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Effects of repeated consumption on sensory-enhanced satiety.

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Abstract

Previous research suggests that sensory characteristics of a drink modify the acute satiating effects of its nutrients, with enhanced satiety evident when a high energy drink was thicker and tasted creamier. The present study tested whether this modulation of satiety by sensory context was altered by repeated consumption. Participants (n=48) consumed one of four drinks mid-morning on seven non-consecutive days with satiety responses measured pre-exposure (day 1), post-exposure (day 6) and at a one month follow-up. Drinks combined two levels of energy (lower energy, LE, 326 KJ: higher energy, HE, 1163KJ) with two levels of satiety-predictive sensory characteristics (low-sensory, LS, or enhanced sensory, ES). Test lunch intake 90 minutes after drink consumption depended on both the energy content and sensory characteristics of the drink before exposure, but on energy content alone at post-exposure and the follow-up. The largest change was an increase in test meal intake over time in the LE/LS condition. Effects on intake were reflected in appetite ratings, with rated hunger and expected filling affected by sensory characteristics and energy content pre-exposure, but were largely determined by energy content post exposure and at follow up. In contrast, a measure of expected satiety reflected sensory characteristics regardless of energy content on all three test days. Overall these data suggest that some aspects of the sensory-modulation of satiety are changed by repeated consumption, with covert energy becoming more effective in suppressing appetite over time, but also suggest that these behavioural changes are not readily translated into expectations of satiety.

Introduction

Although there is considerable evidence that the post-ingestive physiological effects of nutrient intake generate a series of signals that contribute to satiety[1-3] [a], a model of satiety based on gastro-intestinal signalling alone fails to fully explain differences in satiety between products. For example, nutrients ingested as beverages often lead to weak satiety[4], yet similar nutrients ingested as soup generate much stronger satiety[5]. One explanation for discrepancies like this is that information present at the time of consumption generates expectations that modulate post-ingestive satiety processes and the overall experience of satiety reflects this integration of cognitive, sensory and nutrient-induced cues. An increasing number of studies support this view[6-9]. Thus, altering the sensory characteristics of a drink to give it a slightly thicker texture and more creamy flavour both generated expectations that the product would be more satiating[10], and resulted in increased satiety when consumed in combination with additional energy, indexed both from ratings of appetite post-ingestion and intake at a test meal[7,8]. Beliefs about the likely effect of the ingested food or drink do not just alter the behavioural responses, however. Firstly, when participants consumed a solid (gel), or believed that a liquid would turn to a gel in their stomach, they reported greater satiety and showed larger increases in insulin and glucagon-like peptide 1 than when the same nutrients were consumed as a drink or as a gel with the expectation that the gel became liquid[9]. Likewise, ingestion of a product labelled as indulgent produced a steeper decline in the hunger-hormone ghrelin than when labels suggested a low calorie milkshake[11].

Studies of cognitive and sensory influences on satiety to date have concentrated on acute effects, and a key question is whether such effects are maintained following repeat exposure. According to learned satiety[12], repeated co-experience of the sensory characteristics of the consumed product and subsequent experience of satiety should lead to more accurate appetite regulation with experience, evidenced either by more accurate compensation at the test meal[13,14] or changes in the expectations that the drink will be satiating[15]. Although evidence for learned satiety from studies of repeated consumption is weak[16], two studies suggested this was possible here. Firstly, people's expectations about how satiating a product

[a] A distinction can be made between how effective a food is at suppressing appetite while it is being consumed (satiation) and during the period after it has been ingested (satiety).

was changed in line with actual nutrient content after just one exposure[17], although a subsequent study using similar methodology but longer exposure found no such effects[18]. Secondly, there was stronger evidence of learned satiety (indexed by a decrease in *ad libitum* consumption over time) when a drink's textural (viscosity) rather than flavour cues predicted nutrient content[19], perhaps because texture is a more consistent predictor of energy[20]. Thus learned satiety might be more evident after repeated exposure to a high-energy product with sensory characteristics that predict satiety than after exposure to the same product without these sensory characteristics. Building on methodology from studies of sensory-modulation of nutrient-based satiety[7,8], we tested this prediction by repeatedly exposing participants to low or high energy beverage preloads with or without added thick and creamy sensory properties and measuring effects on expected and actual satiety responses.

