Satiety-relevant sensory qualities enhance the satiating effects of mixed carbohydrate-protein preloads1–3

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ABSTRACT

Background: Orosensory cues such as food texture and flavor have been shown to play a role in satiation, but their role in satiety remains less clear.

Objective: The objective was to determine whether satiety-relevant orosensory cues enhance the satiating effects of energy in the context of beverage preloads.

Design: The effects of 6 drink preloads that combined 2 amounts of energy [high energy (HE): 279 kcal; low energy (LE): 78 kcal] and 3 satiety-relevant sensory contexts [low sensory (LS), medium sensory (MS), and high sensory (HS)] on subsequent appetite and test meal intake were assessed in 36 healthy nonobese volunteers.

Results: The ability of the preloads to modify appetite 30 min after consumption depended on both energy content and sensory context (P-interaction < 0.05), with hunger significantly being lower after consumption of the HE than after the LE preload in the HS context (P < 0.001), tending to be lower in the MS context (P = 0.08), but not different in the LS context. Food intake at lunch was lower after the HE than after the LE preloads (effect of energy P < 0.001), but this effect depended on sensory context (P < 0.005). The degree to which reduced test meal intake compensated for the added energy in the HE preloads was 88% in the HS context, which was significantly greater than in the MS (47%) and LS (18%) contexts.

Conclusion: Small changes in the sensory characteristics of drinks altered the degree to which added energy was satiating, which implies that nutrients become more satiating when they are predicted by relevant sensory cues such as thickness and creaminess. This trial was registered at http://www.controlled-trials.com as ISRCTN36258511.

INTRODUCTION

The worldwide increase in prevalence of obesity and overweight (see references 1 and 2) has resulted in an urgent need to better understand the nature of satiety (3). Several lines of evidence suggest that the context in which energy is ingested may be critical in determining whether effective satiety is generated. In particular, energy consumed as a beverage tends to generate weak satiety (4, 5), whereas energy consumed in soup generates much stronger satiety (6, 7). Understanding why satiety should depend on these subtle differences in physical and sensory qualities should greatly aid the future development of more satiating products that could be incorporated into weight-management programs.

One possible explanation for differences in satiating effects of energy between food contexts might be that the characteristics of the food or drink have different capacities to generate satiety expectations. People have clear expectations about how satiating different foods and drinks will be (8). These satiety expectations could modify the response to nutrient-generated satiety signals (9). If so, then the presence of satiety-relevant sensory cues should lead to more effective satiety than would be seen in the absence of such cues, and the overall objective of the study reported here was to test this idea. Several lines of evidence lead to this hypothesis. First, orosensory cues are important in generating satiety, particularly in studies that compare oral with post-oral nutrient administration (10–12). Second, orosensory experience modifies satiation, with foods that provide longer sensory exposure being more satiating (13) and drinks that have sensory-relevant qualities (eg, yogurt flavor and texture) being more satiating than the same energy in juice form (14). Third, although many studies found minimal satiating effects of energy consumed as a beverage, beverage energy added as protein was more satiating than when added as carbohydrate (15), and protein was most effective when it enhanced perceived creaminess (16). Finally, although it has been suggested that the effects of drink thickness (viscosity) on satiety may be due to postingestive effects, such as modification of gastric emptying (17), dilution of beverage ingredients in the stomach may minimize such effects for normal foods (18). Thus, subtle differences in viscosity are more likely to affect satiety through an orosensory than through a postingestive mechanism (19).

The current study contrasted the short-term satiating effects of beverages that differed in sensory quality and energy content. We predicted that the satiating efficiency of covertly manipulated energy (added as maltodextrin and whey protein) would increase as the sensory quality of the beverage became more congruent with satiety expectations. To add satiety-relevant sensory qualities, the viscosity of the beverage was manipulated since manipulated viscosity affects satiation (20) and flavor elements that enhanced creaminess were added (15).

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SUBJECTS AND METHODS

Design

A repeated-measures preload paradigm contrasted the satiating effects of 6 drinks that combined 2 amounts of energy content (HE or LE) and 3 levels of sensory quality (LS, MS, or HS). Test meal intake and subjective ratings of appetite were used to assess satiety.

