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Passive overconsumption? Limited evidence of compensation in meal size when consuming foods high in energy density: Two randomised crossover experiments

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ABSTRACT

Research has drawn contradictory conclusions as to whether humans adjust meal size based on meal energy density (ED) or exhibit 'passive overconsumption'. Recent observational research has suggested that meal EDs greater than 1.7–2 kcal/g are compensated for through consumption of smaller meal sizes. We tested the relationship between ED and meal size by examining energy intake of meals at three levels of ED: low (~1.0 kcal/g), medium (1.7–2.0 kcal/g) and high (>3.0 kcal/g). Two randomised, crossover experiments were conducted with adult participants. In experiment 1 (n = 34, 62% female, mean age 37.4 years), participants were served a lunch including a familiar low, medium or high ED dessert to eat *ad libitum*. In experiment 2 (n = 32, 66% female, mean age 36.4 years), participants were served a lunch meal manipulated to be low, medium or high ED to eat *ad libitum*. For experiment 2, later energy intake (post-meal energy intake) was also measured. In experiment 1, participants consumed a similar amount of energy from the low vs. medium ED food. The high ED food was associated with an increased intake of approximately 240 kcals compared to medium ($p < 0.001$, Cohen's d = 2.31) and low ($p < 0.001$, Cohen's d = 4.42) ED foods. In experiment 2, there were no significant differences in meal size (grams) between ED meals, resulting in a largely linear relationship between meal ED and energy intake across the three ED conditions ('passive overconsumption'). There were no differences in later energy intake between ED conditions. Contrary to recent suggestions, foods higher in ED were not associated with adjustments to meal size and were associated with increased energy intake across two experiments. Reformulation of foods high in ED may be an effective population level approach to reducing energy intake and obesity.

Clinical trial registry number: NCT05744050; https://clinicaltrials.gov/ct2/show/NCT05744050.

1. Introduction

Energy density (ED) is "the energy content per unit weight (kcal/g) of food" (Prentice and Jebb, 2003). A diet characterised as being higher in ED is generally associated with higher daily energy intake (Bell et al., 1998; Ledikwe et al., 2006) and relationships have been identified between a diet higher in ED and heavier body weight in both adults and children (Pérez-Escamilla et al., 2012).

A number of studies suggest that when the energy density of a food or meal is manipulated it has linear effects on energy intake (Klos et al., 2022; Robinson et al., 2022). For example, one study provided healthy males with noodle soup at five different levels of ED (ranging from 0.3 kcal/g to 1.8 kcal/g) (Tey et al., 2016). A strong linear dose-response relationship was identified between ED and energy intake for the meal, indicating no adjustment of meal size as a result of changes to ED, and the possibility that foods with higher ED may lead to 'passive overconsumption'. Previous research has understood passive overconsumption to mean the consumer has no deliberate intention to eat in excess (Blundell & Macdiarmid, 1997) and therefore, does not play an 'active' role in overconsumption, which is instead driven by food characteristics such as ED (Blundell and Macdiarmid, 1997).

A recent observational study by Flynn et al. confirmed the existence of a linear relationship between meal ED and meal energy intake for EDs of approximately 0 up to 1.5–2.0 kcal/g (Flynn et al., 2022). However, beyond this 'break point' the authors observed that increases in ED were associated with decreasing meal size (g) and there was little evidence of further increases in meal energy intake with greater ED. Together, these results do not support the notion of 'passive overconsumption' because consumers are seemingly modifying the amount of food eaten based on energy content. A similar break point was observed in a lab study (Brunstrom et al., 2018), where participants' perceived value of a food was measured according to food choice, liking, expected satiation, and estimated calorie content. In this study, at higher levels of ED (above approximately 1.5 kcal/g), participants were less able to differentiate

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between foods in terms of expected satiation and estimated calorie content than they were at lower levels of ED. This was interpreted as being evidence for humans being relatively insensitive to the energy content of higher ED foods.

Flynn et al. proposed a two-component model of meal size to explain this pattern of findings, whereby volume of food is the dominant signal of meal size for lower ED foods (i.e.<1.5 kcal/g) and energy content (i.e. largely through dietary learning) becomes the dominant signal for higher ED foods (i.e.>2.0 kcal/g) (Flynn et al., 2022). If correct, the proposed model has important implications. First, it would challenge the widely held assumption that highly energy dense foods are a cause of passive overconsumption and higher energy intake (Brunstrom et al., 2018). Second, it would suggest that reducing the ED of very energy dense meals may not lead to reductions in energy intake. This is because the model proposed by Flynn et al. suggests that at high levels of ED there is already compensation and based on the data presented by Flynn et al. any decreases in ED would be predicted to be fully compensated for. This may have implications for public health approaches to addressing population level energy intake and obesity (Rolls, 2017).

There has been limited experimental examination of the effect that foods of higher ED (>2.0 kcal/g) have on meal size and energy intake (Robinson et al., 2022). However, one study found that in high ED conditions (breakfast and lunch ≥2.5 kcal/g) participants consumed significantly more energy (kcal) over the full day compared to those in low ED conditions (breakfast and lunch ≤0.8 kcal/g) (Buckland et al., 2018). Similarly, greater energy intake was observed in response to a lunch meal ED increase of 1.4 kcal/g to 3.0 kcal/g (Devitt & Mattes, 2004). In the latter study, this led to a mean increased intake of 340–366 kcals at the lunch time meal, suggesting little compensation above the 'breakpoint' proposed by Flynn et al.

Therefore, there is a lack of causal evidence supporting the proposition that consumers adjust meal size for higher ED foods, as proposed in Flynn et al. In two experiments we examined meal size and energy intake in response to lower (<1.5 kcal/g), medium (1.7–2.0 kcal/g) and higher (≥3.0 kcal/g) ED foods. The primary objective of experiment 1 was to investigate the relationship between ED and meal size (weight of meal) and energy intake using foods that already differed in ED, were familiar to participants and therefore would have different sensory properties. In experiment 2 we directly manipulated the ED of a meal to limit differences in sensory properties and appearance between lower, medium and higher ED foods in order to explore differences in energy intake when ED was manipulated in the absence of sensory differences. In both experiments, we examined acute meal size in response to ED. By utilising different approaches in each experiment, we were able to test different features of Flynn et al.'s hypothesis:

1) That a breakpoint exists at medium energy density, above which increasing ED does not result in higher energy intake (experiment 1 & 2).
2) That previous dietary learning leads to compensation (by reduced meal size) at higher levels of ED (experiment 1).

In experiment 2 energy intake after the ED manipulated meal was also measured to examine any evidence of later compensatory eating based on earlier meal ED.

2. Subjects and methods

2.1. Experiment 1

This experiment was pre-registered at https://osf.io/nvy6c/and used a randomised crossover design with three conditions, corresponding to three separate sessions. Randomization to the order conditions were presented was completed by researchers using the 'RAND' function in Microsoft Excel with 6 possible orders of food presentation.