Methods

Study design

The satiating effects of one of four versions of a test drink combining two levels of energy (lower energy, LE, 326 KJ: higher energy, HE, 1163 KJ) with two levels of satiety-predictive sensory characteristics (low-sensory, LS, or enhanced sensory, ES) was measured at the start of testing (Pre exposure, day 1) , after four exposure days (Post-exposure, day 6) and one month later (Follow-up, day 7).

Participants

Forty-eight non-obese (BMI mean: 23.6; range: 19-30) young (age mean: 21.3 years; range: 18-34) men participated, mostly undergraduates at the University of Sussex. Volunteer men whose details on a recruitment database suggested they were unrestrained (Three Factor Eating Questionnaire Restraint score ≤8[21]) and who self-reported smoking less than 5 cigarettes a week were told that the purpose of the study was "To investigate how a mid-morning snack influences your mood". Respondents who confirmed that they were generally healthy, were not taking any prescription medication and were not allergic or aversive to any of the foods and ingredients used in the study were assigned at random to one of the four treatment conditions, and these four groups did not differ significantly in age or BMI (Table 1). This study was conducted according to guidelines laid down in the Declaration of Helsinki (1996) and was approved by the University of Sussex ethics committee. Written informed consent was obtained from all participants.

Test foods

Breakfast

Each day participants consumed a set breakfast (total 1678 KJ), consisting of cereal (60g: Crunchy Nut cornflakes, Kellogg's plc UK), semi skimmed milk (160g: Sainsbury's, UK) and orange juice (200g: Sainsbury's, UK).

Beverage preload

Test beverages were 320 gram portions of mango and peach flavoured yoghurt drinks, served in commercial "smoothie" bottles (Esterform, UK). Four versions were developed, two LE (326 KJ) and two HE (1163 KJ), with energy manipulated by adding maltodextrin (C*PUR 1910, Cargill UK) with either LS or ES sensory characteristics (sensory enhancements achieved by adding tara gum (Kalys, France), milk caramel flavour (S Black, UK) and vanilla extract (Neisslen-Massey, UK)) based on previous studies which confirmed LE and HE were sensorially similar, and ES were thicker and creamier than LS[7,8,10]. The full ingredients were: mango juice (all versions: 100g, Tropicana, UK), peach squash drink (all versions: 35g, Robinson's, UK), 0% fat fromage frais (LE versions: 55g; HE versions: 30g, Sainsbury's, UK), water (LE versions: 130g; HE versions: 100g), maltodextrin (HE versions: 55g), yellow colour (LE versions: 8 drops, Silverspoon, UK), red colour (all versions: 2 drops, Silverspoon, UK), tara gum (LE/LS: 0.3g: LE/ES: 1.2g: HE/ES: 1g; Kayls, FR), aspartame (LE versions 0.03g, Ajinomoto, Japan), vanilla extract (all ES versions: 1g), and milk caramel flavour (all ES versions: 0.5g). *Test lunch*

The satiety test included an *ad libitum* two-course lunch consisting of pasta (each serving 250 grams of cooked pasta, "Conchiglie", Sainsbury's UK, plus 250 grams of tomato and basil pasta sauce, Sainsbury's, UK) followed by ice-cream ("Chocolate Inspiration"; Carte D'OR, Unilever). Participants were permitted to consume water *ad libitum* during this meal.

Procedure

Testing took place on seven non-consecutive weekdays at the Sussex Ingestive Behaviour Unit, UK. Satiety responses to the beverages were assessed at the start of testing (Pre-exposure, day 1), after repeated consumption (Post-exposure, day 6) and at the one month follow up (day 7), with test days 2-5 serving as beverage-exposure days. Test days 1-6 were conducted over a three to four week period with each session separated by at least one day; the final follow-up test took place at least one month after the Post-exposure session. On all days participants consumed breakfast in the laboratory between 08.45-09.45 having consumed only water from 11 pm the previous evening. After breakfast they were permitted to leave the laboratory but could consume only water until they returned two hours later.

On their return, participants evaluated their mood and appetite (baseline ratings) using Sussex Ingestion Pattern Monitor software (SIPM version 2.011, University of Sussex[22] run on PC). In line with the guise that the study examined effects of the test drink on mood, participants rated their nervousness, clearheadedness, tiredness, happiness, alertness, nausea as well as hunger and fullness using visual analogue scales (VAS) in the format of "How <target rating> do you feel right now?", end-anchored with "Not at all <target rating> and

"Extremely <target rating>", and in a randomised order. Only ratings of hunger and fullness were analysed.