Subjects

Thirty-six healthy adults participated in the study. Sample size was determined on the basis of the effect size needed to find a difference between high- and low-energy conditions of a related study in which sensory and protein content of a beverage had been manipulated (15). On the basis of a medium effect size ($f = 0.25$), power calculations indicated that we needed a sample size of 24 (power: 0.91), and this sample size was increased further to allow contrast between sensory conditions. All participants were staff or students at the University of Sussex, United Kingdom, who had expressed an interest in participating in appetite research by completing an online questionnaire. Prospective participants were selected on the basis of data obtained from this questionnaire and contacted by a recruitment e-mail, which described the study as “an investigation of the effect of food on mood.” The contact criteria included the following: a score of ≤7 on the Three-Factor Eating Questionnaire scale of dietary restraint, smoking <5 cigarettes/d, and a BMI (in kg/m$^2$) <30. Respondents to this recruitment e-mail were enrolled in the study if they met the following requirements: not taking prescription medicine, not currently pregnant, without any previous or current diagnosis of diabetes or an eating disorder, and without aversions or allergies to the test foods. Written consent was obtained before participation. The test cohort was made up of 18 men and 18 women (age range: 19–33 y; mean ± SD: 21.9 ± 2.7) who were not obese (BMI range: 18.9–29.9; mean ± SD: 22.9 ± 2.6) nor diet restricted (Three-Factor Eating Questionnaire-restraint: range, 0–7. mean ± SD: 2.9 ± 2.1).

Procedure

Participants attended the Ingestive Behavior Unit at Sussex University for 6 sessions, which were restricted to a maximum of 2/wk on nonconsecutive days. The protocol was identical on each test day, with only the preload varying; a summary of the daily protocol can be seen in Figure 1. Participants arrived at a scheduled time between 0830 and 1000, after having consumed only water from 2300 the night before. They consumed breakfast and were instructed to return exactly 3 h later for their lunch session (only water consumption was allowed during this period). To begin the lunch session, participants were taken to a windowless air-conditioned testing cubicle where they tasted, and consumed 300 mL of 1 of the 6 drink preloads. The preload was evaluated for sweetness, creaminess, pleasantness, thickness, and familiarity by using SIPM software (University of Sussex) on a PC computer, which presented randomized VASs headed with the question “How [target rating] is the drink?” and end-anchored with “not at all [target rating]” (scored as zero) and “extremely [target rating]” (scored as 100). To be consistent with the premise that the study examined effects of food on mood, participants rated their mood and appetite, initially in the absence of any food-related cues (the prepreload baseline rating) and again immediately after consuming the preload (postpreload). The mood ratings (alert, anxious, calm, clear-headed, energetic, happy, headache, nauseous, and tired), which were presented as 100-point computerized VASs end-anchored with “not at all [mood]” and “extremely [mood],” were included as distracters, and data were not analyzed. The critical VAS ratings of hunger and fullness were embedded in these series of questions along with a rating of thirst.

A 30-min delay between the preload and lunch was used, as this has been shown to be an optimal time period for detecting preloading effects using drinks of this type (15). On their return to the testing cubicle, participants completed their third set of mood and appetite ratings in the absence of any food cues (the prelunch ratings). Next, 500 g pasta with tomato sauce was served by an experimenter who explained that the participant could eat as little or as much as he or she liked. The SIPM prompted the participants to taste the pasta and rate its pleasantness, savoriness, saltiness, and familiarity followed by further ratings of hunger and fullness to determine the appetizing effects of food presentation (21). The participants were then instructed to eat as much as they desired. A hidden digital balance secured under a placemat and linked to the SIPM recorded the weight of food being eaten. If the participant consumed >400 g pasta, an audible alert accompanied by an onscreen message prompted the participant to call the experimenter. The experimenter then served the participant another 500 g pasta; no limit was placed on the number of refills permitted. To reduce the influence of habit and portion-size effects on intake, participants were encouraged not to use the refill prompt as a cue to end that course. At the end of the pasta course, the participants re-rated their appetite and mood. Next, they were served 150 g chocolate ice cream with the instruction that they could eat as much as they liked after they had completed a taste test to evaluate the pleasantness, sweetness, creaminess, and familiarity of the ice cream followed by further ratings of hunger and fullness to measure the appetizing effects of the second course. For this course, refills were prompted when the participant had consumed 100 g. When participants had confirmed that they had
finished eating, they were asked a final series of mood and appetite ratings; this completed the lunch session.