2.1.1. Participants and sample size

Adult participants were recruited from the local community and were required to visit the University of Liverpool to participate in the experiment. The experiment was defined as 'a study of glucose on cognitive function' in order to mask aims. To be eligible, participants were required to like all provided foods, and those with a history of eating disorders, currently fasting, or with any dietary restrictions (except for vegetarianism), were ineligible to take part. A recent systematic review and meta-analysis (Robinson et al., 2022) examined the influence of ED on energy intake and the smallest effect size across the meta-analyses was $d = 0.8$ (a statistically large effect size). Because we hypothesised that the effect of energy density on energy intake may be smaller dependent on energy density levels, we powered experiment 1 to be able to detect a medium sized effect of ED condition ($f = 0.25$) using a one-way within subjects ANOVA at 0.85% power (1 group, 3 measurements of low ED, medium ED and high ED). Conducted in GPOWER 3.1, a minimum sample of 31 participants was required. In the event of a main effect of ED, follow-up t-tests were used to compare conditions. Using the same parameters as the previous analyses, to detect a medium effect size for a repeated measures *t*-test, a sample size of 34 was required. Therefore, in experiment 1 we aimed to recruit a minimum of $N = 34$ participants. We recruited slightly above this number to account for drop out, or participants not following instructions. Data collection for experiment 1 took place from 30th September 2022 to 25th January 2023.

2.1.2. Foods served

Participants consumed a lunch, including dessert during each session. Participants were first provided with a sandwich and 500 ml of water and consumed the same sandwich type for each session (see Table 1), before being served dessert. The sandwich provided was half of a packaged supermarket sandwich of the participant's choosing (Table 1). This was selected to ensure that participants were served an initial small main lunchtime course, but would still be hungry enough to eat dessert. The desserts served were the experimental foods for which ED varied. The desserts were chosen as they are popular dessert choices in the UK, and are broadly similar in sensory qualities (creamy, vanilla flavour), and recommended serving instructions (served cold), but differ by ED. The low ED dessert was vanilla yogurt (1.2 kcal/g), the medium ED dessert was vanilla ice cream (1.9 kcal/g), and the high ED dessert was vanilla cheesecake (3.5 kcal/g). The specific branded products used for each dessert were selected as they were the closest to the average ED of all vanilla yogurts/ice creams/cheesecakes available at large UK supermarket chains. Product EDs on packaging were confirmed through independent laboratory analysis. The SGS Cambridge Analysis Lab (SGS) conducted the nutritional analyses throughout both experiments, and a bomb calorimeter was used to determine the energy content of provided samples. Full nutritional information of all test foods per 100 g is provided in Table 1. In a minority of instances, test foods were unavailable so comparable substitute foods were used (further details in Supplementary Material I). All test foods were weighed pre- and post-consumption.

2.1.3. Procedure

The study procedure is visually depicted in Fig. 1. Participants were asked to eat the same breakfast in the morning before arriving for each lunch session. This was required to be representative of what they would normally have for breakfast and was not provided by researchers. All participants were asked not to eat in the 2 h prior to their session. The three study sessions were arranged so they would take place over three consecutive weeks. At the beginning of the first lunchtime session participant eligibility was confirmed and a demographic questionnaire was completed. A number of measures of socioeconomic position (SEP) were collected to be examined in sensitivity analyses. Participants reported their highest level of education attained, and completed a subjective measure of SEP (subjective social status) whereby they were

Table 1
All test foods and their nutritional composition for experiment 1.

	Chicken, bacon & lettuce sandwich	Cheddar ploughman's sandwich (V)	Vanilla yogurt (Low ED)	Vanilla ice cream (Medium ED)	Vanilla cheesecake (High ED)
Brand	Tesco	Tesco	Tesco	Walls	Tesco Finest
Description	Chicken, bacon & Lettuce sandwich	Cheddar ploughman's sandwich[1]	Greek Style Vanilla Yogurt	Soft Scoop Vanilla Ice Cream	Madagascan Vanilla Cheesecake
Serving size	½ pack ~190 g	½ pack, ~185 g	*Ad libitum*	*Ad libitum*	*Ad libitum*
Nutritional information per 100g					
Energy	220 kcal	220 kcal	118 kcal	186 kcal	349 kcal
Fat	6.7 g	8.7 g	6.5 g	7.5 g	20.7 g
Saturates	1.6 g	4.7 g	4.2 g	6.8 g	11.1 g
Carbohydrate	23.0 g	24.7 g	11.9 g	27.0 g	35.1 g
Sugars	2.1 g	4.7 g	10.5 g	17.0 g	21.1 g
Fiber	2.6 g	3.0 g	0.4 g	N/A	0.6 g
Protein	15.6 g	9.1 g	2.9 g	2.5 g	5.2 g
Salt	1.10	1.0 g	0.1 g	0.1 g	0.2 g

[1]Cheddar cheese with tomato, pickle and salad leaves on malted bread. Participants chose between one of the two sandwiches based on preference.

asked to place themselves on a ladder where the top rung represents people with the most money, most education and the best jobs and the bottom rung represents people with the least money, least education and worst jobs/no job. Additionally, participants reported their household income and composition so equivalised household income could be calculated, and participant's childhood socioeconomic status was calculated based on their parents' level of education and occupation at the time they were 8–10 years old.

Participants next rated their level of hunger and fullness on visual analog scales (VAS) (1–100), anchored 'not at all' to 'extremely', and completed a short computerised cognitive task (a Stroop task (Millisecond)) to corroborate the cover story. Next, participants were served the sandwich and a glass of water, and asked to inform the researcher when they had finished eating by ringing a bell. At this point, the researcher returned to the room and served the dessert with a serving spoon and dessert bowl. Participants were instructed to have as much or as little of the dessert as they would like, and then to indicate when they were finished. The volume of each dessert served was comparable and filled a large serving bowl (see Fig. 2).

Once the meal was finished, participants completed sensory ratings (pleasant, sweet, thick, creamy, familiar, filling) for the dessert they had just consumed using VAS (1–100; anchored 'not at all' to 'extremely'). This allowed for clarification that one dessert was not liked more than others, which would likely lead to greater consumption of the liked dessert. Additionally, collecting this data allowed for exploration of food characteristics that could be associated with the energy density of a product (e.g. filling and thickness ratings), and therefore inform dietary learning. To further corroborate the cover story, participants were asked to complete ratings of hunger and fullness, and the cognitive task, before being informed that their session was complete.

The second and third lunch sessions followed the same procedure, and on the third session after completing all tasks, participants were asked to complete a food frequency questionnaire which assessed how often participants ate the three desserts from '1–6 times per year' to '2 or more times per day'. Participants also completed questionnaire measures of satiety responsiveness (Hunot et al., 2016) (e.g. "I often leave food on my plate at the end of a meal") and compensatory health beliefs (Knäuper et al., 2004) (e.g. "When I eat less, it's not necessary to have a lot of exercise") by selecting an answer from 'strongly disagree' to 'strongly agree'. These measures were used to examine participant characteristics and motivations that may impact the amount of food eaten. Participants were asked to guess the aims of the experiment and had their weight (in kg) and height (to the nearest mm) measured. Participants also completed a task measured to design perceptions of the portion size required of each dessert food to achieve fullness. On screen, participants clicked through ascending portion sizes of each food (presented as photographs) that increased in increments of 30g and selected the portion size they would need to eat to feel full. Participants were then debriefed and compensated £30 for their time.

2.2. Experiment 2

This experiment was pre-registered at https://osf.io/e67xg/ and used a randomised crossover design with three conditions corresponding to three separate sessions. A similar design was used as in experiment 1, but different foods were provided and subsequent energy intake over the remainder of the day was measured (to examine potential later compensatory eating in response to differing ED of the lunch meal). Later energy intake was measured using snack boxes provided after the manipulated lunch meal, and an evening meal in the laboratory. The portion size and energy density of both was fixed across the three conditions.