Next, at the Pre-exposure, Post-exposure and Follow-up sessions, participants completed an expected satiety task adapted from methodology developed by Brunstrom and colleagues[23,24]. Expected satiety was defined as the anticipated suppression of hunger in the time after ingestion. Participants were presented with a sealed bottle of their beverage as an example of a standard portion plus a 20 ml sample to be used for the task along with the instruction "Take one mouthful of the sample of the yoghurt drink in front of you. Imagine that you had consumed the whole bottle for your breakfast. Now imagine how hungry you would feel just before lunch. In this task you will be asked to select the amount of breakfast cereal that you would need to eat to match the effect of the yoghurt drink on your hunger". They then adjusted the size of portions of cereal displayed on-screen to match their expectations about how much the yoghurt beverage would suppress subsequent appetite. Seven cereal products that are well known by British consumers (Cocopops ,Kellogg's; Branflakes, Kellogg's); Shreddies, Nestle); Cheerios, Nestle); Alpen, Weetabix: Crunchy Nut Clusters, Kellogg's; Cornflakes, Kellogg's) were used, with fifty photos of each cereal increasing logarithmically in portion size from 155 KJ to 1904 KJ. Then on-screen instructions prompted participants to consume one mouthful of the beverage and then complete VAS ratings of its sweetness, creaminess, pleasantness, thickness, fillingness and familiarity using the same format as for the mood ratings. They were then allowed 10 minutes to consume their beverage, before re-rating mood and appetite (post-preload ratings). On the exposure only sessions (days 2-5) participants were free to leave the laboratory but were required to repeat mood and appetite questions (paper version) 90 minutes later, having consumed only water. At the Pre-exposure, Post-exposure and Follow-up sessions, participants returned to the laboratory 90 minutes later for their lunch session having consumed only water.

The lunch session began with participants re-rating their mood and appetite (pre-lunch ratings). They were then served a portion of pasta rated it for pleasantness, savouriness, saltiness and familiarity, before re-rating appetite (lunch appetiser ratings). Intake was covertly recorded by a balance (Sartorius model BP4200) built into the table and hidden underneath a placemat and connected to a PC running SIPM. Every time the participant consumed at least 400 grams of pasta an audible alert and on-screen message prompted the participant to call their researcher, who provided a new serving so participants could not use an empty bowl as a meal-termination cue. Once the participant had eaten enough they selected an on-screen button “course completed”. Participants were then served 150g of ice cream, which they rated for creaminess, sweetness, pleasantness and familiarity before consuming as much as they liked. Refills were provided whenever weight decreased by at least 100 grams. Lunch ended with participants selecting an on-screen button after which they re-rated appetite and mood (post-lunch ratings). Participants were paid £40 on completion of the Post-exposure session and were invited to participate in the follow-up session, for which they were paid an additional £10. Height and weight were recorded at the end of testing followed by structured debriefing to record participant’s beliefs about the purpose of the study.

Data analysis

The key questions were (a) did the degree to which the test drink generated expected and actual satiety depend on both its energy content and sensory characteristics (b) were these effects modified by repeated consumption and (c) were these effects sustained one month later. To test the first two questions, measures of satiety (expected satiety, expected filling, changes in rated appetite post-consumption and intake at the test lunch) on Pre-exposure and Post-exposure days were contrasted using ANOVA with energy density (LE vs. HE) and sensory context (LS vs. ES), both between-participant, and test day (Pre or Post-exposure, within participant) as factors. For expected satiety, where we had estimates of the amount (KJ) of each of seven cereals that were expected to suppress hunger to the same extent as the drink, cereal-type was included as a within-participant factor. For appetite ratings, initial analyses confirmed there were no differences in hunger or fullness prior to drink consumption, allowing calculation of changes from baseline immediately post-consumption, before lunch was served and after tasting the main course. These three rating times were included as a within-participant factor. As only 43 participants completed the 1-month follow-up session, these data were analysed separately. One participant had a BMI greater than 30, and therefore BMI was included as a covariate in all analyses.