With 6 preloads, a full factorial counterbalanced design would have required 720 participants. Instead, a Williams Latin square design (22) was used, which ensures that first-order carryover effects and the number of times a treatment follows another treatment are balanced. This approach generated 6 preload sequences, with each sequence used 6 times; sequences were balanced across sex.

On the final test day, the participants answered a series of questions about the study to assess their awareness of the true rationale. Their height (m) and weight (kg) were measured, and they were paid £50 for participating in the study. The study protocol received ethical clearance from the School of Life Sciences research governance committee (University of Sussex) and adhered to recommendations of the Declaration of Helsinki of 1975 as revised in 1983.

Test foods

**Breakfast and lunch**

On the morning of each test day, participants consumed a breakfast of 60 g of a proprietary breakfast cereal (Crunchy Nut Cornflakes; Kellogg Co) plus 160 mL semi-skimmed milk (Sainsbury’s) and 200 mL orange juice (Sainsbury’s). The breakfast provided 390 kcal, 4.7 g fat, 8.7 g protein, and 77.0 g carbohydrate. For the ad libitum lunch, each 500-g serving of pasta consisted of 250 g cooked weight of pasta [conchiglie (shell pasta); Sainsbury’s] plus 250 g of a prepared pasta sauce (tomato and basil; Sainsbury’s) served hot. The ice cream course was served in a bowl and was chocolate flavored (Chocolate Inspiration, Carte d’Or; Unilever).

**Drink preloads**

Six preload drinks, which differed in energy and sensory characteristics, were tested: LE-LS, LE-MS, LE-HS, HE-LS, HE-MS, and HE-HS. Pilot tests (see Table 1) established that the LE and HE versions were matched for pleasantness, creaminess, sweetness, and novelty; and that the LS, MS, and HS versions differed significantly in thickness, creaminess, and how filling they were expected to be. Sensory and hedonic evaluations of the final versions of these drinks from the pilot study (shown in Table 1) were based on ratings made by 20 healthy, normal-weight volunteers who assessed all 6 drinks in a single tasting session. ANOVA was used to analyze each rating depending on both sensory context and energy content. No significant main effects or interactions were found for energy content with any of these ratings, but significant main effects of sensory context were found for thickness, creaminess, and how filling the drinks were perceived to be. For these evaluations, mean ratings with different superscript letters differed significantly (P < 0.05) on the basis of Bonferroni-protected contrasts between the 3 sensory conditions.

![Image](https://academic.oup.com/ajcn/article-abstract/94/6/1410/4598167)

### Table 1

Sensory and hedonic evaluations (on 100-point visual analog scales) of the test preload drinks both in the pilot study and in the main intake test.