2.2.1. Participants and sample size

The same methods as used in experiment 1 were used to recruit participants for experiment 2, with the exceptions of participation in experiment 1 and vegetarianism as ineligibility criteria. In experiment 1, the influence of ED on intake (g) was significant ($p < 0.001$), with a partial eta squared of 0.4 (large effect). The influence of ED on energy intake was also significant ($p < 0.001$) with a partial eta squared of 0.7 (large effect). To be conservative in anticipation of a smaller effect than experiment 1, we powered experiment 2 to be able to detect a medium effect size ($f = 0.25$) of ED condition in a one-way within subjects ANOVA at 0.85% power (1 group with 3 measurements of low ED, medium ED and high ED). Conducted in GPOWER 3.1, a minimum sample of 31 participants was required. In the event of a main effect of ED, follow-up t-tests were used to compare ED conditions. In experiment 1, preliminary analyses found that the smallest effect observed had a Cohens D of 0.5. We powered the present study to be able to detect effects of this size at 0.8% power in post-hoc t-tests, which required a minimum sample of 32 participants and as in experiment 1, we aimed to recruit slightly above this number. Data collection for experiment 2 took place between 30th January 2023 and 28th April 2023.

2.2.2. Foods served

Participants were served a lunchtime meal of beef chilli con carne and oven cooked potato fries, which varied in ED across sessions. This meal was chosen as it is a popular meal in the UK and found to be generally well liked in previous research (Langfield et al., 2023). All food items, and ingredients along with their nutritional information are provided in Table 2. The ED of the three chilli recipes (devised by the research team) were confirmed via laboratory assessment pre-experiment, and random samples were laboratory assessed during data collection to confirm consistency of ED. The low ED meal was 1.1

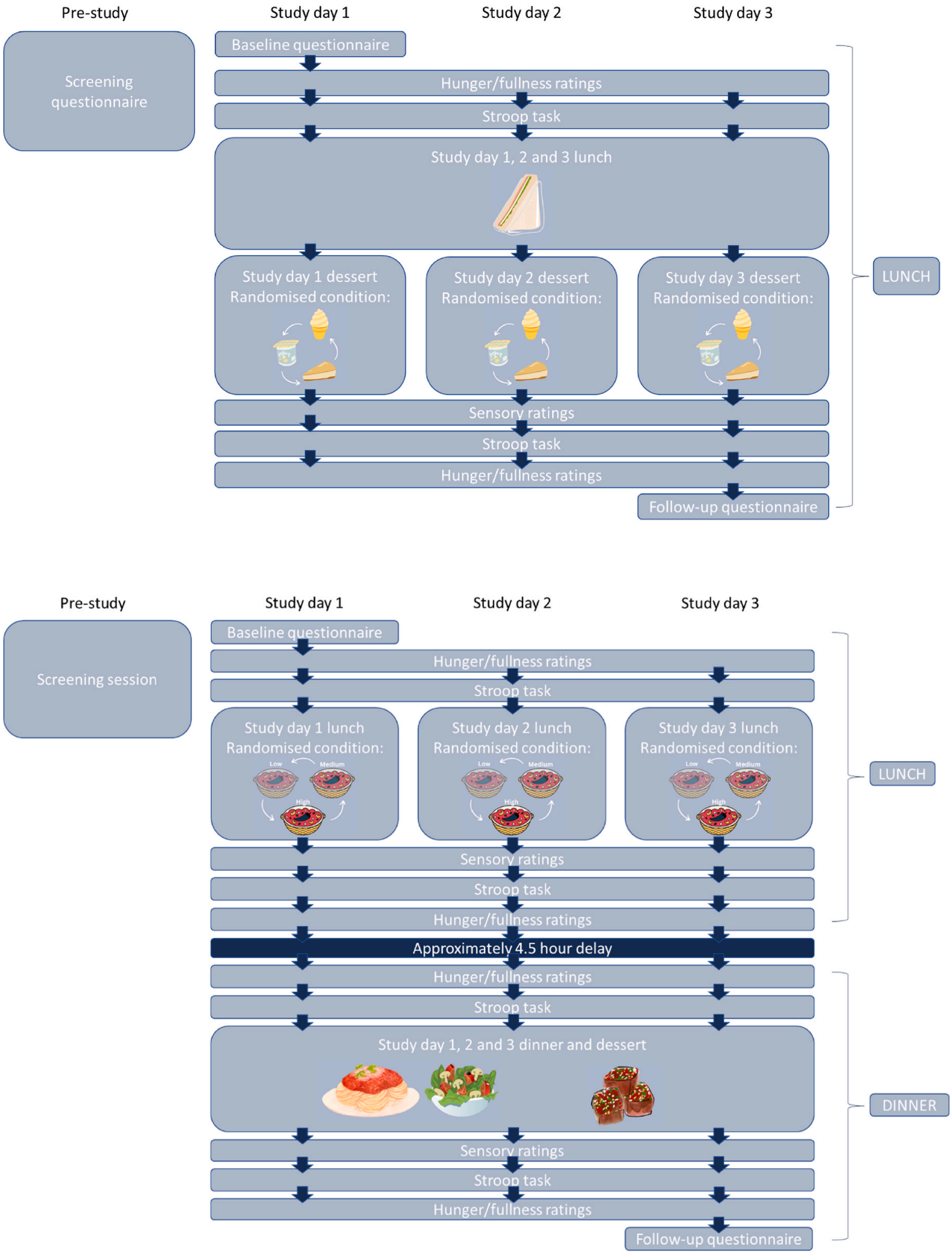

Fig. 1. Visual depiction of the study flow for experiments 1 and 2.

kcal/g, the medium ED meal was 1.7 kcal/g and the high ED meal was 3.0 kcal/g. These levels of ED were chosen to provide meals with an ED below, at and above the proposed 'breakpoint' by Flynn et al. (Flynn et al., 2022). Participants were provided with 670 g of chilli (when reheated, 750 g when initially cooked and frozen) and 405 g of oven cooked potato fries (when cooked, 500 g when frozen), as shown in Supplementary Material II. Different branded oven cooked potato fries were selected for each ED condition as they were the closest match to the ED of the cooked chilli for each condition. For the low ED condition, oven cooked potato fries were 1.2 kcal/g, for the medium ED condition 1.7 kcal/g and for the high ED condition 3 kcal/g. All oven cooked potato fries were cooked according to packet instructions. Participants were also provided with a 500 g serving of water with lunch. All test foods were weighed pre- and post-consumption.

Fig. 2. Serving sizes for each dessert (shown left to right: Yogurt (Low ED), Ice cream (Medium ED), Cheesecake (High ED)).

Table 2
The foods served to participants over the three sessions for experiment 2, and nutritional information for the manipulated meal.