Results

Test lunch intake

Analysis of total energy consumed at lunch (KJ: Figure 1A) at the Pre- and Post-exposure sessions found a significant 3-way interaction between the drink's energy content, sensory characteristics and test day [F(1,43) = 4.58, p=0.038, η^2 = 0.10], a significant main effect of energy content [F(1,43) = 14.73, p<0.001, η^2 = 0.26] and significant 2-way interaction between energy content and day [F(1,43) = 5.11, p=0.029, η^2 = 0.11]. These effects remained significant when only those participants who completed the follow-up session were included (3-way interaction between energy content, sensory characteristics and day [F(2,76) = 3.22, p=0.046, η^2 = 0.08], main effect of energy [F(1,38) = 17.46, p<0.001, η^2 = 0.32]: day x energy interaction [F(2,76) = 3.18, p=0.048, η^2 = 0.08]).

To allow interpretation of the 3-way interaction, follow-up ANOVA contrasted lunch intake (KJ) in the four drink conditions on each day. At Pre-exposure significantly less was consumed at lunch in the HE/ES condition than in either LE condition, with the HE/LS intermediate [F(3,48) = 3.92, p=0.015, η^2 = 0.22]. In contrast, at Post-exposure intake in the two LE conditions was significantly greater than that in both HE conditions, but with no significant differences between the two HE conditions or the two LE conditions [F(3,43) = 5.65, p=0.002, η^2 = 0.28] . To further assess effects of repeated consumption, lunch intake at the Pre- and Post-exposure sessions was contrasted within-participant. The only significant change was an increase in intake in the LE/LS condition [F(1,10) = 4.68, p=0.049, η^2 = 0.08], although all groups tended to eat more overall at the second test lunch. Likewise at the one-month follow-up, lunch intake still depended on which drink had been consumed [F(3,43) = 6.39, p=0.001, η^2 = 0.34], and here intake in the two LE conditions was very similar, and significantly more than in both HE conditions, which were also similar.

We also calculated total energy consumed (preload plus lunch energy: Figure 1B). Total energy intake at the Pre- and Post-exposure again depended on a combination of the drink's energy content, sensory characteristics and test day [F(1,43) = 5.70, p=0.021, η^2 = 0.12]. Separate analyses on each day found a marginally significant 2-way interaction between energy content and sensory characteristics at Pre-exposure [F(1,43) = 3.75, p=0.06, η^2 = 0.08], and a marginal main effect of energy content at Post-exposure [F(1,43) = 3.83, p=0.057, η^2 =

0.08], but no other significant main effects or interactions. Overall total energy intake was least after consuming the HE/ES drink on both these days, and the effect of energy content at Post-exposure confirms that repeat consumption increased the effects of the energy manipulation and reduced the effects of the sensory enhancements. The surprising finding, however, was the relative over-consumption in the LE/LS condition after repeated exposure. Data from the follow-up confirmed that those consuming the HE drinks consumed significantly less in total than those consuming LE drinks [F(1,43) = 4.91, p=0.033, η^2 = 0.11], and again most was consumed in the LE/LS condition.

Expected satiety and ratings of expected filling

To calculate an overall measure of expected satiety, the average energy content (KJ) of the portion of cereal judged to generate the same level of satiety as the test drink was determined from the seven cereal comparisons (Figure 2A). These values varied depending on the sensory characteristics of the drink [F(1,43) = 4.81, p=0.034, η^2 = 0.10]: participants consuming ES drinks expected that they would need to eat more cereal to suppress hunger compared to those consuming LS drinks. Expected satiety did not depend on energy content [F(1,43) = 0.15, p=0.70, η^2 = 0.01] nor was there any energy x sensory interaction [F(1,43) = 0.20, p=0.66, η^2 = 0.01]. There was also no evidence that expected satiety changed with exposure: the interaction between energy content, sensory context and test day was not significant [F(1,43) = 0.14, p=0.71, η^2 = 0.01], nor was there any other significant interactions involving test day. Analysis of one-month follow-up data also found a significant effect of sensory characteristics on expected satiety [F(1,38) = 5.34, p=0.026, η^2 = 0.12], but no other effects were significant. Thus there was no evidence that drink's energy content moderated expected satiety, nor that repeated exposure led to changes in expected satiety.

