we collected sensory memory ratings of the smoothie drinks at the end of the experiment, which are displayed in Table 2. Participants rated the LE and HE drinks to be similar in how pleasant and sweet they remembered it being, all *ps* > .142. The HE preload was rated as significantly creamier than the LE preload (this was intentional in our design), $F(1, 116) = 12.23$, $p = .001$, $N_P^2 = .10$. However, unexpectedly participants who consumed the preload under high perceptual load rated it as significantly creamier than participants who consumed it under low perceptual load, $F(1, 116) = 6.89$, $p = .010$, $N_P^2 = .06$. There was a non-significant interaction between preload type and perceptual load, $F(1, 116) = .24$, $p = .626$, $N_P^2 = .00$. Crucially, the lack of interaction between preload type and perceptual load on all three sensory memory ratings reflects that there was no evidence of an effect of perceptual load on memory for preload sensory characteristics.

We also asked participants how “filling” they remembered each preload to be, and this neither differed between preloads, $F(1, 116) = .99$, $p = .322$, $N_P^2 = .01$, or perceptual load conditions, F(1, 116) = .06, p = .802, $N_P^2 = .00$. There was also no preload x perceptual load interaction, $F(1, 116) = .19$, $p = .663$, $N_P^2 = .00$.

Table 2

Sensory memory ratings (mean and standard error) between experimental conditions.

	Low perceptual load		High perceptual load	
	Low energy preload	High energy preload	Low energy preload	High energy preload
Pleasant	66.33 (4.07)	60.13 (4.81)	57.30 (2.94)	62.93 (3.97)
Sweet	65.37 (2.33)	71.40 (2.61)	67.77 (2.55)	66.77 (3.62)
Creamy	39.17 (4.09)	54.40 (3.92)	51.07 (3.20)	62.57 (4.02)

4. Discussion

Together, the results show that satiety-based control over appetite can be disrupted when attention is absorbed in a perceptually demanding task. When attention was available under low perceptual load, participants consuming the HE thick preload ate 45% fewer crisps at a subsequent snack test and reported more than double the level of experienced satiety than those who consumed the LE thin preload (note that while participants did not fully adjust their intake for the energy difference between preloads, the size of the observed effect is similar to previous research, e.g., Almiron-Roig et al., 2013; McCrickerd et al., 2014). Neither of these effects were observed when attention was occupied by a perceptual load task during consumption, suggesting that attention is required for the brain to be aware of the sensory and subtle nutrient cues generated in the gut by ingestion of the two preload drinks. Importantly, these effects were observed in the absence of any load effect on mood or memory ratings of how filling, pleasant or sweet the preload beverage was. The thick texture beverage was rated as creamier than the thin texture beverage under both low and high perceptual load, suggesting that perceptual load did not reduce memory for that feature of the drink preloads.

Our results provide the first evidence that Load Theory of attention can be successfully applied to study ingestive behaviour. Furthermore, even when a strong effect of satiety was expected in response to a thick texture, high energy beverage, perceptual load significantly disrupted the satiety response. As has been pointed out, a reliable satiety response is dependent on the combination of sensory and physiological cues (Chambers, Ells & Yeomans, 2013; Yeomans & Chambers, 2011; Camps, Mars, De Graaf, & Smeets, 2016; McCrickerd, Tay, Tang & Forde, 2020), and therefore while we controlled for a variety of pre-ingestive cues in our design (e.g., visual cues and motor actions), the beverages differed on the key sensory characteristic of texture. As this was the first application of Load Theory in this area, it was most important to test whether perceptual load would modulate a strong satiety response. The pattern of observed results regarding satiety response suggest that perceptual load modulated the effect of both sensory and physiological cues, as satiety was completely eliminated in this context. If perceptual load was only acting on either sensory or physiological cues, a partial reduction in satiety response would have been expected. However, it should also be noted that memory ratings of the difference in 'creaminess' of the two preload drinks were not affected by perceptual load. Therefore, this suggests participants had some awareness of the sensory difference but were unable to integrate this information with internal physiological control of appetite at the time of consumption. We note that for consistency with previous studies (e.g., McCrickerd et al., 2014; Bertenshaw, Lluch & Yeomans, 2013) a sensory rating of 'thickness' may have also been useful. However, the fact that perceptual load did not impact awareness of LE/HE differences in pleasantness, sweetness and creaminess, and in particular that the creaminess LE/HE difference was noticed irrespective of load, makes it unlikely that our key findings were in any way impacted by load effects on awareness of the LE/HE thickness difference. Future research could adapt our paradigm to isolate the effect of perceptual load on sensory and physiological cues, by using a more subtle preload based only on one of these factors.