<table>
<thead>
<tr>
<th>Evaluation</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
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<tbody>
<tr>
<td>Thick</td>
<td></td>
<td></td>
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<tr>
<td>Pilot study</td>
<td>49.8 ± 3.7a</td>
<td>53.6 ± 2.8a</td>
<td>58.7 ± 2.5b</td>
</tr>
<tr>
<td>Main study</td>
<td>61.3 ± 3.0a</td>
<td>62.8 ± 3.5a</td>
<td>68.3 ± 2.6a</td>
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<tr>
<td>Creamy</td>
<td></td>
<td></td>
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<tr>
<td>Pilot study</td>
<td>54.8 ± 3.0a</td>
<td>58.1 ± 2.5a</td>
<td>66.1 ± 2.6b</td>
</tr>
<tr>
<td>Main study</td>
<td>64.2 ± 3.1a</td>
<td>66.3 ± 3.0a</td>
<td>70.5 ± 2.3a</td>
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<tr>
<td>Sweet</td>
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<tr>
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<td>62.1 ± 3.7a</td>
<td>62.1 ± 2.6a</td>
<td>62.4 ± 2.8a</td>
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<tr>
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<td>74.0 ± 2.4a</td>
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<td>Pleasant</td>
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<tr>
<td>Pilot study</td>
<td>58.9 ± 3.0a</td>
<td>53.8 ± 3.7a</td>
<td>55.5 ± 3.9a</td>
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<tr>
<td>Main study</td>
<td>72.7 ± 4.7a</td>
<td>73.6 ± 4.2a</td>
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<tr>
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<td>50.3 ± 3.4a</td>
<td>52.3 ± 3.3a</td>
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<tr>
<td>Main study</td>
<td>54.9 ± 1.9a</td>
<td>56.3 ± 2.3a</td>
<td>60.9 ± 3.5a</td>
</tr>
</tbody>
</table>

*All values are means ± SEs, n = 20 for the pilot study; n = 32 for the main study. In the pilot study, healthy normal-weight volunteers (12 women and 8 men) assessed all 6 drinks in a single taste test. ANOVA was used to analyze each rating depending on both sensory context and energy content. No significant main effects or interactions were found for energy content with any of these ratings, but significant main effects of sensory context were found for thickness, creaminess, and how filling the drinks were perceived to be. For these evaluations, mean ratings with different superscript letters differed significantly (P < 0.05) on the basis of Bonferroni-protected contrasts between the 3 sensory conditions.*

of the high- and low-energy drinks in the LS version, 0.3 g tara gum (Kalys) was added to the LE-LS drink. For the MS and HS versions of the drink, sensory manipulations were achieved by adding tara gum (LE-MS: 0.45 g; LE-HS: 0.9 g; HE-MS: 0.5 g; HE-HS: 1.5 g), milk caramel flavor (S Black; LE-MS: 0.1 g; LE-HS: 0.3 g; HE-MS: 0.1 g; HE-HS: 0.3 g), and vanilla extract (Nielsen-Massey; LE-MS: 20 drops; LE-HS: 60 drops; HE-MS: 20 drops; HE-HS: 60 drops).

**Data analysis**

The aim of the study was to test whether altering the sensory context in which energy was delivered altered subsequent appetitie, measured both as intake at a subsequent test lunch and through ratings of appetite both during the period between consuming the preload and starting lunch and during the test lunch. One of the key measures of satiety is the degree to which increased energy intake before a meal results in reduced intake at that meal (energy compensation). We therefore calculated the degree of compensation for the extra 201 kcal in the HE drinks by calculating the difference in energy intake at the test meal between HE and LE conditions in each sensory context and expressing that change as a percentage of the difference in preload energy to produce a compensation measure. Initial analysis of these compensation values indicated that the data were not normally distributed, and this was not corrected by data transformation. Outlier analysis indicated that 4 compensation values from male participants were >2 SDs from the relevant condition mean, and consequently data from these 4 subjects
were omitted from all further analyses. Compensation data distributed normally once the outliers had been removed. All analyses were based on the remaining sample of 32 participants.

Initial analyses contrasted compensation data between the 3 sensory contexts with the use of a repeated-measures ANOVA, with protected contrasts between conditions. Overall energy intakes at lunch were also contrasted by using ANOVA with sensory context and preload energy as within-subject factors because compensation measures provided an index of the difference between energy conditions but did not determine whether it was intake in the HE or LE conditions that varied between sensory contexts. Finally, because the lunch consisted of 2 courses, intake at each course was analyzed, because this provided an indication of whether energy caused a general suppression of intake or altered decisions on when to end the one course and start the next.

Appetite ratings were made before and after preload consumption, 30 min after the preload, and periodically throughout the test meal. A full analysis of these data was beyond the scope of this study. The key question was whether the energy content and sensory context of the drink modified appetite. To test this, ratings at 5 key points were used: before and after preload consumption, 30 min after preload, once the first course had been tasted, and at the end of the test meal. These ratings were contrasted by using ANOVA, with rating time, sensory context, and energy content as within-subject factors.