Participants also rated how filling they expected the drink to be when they first tasted it on all days (Figure 2B). Analysis of these ratings on days 1-6 found that expected filling varied both with the energy content [F(1,42) = 13.72, p=0.001, η^2 = 0.25] and sensory characteristics [F(1,42) = 7.77, p=0.008, η^2 = 0.31], and also found a significant interaction between energy content and test day [F(5,210) = 2.92, p=0.014, η^2 = 0.07]. At Pre-exposure expected filling only varied with sensory characteristics [F(1,43) = 8.18, p=0.007, η^2 = 0.16], with the LS expected to be less filling than ES. However, ratings of expected filling increased over the six days in both HE conditions, and decreased in the LE/ES condition. Consequently at Post-exposure, expected filling ratings were significantly higher in HE than LE conditions [F(1,43) = 19.68, p<0.001, η^2 = 0.31], but did not now differ depending on sensory characteristics. At the one-month follow-up, filling ratings still depended on energy content [F(1,38) = 8.66, p=0.006, η^2 = 0.19] but not sensory characteristics.

Rated appetite

Initial analyses confirmed no significant effects of test day, drink energy content or sensory characteristics on baseline hunger and fullness ratings and so data were converted to changes from pre-drink ratings. As expected, hunger decreased immediately post-ingestion and then recovering over the 90 min before lunch (main effect of time [F(1,43) = 198.23, p<0.001, η^2 = 0.82]: Table 2). However, these changes depended on test day, and the sensory characteristics and energy content of the drink, with significant interactions between sensory and day [F(1,43) = 7.72, p=0.008, η^2 = 0.15] and between time and energy [F(1,43) = 5.29, p=0.026, η^2 = 0.12]. At Pre-exposure, hunger decreased more immediately after consuming ES than LS drinks [F(1,43) = 4.78, p=0.034, η^2 = 0.10], and although hunger then increased by lunch, it increased less in HE than LE conditions [F(1,43) = 4.29, p=0.044, η^2 = 0.09], with the lowest increase in HE/ES. There was no significant difference between conditions in hunger change immediately after consuming the drink, but these ratings differed immediately before lunch, with a significant effect of energy [F(1,43) = 4.32, p=0.044, η^2 = 0.09] , marginal effect of sensory [F(1,43) = 3.46, p=0.07, η^2 = 0.07] and marginal sensory x energy interaction [F(1,43) = 2.96, p=0.09, η^2 = 0.06], with hunger significantly greater in the LE/ES condition than in the other three conditions, which were similar. Analysis of changes in hunger at follow-up found no significant effects, although the data pattern (Table 2) was consistent with a sustained ability of the HE/ES combination to suppress hunger post-ingestion, which was masked by reduced power due to participant drop-out.

Ratings of fullness tended to mirror hunger ratings (Table 2), with increased fullness immediately post-drink and then recovery up to lunch ([F(1,43) = 203.51, p<0.001, η^2 = 0.82]). Although change in fullness did not vary across days [F(1,43) = 0.04, p=0.85, η^2 = 0.01], this depended both on the sensory characteristics (day x sensory interaction: [F(1,43) = 4.10, p=0.0491, η^2 = 0.08]) and energy content (day x time x energy: [F(1,43) = 5.55, p=0.023, η^2 =

0.11] of the test drink. At Pre-exposure, the increase in fullness immediately after drink consumption depended on sensory characteristics [$F(1,43) = 6.27$, $p=0.016$, $\eta^2 = 0.13$], with a larger increase in fullness after ES than LS versions, but was not affected significantly by energy content. Immediately before lunch fullness had decreased in all conditions except HE/ES, although data variability meant the effects of condition was marginal [$F(3,43) = 2.31$, $p=0.09$, $\eta^2 = 0.14$]. In contrast, at Post-exposure (day 6) fullness increased similarly in all conditions immediately post-consumption, but fullness tended to be lower after LE than HE conditions just before lunch [$F(1,43) = 3.82$, $p=0.057$, $\eta^2 = 0.08$], and a similar pattern was seen at one month follow-up.