Our findings build on existing models of appetite control, such as the satiety cascade (Bellisle & Blundell, 2013; Blundell & Tremblay, 1995), which have increasingly allowed for cognitive influences on satiety. However, these influences have been suggested to operate at early stages of ingestion as modulators of post-ingestive nutrient based satiety. For example, Rolls, Bell and Waugh (2000) found that doubling the perceived volume of a milkshake preload reduced subsequent intake by 12%, suggesting that cognition was having a moderate impact on satiety, but did not override later physiological aspects of ingestion (i.e., the actual energy content of the preloads). In contrast, our experiment found that the satiety response was entirely eliminated by high perceptual load, suggesting that factors acting throughout the satiety cascade (such as post-ingestive nutrient-derived cues) are dependent on the availability of basic perceptual capacity. Therefore, the current findings support growing research emphasising the role of cognition in satiety (Higgs et al., 2017). They are also consistent with previous studies showing that attentionally demanding real-world tasks at the time of initial consumption increase subsequent intake (Higgs, 2015; Higgs & Woodward, 2009; Mittal et al., 2011; Oldham-Cooper et al., 2010; Robinson et al., 2013). By integrating a more direct perceptual load manipulation of attention with a controlled preload manipulation of satiety, our findings extend these earlier findings by demonstrating that, at least within the context of our design, the impact of a cognitive factor (attention) is not limited to decreasing satiety, but can in fact entirely eliminate the satiety response.

Based on our findings here, we propose that perceptual load may also disrupt the brain's ability to adequately integrate satiety signals in a manner that affects behaviour or awareness of internal states, despite the presence of nutrients in the gut accompanied by a congruent sensory cue. Perceptual load is known to substantially disrupt information processing from the earliest stages of perceptual processing to encoding into memory, indexed by both behavioural and neural measures (Lavie, 2005; 2010). As such, an important direction for future research could be to elucidate the precise mechanisms underlying the perceptual load effects observed here. One possibility is that perceptual load would reduce neural activity associated with satiety. For example, after eating to satiation, previous research has found that activity in the hypothalamus and reward-related brain regions (nucleus accumbens, ventromedial prefrontal cortex and orbitofrontal cortex) was attenuated but activity in the dorsolateral prefrontal cortex was increased (Thomas et al., 2015). Future neuroimaging research could test whether neural activity associated with satiety is altered under high perceptual load (i.e., typical reduction or increase in neural activity does not occur), further elucidating the underlying attentional mechanism.

It should be acknowledged that these results have been obtained from a single experiment study conducted with a healthy-weight, female and predominately student sample. A vital next step is, of course, to replicate this finding in wider samples, considering individual differences in eating behaviour. Keeping these limitations in mind, the results could have substantial potential implications for both research and healthcare. Firstly, the effect of distraction on subsequent intake has been argued to influence intake via a variety of mechanisms (such as mood and reduced memory), while the current findings suggest that increased intake can also occur due to a basic lack of perceptual resources. Secondly, Load Theory argues that perceptual load has a distinct effect on attentional processing by exhausting capacity and filtering out non-task stimuli in a passive manner (in this situation, satiety signals), whereas other forms of task load, such as cognitive demand, have the opposite effect on attentional processing and instead tax cognitive control resources. Establishing a role of perceptual capacity in existing theory will allow predictions over real world eating behaviour to be more specific about the nature of attention and future research to be mindful of processing limits.

The knowledge that satiety, one of the most important determinants of intake, is strongly affected by availability of attentional capacity could help to inform cognitive dietary interventions. Our findings suggest the focus of such interventions should be on ensuring attentional capacity remains available for the duration of ingestion and the subsequent period, as cognition is a key component of regulating intake. Therefore, tasks which may involve high perceptual demand, such as television and video games, should be avoided when consuming food. Our results might also suggest that perceptual load particularly affects physiological components of satiety, as participants still remembered some sensory differences in the preload beverages (although a more direct test of sensory and physiological factors is required).

To summarise, our study shows that perceptual load strongly disrupts the satiety response to a high energy, thick texture preload beverage. This supports recent cognitive models of satiety, suggesting that accurate appetite control requires attentional resources to be available. Load Theory may be a useful framework from which to predict intake and subjective appetite. Practically, it may be a useful recommendation to avoid high perceptual tasks, and potentially, the success of cognitive dietary interventions could be affected by whether participants are able to pay attention to the processing of satiety-related information.

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Author contributions: S. Forster suggested the broad concept for the study, which was developed by M. R. Yeomans. J. Morris, S. Forster and M. R. Yeomans designed the study. C. T. Vi and M. Obrist provided equipment (Tastebud) necessary for the study and C. T. Vi provided technical support. J. Morris collected the data, analysed the data and prepared the original draft manuscript. J. Morris, S. Forster and M. R. Yeomans reviewed and edited the manuscript.

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Ingested but not perceived: response to satiety cues eliminated by inattention

Jenny Morris, Chi Ti Vi, Marianna Obrist, Sophie Forster, Martin R. Yeomans

Ethical statement

The study was conducted in accordance with the Declaration of Helsinki and was approved by the University of Sussex Sciences & Technology Cross-Schools Research Ethics Committee (approval code: ER/JM560/7). All participants provided informed consent.