	Low ED (1.1 kcal/g)		Medium ED (1.7 kcal/g)		High ED (3.0 kcal/g)	
Lunch	**g**	**kcal**	**g**	**kcal**	**g**	**Kcal**
Potato fries	405	474	405	705	405	1215
Chilli	670	710	670	1145	670	2074
Chilli (ingredients)	**Amount per serving (g)**					
Beef mince meat (5%/15%/20% fat)	250		313		769	
Onion	75		68		12	
Carrot	100		52		6	
Mushroom	100		52		6	
Tomato	100		52		6	
Tinned tomatoes	300		209		123	
Cumin	2		2		2	
Worcester sauce	2		2		2	
Garlic	10		10		12	
Beef stock	150		104		62	
Kidney beans	100		78		68	
Oregano	1		1		1	
Cream	50		52		123	
Salt	1		1		1	
Pepper	1		1		1	
Chilli (nutritional value)[a]						
KJ/100g	445.4		648.0		1285.5	
Kcal/100g	106.0		171.0		309.5	
Fat/100g	4.2		10.8		23.8	
Carbohydrate/100g	9.2		7.1		5.2	
Protein/100g	8.0		11.0		18.8	
Moisture/100g	77.4		69.8		50.5	
Oven-cooked potato fries (nutritional value)						
KJ/100g	492.0		733.0		1259.0	
kcal/100g	117.0		174.0		300.0	
Fat/100g	3.6		4.1		12.0	
Saturates/100g	0.4		0.5		1.3	
Carbohydrate/100g	18.0		30.9		42.0	
Sugars/100g	<0.5		0.7		<0.5	
Fiber/100g	2.4		2.5		3.9	
Protein/100g	2.0		2.1		4.6	
Salt/100g	0.4		0.4		1.2	
Lunch nutritional value (weighted average)						
KJ/100g	464.0		682.0		1274.9	
Kcal/100g	110.4		172.2		305.7	
Fat/100g	4.0		8.1		19.1	
Carbohydrate/100g	12.7		16.6		19.9	
Protein/100g	5.6		7.4		13.12	

[a] Values are averaged from the two nutritional analyses received.

Participants were provided with a snack box to eat from after the lunch session. When participants returned for the evening meal, they were served a main course of a cheese and tomato pasta, as used in a previous study (Langfield et al., 2023), a side serving of vegetables, a dessert buffet and 500 g of water (See Supplementary Material III for all additional foods).

2.2.3. Procedure

The study procedure is visually depicted in Fig. 1. The same pre-experiment procedures were used as in experiment 1, and participants completed the same ratings of hunger and fullness, and the cognitive task at the start of the lunch session. Participants were then provided with a large bowl of chilli (670 g) and a large bowl of oven cooked potato fries (405 g), with ED varying between conditions, and instructed to serve themselves as much or as little as they would like. Participants were informed that if they finished the food provided they could request more. After they finished eating, participants rated the food on sensory aspects (pleasant, sweet, salty, savoury, appetising (visually), familiar, filling, soft) presented on VAS (1–100) anchored 'not at all' to 'extremely'. Participants completed the cognitive task and hunger and fullness ratings again and were then provided with a snack box. Participants were told they could eat as much or as little as they liked from the snack box during the remainder of the day, but to refrain from eating anything else that wasn't provided in the snack box.

Evening meal sessions took place approximately 4.5 h later. Participants first completed hunger and fullness ratings followed by the cognitive task. Participants were then provided the evening meal, a large bowl (800 g) of cheese and tomato pasta, and bowl of mixed vegetables (225 g) with no difference in ED between conditions, and were told they could eat as much or as little as they liked. Sensory ratings for the meal were then completed. Finally, to further corroborate the cover story, the cognitive task was repeated and participants provided final hunger and fullness ratings before being reminded to return their snack box (including uneaten items) the following morning. During the final evening meal session, participants completed the same post-meal measures as in experiment 1 (with the exception of the portion size perception task). Next, participants were provided with an explanation of ED ("Energy density can be described as the number of calories per gram of food") and asked to order the three lunch sessions they had completed by ED ("Please rate your lunches for the past three weeks in order of energy density") to measure awareness of differences in ED between foods. Participants were debriefed and compensated £60 for their time.

2.3. Analyses

In experiment 1 we examined the effect of ED condition on weight and energy intake of desserts using one-way within subjects ANOVAs. In experiment 2, we used the same approach to examine weight and energy intake of the ED manipulated food. For all ANOVAs across the two experiments, significant differences were explored through Bonferroni post-hoc comparisons. These were completed using a Bonferroni correction on SPSS statistics which adjusts the alpha level for multiple comparisons. Planned secondary analyses explored whether any effects of ED condition interacted with participant characteristics (BMI, education, satiety responsiveness and compensatory health beliefs) to influence weight and energy intake. In experiment 2 we used the same approach as in primary analyses to examine effects of ED condition on total weight and energy later consumed (snack box and evening meal combined) during the remainder of the day. Results of primary analyses were considered significant at $p < 0.05$, and for secondary analyses $p < 0.01$ to account for multiple comparisons. Sensitivity analyses examined the influence of extreme outliers, any differences in sensory ratings of foods between ED conditions, and if results differed among participants who guessed the aims or were aware of the ED of manipulated foods. For the full analysis strategy see Supplementary Material IV. For both experiments, if participants had any missing data (i.e. did not complete all three sessions), they were excluded from analyses. The participant flow diagrams in Supplementary material V document instances where participants did not complete all sessions. All analyses were conducted in SPSS 26.0.

2.4. Ethics

Ethical approval was obtained from the University of Liverpool Ethics committee (approval code: 4612), and informed consent was obtained from all participants before they took part in the study.

3. Results

3.1. Experiment 1

3.1.1. Participant characteristics

Thirty-seven participants took part in the experiment. N = 3 were excluded from analyses as they did not complete all experimental sessions, resulting in a final sample size of 34 participants (62% female), with a mean age of 37.4 ± 18.1 years and a mean body mass index (BMI) of 25.0 ± 4.6 kg/m^2 (Table 3).

3.1.2. Food intake

Table 4 shows the means and standard deviations for food intake over the three lunch time sessions and dessert (low, medium, high) consumption is visually represented in Fig. 3.

There was a significant effect of ED on weight of dessert consumed ($F(2,66) = 21.0$, $p < 0.001$, $\eta p2 = 0.389$). Bonferroni post-hoc comparisons identified that participants consumed significantly fewer grams of the medium ED dessert ($p < 0.001$, Cohen's d = 0.97) compared to the low ED dessert. Additionally, participants consumed significantly fewer grams of the medium ED dessert compared to the high ED dessert ($p = 0.044$, Cohen's d = 0.41). The difference between the high ED dessert and low ED dessert was also significant ($p < 0.001$, Cohen's d = 0.94) whereby fewer grams of the high ED dessert were consumed compared to the low ED dessert.

A one-way within subjects ANOVA identified that there were significant differences in energy intake for the three desserts ($F(1.7,55.4) = 94.8$, $p < 0.001$, $\eta p2 = 0.742$). There was no significant difference between the low and medium ED dessert ($p > 0.999$, Cohen's d = 0.00). However, participants consumed significantly more energy from the high ED dessert compared to the medium ED dessert ($p < 0.001$, Cohen's d = 2.31) and compared to the low ED dessert ($p < 0.001$, Cohen's d = 4.42).

ED condition did not interact with any participant characteristics (satiety responsiveness, compensatory health beliefs, BMI or level of education) to influence energy or weight intake. For further information see Supplementary Material VI.

Table 3
Participant characteristics for experiments 1 and 2.