Evaluations of drink preloads

The drinks were designed so that ES versions had a thicker texture and more creamy flavour than the LS versions, and to confirm this ratings of thick and creamy on days 1-6 were contrasted. These analyses confirmed that ES versions of the drink rated as more thick (72 ± 3) and creamy (73 ± 2) than LS versions (thick, 56 ± 3: creamy, 63 ± 2: thick [$F(1,42) = 18.90$, $p<0.001$, $\eta^2 = 0.31$], creaminess [$F(1,42) = 8.40$, $p=0.006$, $\eta^2 = 0.17$]. No other effects were significant. Importantly drinks were matched across energy content and the sensory characteristics did not change with exposure.

Rated pleasantness increased significantly across days 1-6 (linear contrast of day: [$F(1,42) = 4.60$, $p=0.037$, $\eta^2 = 0.10$], but these changes did not differ significantly between drink energy or sensory conditions (Figure 3).

Discussion

The present study suggests that a drink's nutrient content and sensory characteristics can both impact on satiety, but that repeated consumption changes the relative influence of these two drink aspects. Higher energy drinks generated much stronger satiety than did low energy drinks, and this effect was most pronounced in the high energy drink with enhanced sensory characteristics, though repeated consumption diminished this sensory effect. The low energy versions of the drinks had weak effects of satiety and repeated consumption served to magnify this effect, particularly in the thinner less creamy versions of these drinks

The key aim of the present study was to evaluate whether sensory-enhanced satiety was modified by repeated consumption. Consequently, it was important that sensory-enhanced satiety was evident before exposure, and analysis of data from day 1 confirmed this was so. Thus the strongest satiety, indicated by reduced lunch intake and increased rated satiety (decreased hunger/increased fullness), was seen in the HE/ES condition, and the pattern of data from these between-participant contrasts was similar to that reported previously using within-participant designs[7,8]. However, while the HE/ES condition continued to generate the strongest satiety after repeated consumption, the difference between HE/ES and HE/LS decreased with repeated consumption. The largest effects of repeated consumption, however, was for the LE/LS drink, which generated weaker satiety after repeated consumption with significantly increased intake at the test meal both immediately after the exposure period and at the one-month follow-up.

The present study also tested whether repeated consumption modified expectations about satiation and satiety. When ratings of how filling participants expected the drinks to be (interpreted as expected satiation) were analysed, there was clear evidence that repeated exposure altered their perceptions. Thus before exposure, expected satiation was determined solely by sensory characteristics: both ES versions were rated as more filling than the LS ones regardless of energy content. However, over time expected satiation increased for both HE drinks, and decreased for the LE/ES drink, so that after the exposure period this measure reflected energy content rather than sensory characteristics, and this effect was still evident at the one-month follow-up. These data suggest that participants learned about the relative satiating effects of these products. The results from the ratings of how filling the product was expected to be are in line with an earlier finding that expected satiation increased after consumption of a higher-energy product[17], although a subsequent study found no changes in a similar measure of expected satiation after repeated consumption[18]. The changes here in expected satiation were not seen for a measure of expected satiety based on the estimated portion of a breakfast cereal needed to suppress hunger to the same extent as the drink. As with expected satiation, before exposure, expected satiety varied with sensory characteristics, with higher expected satiety for ES than LS versions regardless of nutrient content. However, despite clear changes in satiety responses to the different drinks, expected satiety measures did not change with repeated consumption. The difference between expected satiation and expected satiety measures might suggest that subtle changes in expectations about how satiating a product will be are not readily translated into estimates of how much of a different food would need to be consumed to generate the same level of satiety. Previously we noted that responses to the two measures used here did not correlate significantly[10], suggesting they tapped into different aspects of expectations, although when expected satiety and expected satiation were both measured using portion-size estimation the two measures were highly correlated (Brunstrom, unpublished data). Further research on the nature of these expectations is therefore needed.

It was predicted that the enhanced satiating effects of a thicker/creamier higher-energy drink would increase with repeat exposure through learned satiety. Since the effects of the sensory manipulations in the high energy drink were less evident after exposure and at the 1 month follow up than at the start of the study (Pre-exposure), the current study does not support the view that sensory manipulations can facilitate learned satiety. However, the largest changes in behaviour occurred with the low energy drinks, and in particular repeated consumption of the LE/LS drink, where satiety became noticeably weaker over repeated consumption. The contrast of effects of repeat consumption of the LE/LS and LE/ES drinks suggests that the presence of sensory characteristics that are associated with satiety (as evidenced by the higher expected satiety and filling measures for the LE/ES than LE/LS drink) seemed to protect from over-consumption at lunch after a low energy drink, suggesting that inclusion of sensory characteristics that generate satiety expectations might limit learning about the lack of nutrients and be beneficial in the context of low energy drink products.