To ensure that preloads differed in key sensory dimensions, but were similar on other dimensions, we analyzed ratings of the sensory and hedonic quality of the preloads when they were first tasted by using 2-factor ANOVA. To test how preloading altered the evaluation of the 2 lunch foods, we conducted similar analyses on pasta and ice cream ratings.

To control for order effects, the 6 preload sequences were included as a between-subject factor in all analyses. Sex was also included as a between-subject factor in all analyses; however, because sex was not a focus of the study and did not alter the primary findings, for brevity full details of all effects of sex have been omitted.

RESULTS

Lunch intake

Total energy consumed at lunch depended on both the energy content and sensory quality of the preload drink (Figure 2), with the difference in lunch intake between LE and HE preload conditions increasing as the drinks increased in thickness and creaminess.

Although the adoption of a 2-course meal model made the eating test more realistic than previous single-food lunch tests, one potential concern was that the high palatability of the ice cream might have ameliorated effects of the energy and sensory manipulations, particularly because lunch palatability has been shown to counteract the satiating effects of energy preloads (23). We therefore also analyzed intake separately for each course. As shown in Figure 2, intake of the pasta course did not differ significantly between the LE and HE conditions in the LS context, but significantly less was consumed in HE than in LE conditions in both the MS and HS contexts. Less ice cream was also consumed after the HE than after the LE preloads, and ice cream intake decreased from LS to HS contexts. These 2 effects combined meant that most of the ice cream was consumed in the LE-LS condition and the least was consumed in the HE-HS condition.

In relation to the study hypotheses, the critical question was to what extent the change in intake at lunch compensated for the extra energy in the HE preloads. To test this, the difference in energy intake between equivalent HE and LE conditions for each sensory level was calculated and expressed as a percentage of the actual energy difference between LE and HE conditions such that a value of 100% would reflect full compensatory eating (24). Compensation was significantly greater in the HS (87%) than in the LS (18%) context (P < 0.005); the MS context was intermediate.

As would be expected, men tended to eat more overall at lunch than did women (P = 0.051). There were also complex significant interactions between the 2 test conditions and effects of order and sex, with a 4-way interaction between sensory context,
energy content, test order, and sex ($P = 0.03$). Across all conditions, participants consumed the least at the last session but similar amounts on other days, suggesting possible boredom effects at the last session. Inspection of these data suggested that intake at lunch after the HE preload in the LS context was less when this was experienced early in the study than at the end, suggesting that energy became increasingly less effective at generating satiety in that context. In contrast, meal size after the HE preload was similar regardless of when they were experienced in both the MS and HS contexts. Thus, the repeated-exposure effects of the study seem to have reduced the effectiveness of energy in the LS context, particularly in female participants, and this likely explains the 4-way interaction.

**Appetite ratings before lunch**

We hypothesized that the extent to which the experience of appetite changed in the period between consuming the drink and starting the test lunch would depend both on the energy content and sensory quality of these drinks. To test this, ratings of hunger and fullness before and after consuming the drink, 30 min later (just before lunch) and after first tasting the lunch were contrasted. To test whether participants also consumed their lunch to the same level of satiety, ratings at the end of the meal were also included. For hunger (Figure 3, left), analysis showed 2 key interactions: a 2-way interaction between the energy content and time of rating ($P = 0.021$) and a 3-way interaction between energy, time of rating, and the sensory condition ($P = 0.023$) as well as a main effect of time ($P < 0.001$), with hunger decreasing immediately after drink consumption and then tending to increase over the subsequent 30 min before decreasing to a low value at the end of the test lunch. There were no significant differences between energy or sensory conditions before or immediately after the drinks were consumed. However, whereas hunger before lunch being served did not differ significantly between HE and LE conditions in the LS context, these ratings tended to be lower in HE than in LE conditions in the MS context ($P = 0.08$) and were significantly lower after HE than after LE preloads in the HS context ($P = 0.007$; see Figure 3). Because hunger ratings once food has been tasted have been shown to have the strongest correlation to meal size (25), we also looked at hunger ratings immediately after tasting the pasta, which again depended both on energy content and sensory quality of the preload. After tasting the lunch, there was still no significant difference in hunger between LE and HE preloads in the MS context, there was a marginally significant difference in hunger in the LS context ($P = 0.07$), and there was a significant difference between preload energy conditions in the HS context ($P = 0.002$). There were no differences in hunger between conditions at the end of the meal despite differences in lunch intake.