	Experiment 1		Experiment 2	
	Mean (sd)	Range	Mean (sd)	Range
Age	37.4 (18.1)	18.0–73.0	36.4 (19.2)	18.0–76.0
Body Mass Index (BMI)	25.0 (4.6)	18.3–33.3	23.6 (3.1)	18.9–33.1
Childhood socioeconomic status	4.0 (1.3)	1.5–6.0	4.5 (1.5)	2.0–7.0
Satiety responsiveness	9.2 (3.1)	4.0–15.0	9.7 (2.3)	6.0–14.0
Compensatory health beliefs	22.6 (4.6)	10.0–29.0	22.2 (4.4)	16.0–32.0
Equivalised household income	£20,314.0 (13,898.7)	£4285.7–75,000.0	n/a	n/a

	Category	Experiment 1 N (%)	Experiment 2 N (%)
Gender	*Female*	21 (61.8%)	21 (65.6%)
	Male	13 (38.2%)	10 (31.3%)
	Other	0	1 (3.1%)
Ethnicity	*White British*	24 (70.6%)	18 (56.3%)
	Chinese	4 (11.8%)	n/a
	Caribbean	n/a	1 (3.1%)
	Indian	n/a	9 (28.1%)
	Pakistani	1 (2.9%)	0
	Other Asian	2 (5.9%)	0
	Other White background	2 (5.9%)	1 (3.1%)
	Other mixed/multiple ethnic background	1 (2.9%)	3 (9.4%)
Subjective Social Status[a]	*2*	1 (2.9%)	0
	3	0	3 (9.4%)
	4	3 (8.8%)	1 (3.1%)
	5	9 (26.5%)	1 (3.1%)
	6	8 (23.5%)	15 (46.9%)
	7	11 (32.4%)	7 (21.9%)
	8	1 (2.9%)	5 (15.6%)
	9	1 (2.9%)	0
Education	*Less than high school completion*	0	1 (3.1%)
	High school completion	3 (8.8%)	3 (9.4%)
	College or foundation degree	5 (14.7%)	3 (9.4%)
	Bachelor's degree	12 (35.3%)	14 (43.8%)
	Master's degree	11 (32.4%)	11 (34.4%)
	Doctoral or professional degree	3 (8.8%)	0
Weight status[b]	*Underweight (BMI < 18.5)*	2 (5.9%)	0
	Healthy weight (BMI 18.5-24.9)	17 (50%)	23 (71.9%)
	Overweight (BMI 25-29.9)	8 (23.5%)	7 (21.9%)
	Obesity (BMI > 30)	7 (20.6%)	2 (6.3%)

[a] Participants rated themselves on a scale from 1 to 10 where 1 represents people with the least money, least education and worst jobs/no job and 10 represents people with the most money, most education and best jobs.
[b] Weight status was grouped using BMI data measured by researchers.

3.1.3. Sensory ratings, familiarity and portion size selection

Fig. 4 shows the mean sensory ratings for each dessert. Findings from ANOVAs relating to sensory ratings are summarised in Supplementary Material VII. An ANOVA identified significant differences for ratings of thickness, indicating that the medium and high ED desserts were perceived as thicker than the low ED dessert, however follow-up pairwise comparisons were not significant at $p < 0.01$. Significant differences were also identified for ratings of sweetness, and filling, whereby the medium ED dessert (12.1 ± 2.8, $p < 0.001$, Cohen's d = 0.71) and high ED dessert (11.8 ± 3.2, $p = 0.002$, Cohen's d = 0.54) were rated significantly sweeter than the low ED dessert, and the high ED dessert

Table 4
Foods consumed in experiments 1 and 2, with means and standard deviations for intake (weight (g) and energy (kcal)).

[a]	Weight eaten (g)	Served energy density (kcal/g)	Energy eaten (kcal)
	Experiment 1		
Sandwich[b]	93.6	2.2	205.4
	M(SD)		**M(SD)**
Low ED dessert (Yogurt)	157.8 (50.1)	1.2	186.2 (59.2)
Medium ED dessert (Ice Cream)	100.2 (48.0)	1.9	186.3 (89.2)
High ED dessert (Cheesecake)	123.1 (40.1)	3.5	426.9 (138.6)
Low ED lunch[c]	251.3	1.6	392.0
Medium ED lunch	193.7	2.0	395.1
High ED lunch	216.7	2.9	635.5
	Experiment 2		
Low ED lunch	480.7 (190.8)	1.1	530.3 (207.1)
Medium ED lunch	481.9 (162.7)	1.7	848.2 (292.2)
High ED lunch	430.6 (180.2)	3.1	1313.7 (552.4)
Low ED later intake[d]	778.9 (280.6)		1424.7 (467.5)
Medium ED later intake	875.1 (381.7)		1509.3 (565.6)
High ED later intake	846.9 (293.2)		1454.0 (490.1)
Low ED daily intake		1955.0 (596.8)	
Medium ED daily intake		2357.4 (691.7)	
High ED daily intake		2767.7 (835.5)	

[a] Results are represented visually in Fig. 3.
[b] Participants were given their preferred sandwich (chicken, bacon & lettuce or cheddar ploughman's) and required to eat all of the sandwich provided. Sandwich means are weighted according to the proportion of participants receiving each filling.
[c] Sandwich and dessert means combined.
[d] ″Later" refers to intake for the remainder of the day, following the manipulated meal.

was rated significantly more filling than the low ED dessert (14.7 ± 3.6, p = 0.001, Cohen's d = 0.63) and medium ED dessert (9.2 ± 2.7, p = 0.006, Cohen's d = 0.54). These findings indicate that sensory properties of the foods that differed as a function of ED were perceivable by participants.

Participants were familiar with the desserts, reporting consuming the low ED (9.8 ± 12.6 times/month), medium ED (2.3 ± 1.9 times/month) and high ED (0.9 ± 1.3 times/month) with regular frequency. When controlling for familiarity to account for these differences, the majority of findings remained the same, however participants no longer consumed significantly fewer grams of the medium ED dessert compared to the high ED dessert (p = 0.051). In the computerised task in which participants selected a portion size of each of the three ED foods, portion size selections show the same pattern as measured intake for the three desserts (Supplementary Material VIII). There were no substantial differences in mean hunger and fullness ratings between the three ED conditions. See Supplementary Material IX for hunger and fullness ratings for experiment 1.

When adjusting based on ratings of sweetness, primary findings remained the same. There was no longer a significant difference in weight eaten across conditions when controlling for both filling ($F(2,60) = 0.1$, $p = 0.887$, ηp2 = 0.229) and thickness ratings ($F(1.6,48.1) = 1.8$, $p = 0.188$, ηp2 = 0.055), indicating that the differences observed in meal size (grams) between the low vs. medium ED foods may have been in part influenced by sensory cues. All results were found to be similar in sensitivity analyses (See Supplementary Material VI).

3.2. Experiment 2

3.2.1. Participant characteristics

Thirty-five participants took part in the experiment (Table 3). N = 1 were excluded from analyses as they did not complete all sessions. A further n = 2 were excluded as they consumed additional food not provided by researchers, although results were the same when included (see Supplementary Material X). The final sample (n = 32) was 65.6% female, with a mean age of 36.4 ± 19.2 years, and a mean BMI of 23.6 ± 3.1kg/m2. For a participant flow diagram see Supplementary Material V.