However, there was a tendency for the LE/ES drink to increase appetite and lunch intake when first encountered, an effect noted in other studies (rebound hunger[7,8]), but which was not evident here after exposure. The change in expected filling with exposure could be interpreted as evidence of learned satiety, with this evaluation changing as a consequence of exposure in line with the experience of actual satiety, although the lack of similar effect with the expected satiety measure does limit this conclusion. Expected satiation has been shown to increase with familiarity[25], although that study suggested that all foods tend to be expected to be more filling once they have been consumed repeatedly regardless of actual nutrient content while the present data suggest that these changes are related to actual nutrient content.

One important feature of the present study was inclusion of one-month follow-up data, which clearly showed that the changes in response to the drinks immediately after exposure was maintained one month later despite any further experience of the drink. This suggests that the specific learning about the test products was robust, and suggests that learning that specific products are effective at suppressing appetite should lead to consistent and sustained improvements in appetite control.

In the present study we manipulated both the thickness and creamy flavour of the drinks to generate the ES versions. Other data from our laboratory suggests that the thickness manipulation is most likely to impact on behaviour[10]. However, thickness was manipulated by addition of small amounts of tara gum, and an alternative explanation for the effects of this manipulation could be through a post-ingestive effect of the added tara gum. The addition of tara gum would have increased viscosity[10], and viscosity has been reported to enhance satiation[26] and satiety[27,28], perhaps by changing gastric empting rate. However, the effects of the sensory manipulation were ameliorated by repeated exposure, while the effects of added energy became more clear. Thus, even if the apparent effects of the sensory manipulations could be explained by a post-ingestive effect, and various reasons suggest this is unlikely[8], any such effects are clearly modified by experience suggesting that a simple post-ingestive effect of tara gum alone cannot readily explain the data.

It might have been predicted that repeat consumption of the HE drinks would have lead to increased liking for these products as a consequence of associations between their sensory characteristics and subsequent experience of satiety (flavour-nutrient learning[14,29]). Rated pleasantness increased similarly for all four drinks. These results need to be interpreted with caution, however, as baseline liking was relatively high so limiting the scope for increased liking through exposure, and whether liking change is the best measure of flavour-nutrient learning is questionable. Moreover, novelty is critical for flavour-nutrient learning[16], and these products were not particularly novel. It would be therefore premature to consider the lack of liking change as evidence against the concept of flavour-nutrient learning. In contrast, the changes in expected filling with exposure suggest that participants were learning about the consequences of consuming these products in support of flavour-nutrient learning. What aspect of nutrient detection underlies this effect cannot be determined from the present study, although animal studies suggest flavour-nutrient preference development is reinforced more by gut nutrient-sensing than post-ingestive use of nutrients[30].

Overall the present data confirm that in the short-term the satiating effects of a high energy drink are modified by enhancing its satiety-relevant sensory characteristics, but that the effects of these sensory enhancements decrease, and effects of its nutrients become more pronounced, following repeated consumption. The present data also suggest that drinks with minimal energy generate weak satiety and that repeat consumption of such drinks can lead to progressively weaker satiety responses, but that sensory modifications may help to ameliorate this effect.

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Conflicts of Interest

None of the authors had a conflict of interest in regard to conducting or reporting this study.

Author Contributions

MRY is the grant holder. LC developed the design with input from MY and KMc. LC conducted the experimental work. MY took the lead in analysing data and preparing the manuscript. JB programmed the expected satiety task and made critical comments on the study design and draft manuscript.

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Table 1. Mean (±SEM) age, body mass index and restraint scores for the four groups of participants. N=12.

Drink condition	Age (years)	BMI (kg/m^2	Restraint
LE/LS	21.6 ± 0.7	24.4 ± 0.9	3.8 ± 0.5
LE/ES	19.2 ± 0.3	22.9 ± 0.7	2.1 ± 0.5
HE/LS	21.2 ± 0.5	24.9 ± 1.3	3.1 ± 0.5
HE/ES	23.3 ± 1.3	23.3 ± 0.7	4.3 ± 0.7