Analysis of fullness ratings (Figure 3, right) also found the expected significant main effect of time of rating ($P < 0.001$), with fullness mirroring the changes in hunger. There were also a significant 2-way interaction between energy and sensory ($P = 0.002$) and a significant 3-way energy × sensory × time interaction ($P = 0.015$). Surprisingly, fullness ratings were significantly lower after the HE than after the LE preload in the LS context immediately after the drink was consumed ($P = 0.048$) but did not differ between energy conditions either before lunch or once food had been tasted in the LS context. In contrast, fullness was significantly greater after the HE than after the LE preload in both the MS and HS contexts before lunch ($MS = 0.039, HS = 0.001$) and after lunch had been tasted ($MS, P = 0.048; HS, P = 0.002$). Fullness did not differ significantly between conditions at the end of the test lunch.

**Evaluations of the drink preloads and test lunch**

The drink preloads were designed to be matched in sensory quality between the LE and HE formulations within each sensory context but to increase in thickness and creaminess from the LS through the MS and HS contexts. Pilot data suggested that the preloads had these qualities, and the actual evaluations of the drinks when they were first tasted on each preload session (Table 1) were analyzed to ensure this. As expected, the perceived thickness and creaminess of these drinks increased from LS to HS contexts but was unaffected by energy content. The drinks did not differ significantly in terms of pleasantness, but there was an unexpected effect of energy content on perceived sweetness, with HE drinks being rated slightly sweeter than LE drinks regardless of sensory context, an effect that was not evident in the pilot studies.

There were no significant effects of the preload manipulations on the rated pleasantness of either the pasta or ice cream consumed in the test lunch.

**DISCUSSION**

Our main finding was that the degree to which a beverage generated satiety depended on both its nutrient content and sensory quality: participants consumed less after an HE preload in the HS context than in the LS context. In the HS context, compensation for the extra energy in the HE drink was 87%, compared with 47% in the MS context and only 18% in the LS context. Given the potential importance of this outcome, future studies should aim to replicate this finding and to determine whether these effects are sustained beyond the immediate test meal.

How might sensory context modify the response to added nutrients? One possibility is that orosensory cues generate expectations about satiety that prime the appetite system to respond to subsequent nutrient-derived satiety cues. Accordingly, when the cues generated lower satiety expectations (our LS context), the lack of preparatory changes reduced the efficiency of nutrient processing. This view is consistent with evidence that food-related cues result in learned preparatory responses (9, 26) and that sensory qualities generate clear satiety expectations (27). Our findings may explain differences in the satiating effects of foods and drinks varying in sensory quality (14, 28) and suggest that caution is needed in interpretation of studies that report differences in satiety where nutrient and sensory differences are confounded: thus, for example, the finding that a breakfast with skimmed milk is more satiating than is the same breakfast with an isocaloric juice (29) could be attributed to sensory or nutrient differences.

A corollary of the idea that sensory cues that predict energy increase the efficiency of nutrient processing is that experience of such cues followed by an absence of nutrient ingestion could leave the body prepared for nutrients, resulting in rebound hunger. The higher prelunch hunger ratings in the LE–HS condition fits with this idea, and participants consumed more after the
LE preload in the HS than in the LS context. These findings need substantiation but imply that diet-related products that generate satiety expectations but fail to deliver nutrients may lead to subsequent increased appetite and overeating.