3.2.2. Food intake

Table 4 shows the means and standard deviations for food intake at lunch time, after the manipulated meal and total daily energy intake. Lunch time weight and energy intake are represented visually in Fig. 3. Differences in weight consumed for the three manipulated lunch time meals were close to but not significant ($F(2,62) = 3.2$, $p = 0.050$, ηp2 = 0.092). This trend appeared to be driven by meal size being slightly smaller in the high ED condition than other conditions.

There was a significant effect of ED condition on energy intake ($F(1.3, 41.0) = 69.5$, $p < 0.001$, ηp2 = 0.692). Participants consumed significantly more kcal of the medium ED meal ($p < 0.001$, Cohen's d = 1.94) compared to the low ED meal. Additionally, participants consumed significantly more kcal of the high ED meal compared to the medium ED meal ($p < 0.001$, Cohen's d = 1.65) and the low ED meal ($p < 0.001$, Cohen's d = 5.89).

ED condition did not interact with any participant characteristics (satiety responsiveness, compensatory health beliefs, BMI or level of education) to influence energy or weight intake at the lunch meal (ps > 0.05).

3.2.3. Sensory ratings

Fig. 4 shows the mean sensory ratings for manipulated meals. Results from ANOVAs comparing sensory ratings are shown in Supplementary Material VII. Significant differences were observed for ratings of saltiness (p = 0.045), although pairwise differences between meals were not significant (ps > 0.108). When controlling for ratings of saltiness in primary ANOVAs, differences in both weight and energy intake at lunch remained the same. No significant differences were found for other sensory ratings (ps > 0.078). Hunger and fullness ratings for experiment 2 show the same pattern across the course of the study day, with little difference across ED condition. These ratings are shown in Supplementary material IX.

3.2.4Secondary findings.

One-way within subjects ANOVAs found no significant differences in weight intake ($F(2,62) = 0.8$, $p = 0.452$, ηp2 = 0.025) or energy intake ($F(2.62) = 0.4$, $p = 0.688$, ηp2 = 0.012) of other foods later in the day following the three manipulated lunch conditions. This indicates that no significant compensation took place following the manipulated meals. As a result, significant differences were observed for daily energy intake by ED condition ($F(2,62) = 27.0$, $p < 0.001$, ηp2 = 0.465). Participants consumed significantly more energy from the medium ED study day (p = 0.002, Cohen's d = 0.74) compared to the low ED study day. Additionally, participants consumed significantly more energy on the high ED compared to the medium ED study day (p = 0.008, Cohen's d = 0.65). The difference in daily energy intake was also significant for high ED compared to low ED study days ($p < 0.001$, Cohen's d = 1.90). All results were found to be similar in sensitivity analyses (See Supplementary Material VI).

4. Discussion

Across two experiments we examined the effect of varying food energy density on meal size. Contrary to recent suggestions (Flynn et al.,

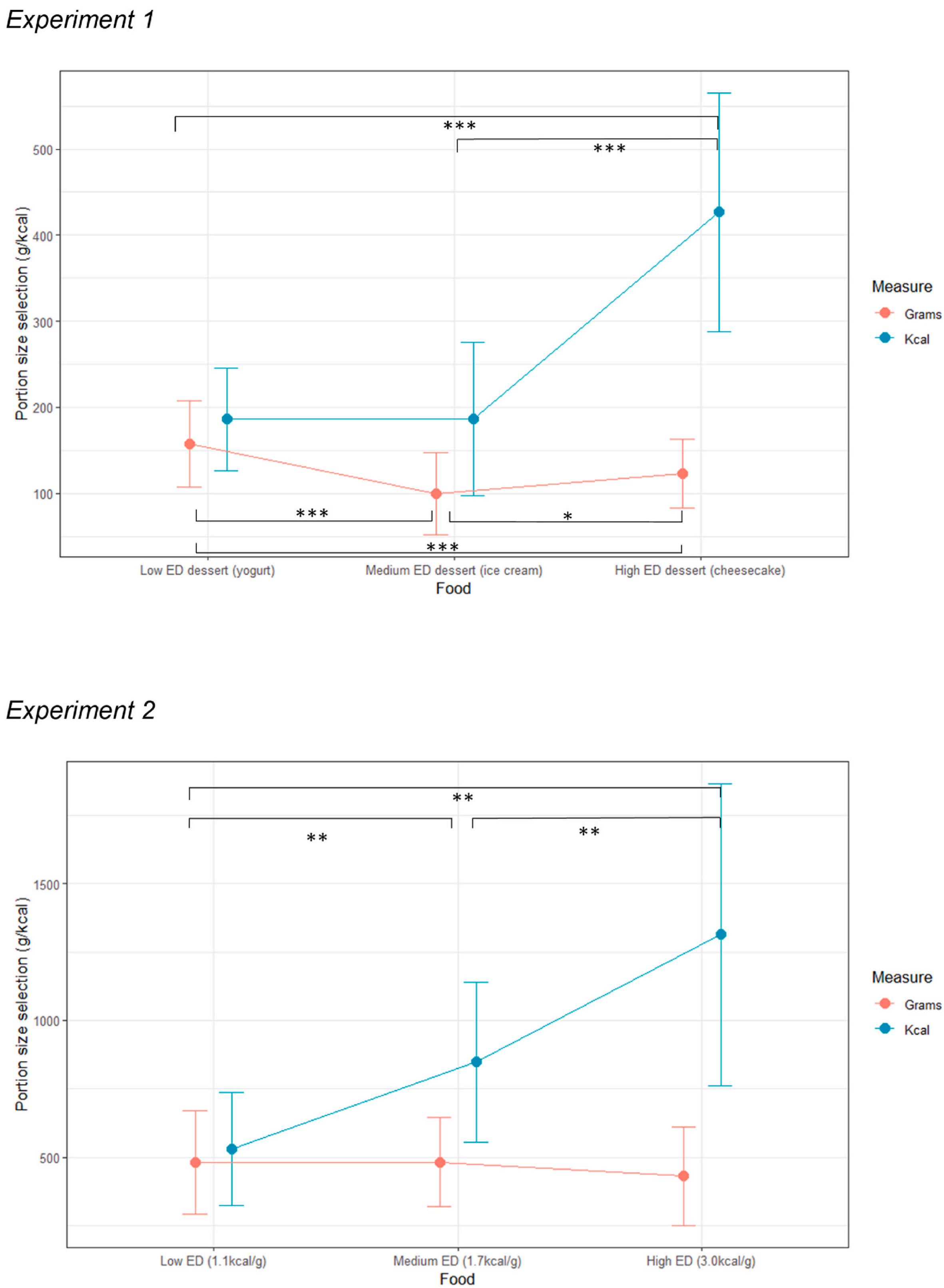

Fig. 3. Means and standard deviations for weight and energy intake for ED manipulated foods. [1]Error bars represent standard deviation. [2]*p < 0.05; **-<0.01; ***p < 0.001.

2022), there was little evidence that participants adjusted meal size when consuming foods high in ED.

When participants consumed foods high in ED (>3 kcal/g) in experiment 1 and experiment 2, total meal energy intake was substantially increased (by 241 kcal and 466 kcal respectively), compared to when served similar foods of medium ED (1.7–2.0 kcal/g). These increases in energy intake were observed because the weight of food consumed was similar for medium and higher ED foods. These

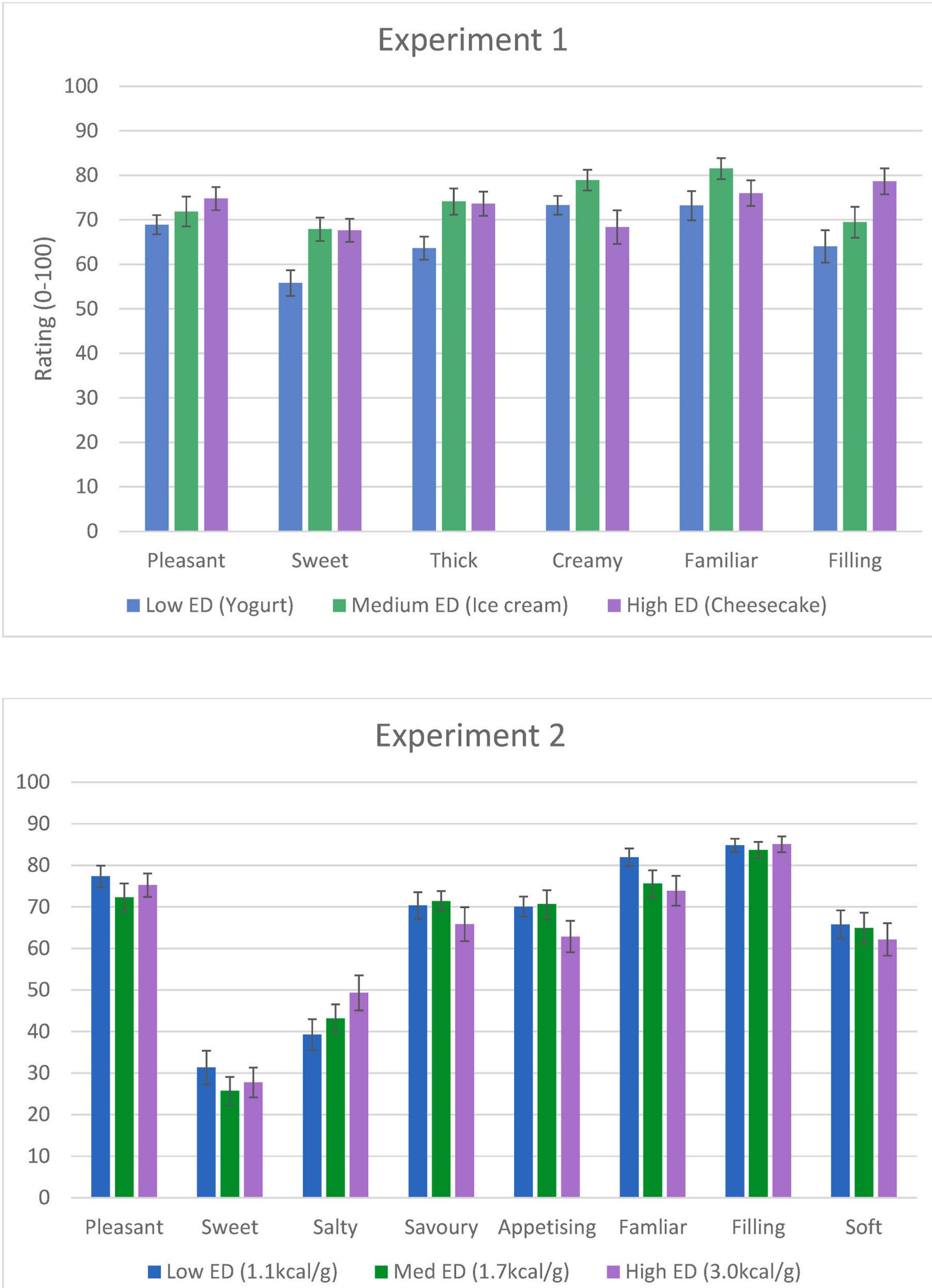

Fig. 4. Sensory ratings for ED manipulated foods in experiment 1 (top panel) and experiment 2 (bottom panel). [1]Error bars represent standard error.

findings do not support the suggestion made by Flynn et al. that above an ED of 1.5–2.0 kcal/g meal size (grams) is reduced and sometimes overcompensated for due to sensitivity to the energy content of meals above this ED (i.e., energy content – rather than volume of food – is the dominant signal). Critically, in the present study, when the food higher in ED was familiar to participants (experiment 1), and therefore previous dietary learning would have been possible, even though the food was perceived as being more filling than the lower ED foods, there was little or no reduction in meal size (i.e. volume of food – rather than energy content – is the dominant signal).

In experiment 1 when familiar foods with some sensory differences were served that differed in ED (desserts as part of a main meal), participants consumed fewer grams of the medium ED food compared to the low ED food. This resulted in similar energy intake for the two foods. Comparatively, in experiment 2 where meals with limited sensory differences were served (a relatively covert ED manipulation), participants consumed a similar meal size for all ED manipulated meals which resulted in a largely linear relationship between ED and energy intake. The results for low vs medium ED comparisons for experiment 2 are therefore consistent with Flynn et al.'s two component model, whereby at EDs lower than 1.5–2.0 kcal/g (medium and lower EDs) there is no adjustment of meal size based on ED. Interestingly the findings of experiment 1 were not consistent with Flynn et al., because meal size was smaller in the medium ED vs. lower ED condition. Self-reported data indicated that participants were generally aware they needed to eat less of the medium ED (ice cream) than the low ED (yogurt) food to feel full, which is consistent with meal size adjustment based on dietary learning (i.e. an energy content as opposed to volume as the dominant signal). Consistent with this interpretation, when differences in sensory ratings relating to thickness and how filling foods were perceived to be between ED foods were controlled for, the differences in meal size (i.e. reduced meal size in medium vs. low ED condition) became non-significant. Therefore, participants in experiment 1 appeared to show some evidence of meal size sensitivity to ED based on food sensory characteristics, but not for higher ED foods.

Neither of our experiments fully support the hypothesis made by Flynn et al. who suggested humans show insensitivity to energy density at a lower level (up to 1.5 kcal/g), and EDs upwards of this level are compensated for (and sometimes overcompensated for) through a reduction in meal size. Experiment 2 demonstrated that participants showed insufficient sensitivity to the ED of all manipulated meals thus supporting a 'passive overconsumption' hypothesis. As discussed above, in experiment 1 meal size differed for low vs. medium ED foods in a manner consistent with adjustment for energy content. An alternative explanation is that the smaller meal size for the medium ED food observed in experiment 1 may be unrelated to dietary learning and due to unmeasured differences between the low, medium and high ED foods studied.

There are a number of possible explanations as to why our findings are not consistent with the proposed model by Flynn et al. Importantly, Flynn et al. used observational data where intake may have been influenced by confounding unmeasured factors aside from the ED of foods (Robinson et al., 2023). For example, it is possible that the serving sizes of foods provided differed by the level of ED recorded (e.g. lower ED foods may have been served in larger portions than higher ED foods), and research has consistently shown that being served a larger vs. smaller portion of a food increases vs. decreases meal energy intake (Hollands et al., 2015; Roe et al., 2016). Additionally, types of food may differ by ED. Typically, foods higher in ED have a high fat content (e.g. peanut butter), while foods lower in ED have a high water content (e.g. fruits and vegetables) (Drewnowski, 2003) and these differences may indirectly affect energy intake through other mechanisms such as texture (Bolhuis & Forde, 2020). There may also be differences in food liking between consumed meals varying in ED that would contribute to differences in meal size patterns (Brunstrom & Rogers, 2009; Diktas et al., 2022; Keller et al., 2022), as research suggests that humans may show an innate preference for foods higher in ED (Stubbs and Whybrow, 2004). In the present experiments we addressed a number of these concerns by equivalising food types and serving sizes provided by ED, in addition to statistically (experiment 1) and experimentally (experiment 2) controlling for differences in sensory ratings between ED conditions.

Flynn et al.'s proposed model of ED on energy intake focused on data examining acute energy intake at a single meal only. In experiment 2, we examined whether manipulating ED affected meal size and energy intake later in the day. Differences in energy consumption at lunch time were not compensated for later in the day, resulting in overall greater daily energy intake of 400 kcal on medium vs. low ED study days and 410 kcal on high vs. medium ED study days. These findings suggest that reformulation of high energy dense foods would decrease total daily energy intake and therefore have the potential to benefit population level health, assuming there is minimal dietary compensation over time through dietary learning.

When conducting research into ED, it is important to consider the role of dietary learning. It is possible that over time and repeated exposure, individuals learn about the satiating properties of a food, and adjust their intake accordingly. If such learning does occur, thus indicating sensitivity to ED, then reformulation strategies may have little benefit in the long term. Two studies explored learning of ED by providing repeated exposure on 5 (Specter et al., 1998) and 10 occasions (Miller et al., 1998) respectively. In the first of these studies, two flavours of ice cream were provided at different levels of ED (1.5 vs 2.1 kcal/g) for five days each. In the second study, potato chips were provided at two different levels of ED (2.5 vs 5.5 kcal/g) for 10 days each. For both studies, no adjustments to meal size were observed. Participants consistently consumed the same weight of the provided foods and so had significantly higher energy intake from the high ED foods. These findings suggested a sustained impact on energy intake of energy reformulation, however exploration of dietary learning for a range of foods is warranted, over longer study periods (Stubbs et al., 2000).

4.1. Strengths and limitations

We used an experimental approach and this allowed us to choose and manipulate foods that were lower ED, higher ED and around the proposed 'break point' suggested by Flynn et al. Experiment 1 used familiar foods differing in ED to examine the influence of dietary learning on energy intake in response to ED when sensory differences between foods were present. The use of different desserts that would be familiar to participants was necessary to test the theory that dietary learning leads to reductions in meal size based on food energy density. Due to the underlying differences in the foods used in experiment 1, there may have been pre-existing preferences, perceptions, or sensory differences that could have influenced intake. However, where any differences in preferences or sensory differences were observed, these were controlled for in analyses. If participants had pre-existing perceptions regarding the healthiness of the desserts provided, these may have influenced the amount eaten to some extent. However crucially our findings show that energy intake of the highest ED dessert (and therefore most likely to be considered unhealthy) was the highest, so any impacts of perceptions appeared insufficient to counteract the effect of the highest ED on energy intake. Pre-existing perceptions may have played a role in the serving size choices for the medium ED dessert (i.e., ice cream = unhealthier than yoghurt and/or inappropriate to consume for dessert at lunchtime) and this may explain why meal size was lower than expected. Differences were also observed for frequency of consuming the three foods provided, however when this was adjusted for in the analyses, there were limited changes to results. Experiment 2 addressed these limitations by using a manipulated meal with similar ingredients and sensory characteristics to examine whether foods with a largely unknown ED differed in energy intake. Additionally, experiment 2 considered later energy intake following the manipulated meal. Later intake may have been different following intake of foods where the differences in ED would be familiar to participants (i.e. experiment 1). Additionally, across both experiments, we tested hypotheses using a limited number of foods, and so future research would benefit from extending our manipulations to a wider range of foods over longer periods of follow-up. A limitation of experiment 1 is that only the dessert component of the meal was manipulated as opposed to all components (as in experiment 2). Nonetheless, we found evidence that participants readily ate the desserts (mean of 127 g and 266 kcal across the three conditions) and the dessert consumption amount varied between and within participants suggesting that meal size adjustment was possible in this design. Moreover, EDs of the total lunch meal consumed (including sandwich and dessert components) were low, medium and high.

Altering the ED of a food requires altering its nutritional components (e.g. fat/protein content), which have different impacts on satiety (Marmonier et al., 2000). One study investigated three methods of altering energy density; reducing fat, increasing fruit and vegetables and increasing water (Williams et al., 2013). All methods significantly reduced energy intake but greatest reductions were observed when fat content was reduced. In both of our experiments, a range of methods were used to manipulate ED whilst preserving the likeability of the foods. In experiment 1, increases in carbohydrates and sugar contributed the greatest differences in ED at low vs. medium levels. The increase from medium to high ED appeared to largely result from increases to fat and carbohydrates. In experiment 2, an increase in carbohydrates contributed the greatest differences at low vs. medium EDs, while differences between medium vs. high EDs were largely a result of increased fat. Interestingly, protein content was substantially increased in the higher ED foods across both experiments, but we found no evidence of decreased meal size in higher ED foods which appears to be inconsistent with the proposition that dietary protein is particularly satiating (Morell & Fiszman, 2017; Westerterp-Plantenga et al., 2012). Future work examining whether specific combinations of macronutrients are more or less likely to affect adjustments to meal size would therefore be informative.

Across both experiments, we chose not to account for physical activity levels of participants. There is limited evidence that in the short term (i.e. a single exercise session), physical activity increases appetite (Dorling et al., 2018). Some research suggests that over longer periods of participation in physical activity, partial compensation may occur through increased intake (Drenowatz, 2015). However, as our experiments tested participants through repeated measures is it unlikely this would have had a great impact on our findings.

While we sought to recruit a wide range of participants, our samples were not representative of the UK population. Specifically, our sample were majority female, higher educated, healthy weight participants, and not representative in terms of the ethnicity of the UK population. Further research examining the generalisability of our findings may therefore be valuable.

5. Conclusion

Contrary to recent suggestions, foods high in ED were largely not associated with adjustments to meal size and were associated with increased energy intake in adults across two experiments. Reformulation of foods high in ED may be an effective population level approach to reducing energy intake and obesity.

Ethics statement

Ethical approval was obtained from the University of Liverpool Ethics committee (approval code: 4612), and informed consent was obtained from all participants before they took part in the study.

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CRediT authorship contribution statement

Amy H. Finlay: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Writing – original draft. **Emma J. Boyland:** Funding acquisition, Supervision, Writing – review & editing, Conceptualization. **Andrew Jones:** Conceptualization, Supervision, Writing – review & editing. **Tess Langfield:** Conceptualization, Data curation, Investigation, Methodology, Project administration, Writing – review & editing. **Eve Bending:** Data curation, Investigation, Methodology, Project administration, Writing – review & editing. **Manraj S. Malhi:** Data curation, Investigation, Methodology, Project administration, Writing – review & editing. **Eric Robinson:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing.

Declaration of competing interest

ER has previously received research funding from Unilever and the American Beverage Association for unrelated research projects. Other authors have no competing interests.

Data availability

Data will be made available on the open science framwork

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.appet.2024.107533.

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