A potential alternative explanation for the enhanced satiating effects of energy in the HS context might be that the constituents used to modify sensory characteristics enhanced the satiating effects of added nutrients through a postingestive effect. The
addition of tara gum increased viscosity, and viscosity has been reported to enhance satiation (20) and satiety (19, 30–32), perhaps by altering the gastric emptying rate. However, studies to date cannot dissociate whether viscosity operates through an orosensory or a postigestive effect. If increased viscosity alone was important, then drinks with a higher gum content should have produced more satiety than a drink with the same energy but lower gum content (LE-HS compared with LE-LS). However, this was not the case. Amounts of tara gum used were very low: 1.5 g in total in the most satiating drink (HE-HS) compared with 0.3 g added in the control (LE-LS). Studies that report significant effects of added gum alone use substantially higher amounts—for example, 12 g guar gum increased the satiating efficiency of a high-fat soup (33). Likewise, enhanced satiety was reported after addition of 12 g inulin in a protein-rich beverage (34), although other studies failed to find fiber and protein more satiating than protein alone (28). Taken together, these various findings cannot fully discount an explanation in terms of possible postigestive effects of tara gum, but they do suggest that an orosensory explanation is more plausible.

Previous studies have reported variable effects of drink preloads on appetite (see reference 35). In particular, studies that use recognizable beverages such as drinks sweetened with sucrose or artificial sweeteners often report minimal compensatory eating (36–40), but other studies report at least partial compensation for energy consumed as drinks (15, 41). Our present results may explain this variability. Drinks often lack the sensory elements that generate satiety expectations. In the absence of such expectations, the appetite system appears to be less able to respond to nutrient signals. Previous studies that reported some degree of compensation for energy in a beverage context had sensory elements that should generate satiety expectations: chocolate-flavored milk was more satiating than was cola (42) and a yogurt/fruit drink was more satiating than an equally caloric fruit juice (14). Thus, although drinks tend to be less satiating than solid foods (35), drinks may be satiating when they have sensory qualities that lead to satiety expectations.

In addition to the role of sensory cues in satiety indicated by the present results, similar cues reduced meal size (ie, enhanced satiation) irrespective of nutrient content (13, 43). As a consequence, because our participants consumed all of each drink it might have been expected that we would see greater satiation immediately after consuming the HS and MS drinks relative to the LS context. However, no such effect was evident.

The outcome of the present study relied on the successful manipulation of the sensory characteristics of the drinks. Evaluations of preloads both in the pilot and main study confirmed that the HS drinks were thicker, creamier, and more filling than the LS drinks; the MS drinks were intermediate in these characteristics. However, ratings in the main study were substantially different from those in the pilot study. The likely explanation is that contrast effects made subtle differences more evident when drinks were rated at the same time (the pilot) than when evaluated on separate days. The HE and LE versions were matched in thickness, creaminess, how filling they were perceived to be, and pleasantness, but a significant increase in sweetness for all HE versions was seen in the main study. Because the key findings were for different effects of added energy across contexts, it is unlikely that the effects on satiety could be explained by small differences in preload sweetness.

One limitation of the study was that it tested only normal-weight, unrestrained participants. Accuracy of compensatory eating (44, 45) and responses to sensory quality (46, 47) vary across individuals depending on body size, physical activity, age, and restraint. Whether the same outcome would be seen in restrained and overweight or obese participants needs to be explored. The study looked only at effects of single exposures to each preload, and the interaction between test order and preload effect in women might suggest some changes in the relation between sensory quality and nutrients through learning (48). Finally, both the breakfast and test lunch were relatively rich in carbohydrate. Whether similar effects would be seen with test meals with higher fat or protein content should be explored. In particular, it is clear that different macronutrients selectively modify physiologic satiety cues such as polypeptide YY, cholecystokinin, and glucagon-like peptide 1 (see reference 49), and if one effect of sensory cues was to modify release of these or related hormones, then the macronutrient specificity of the sensory context effect could be modified accordingly.

Overall, the present study provides evidence that the sensory context in which nutrients are consumed modifies subsequent satiety, with higher-energy beverages being more satiating when experienced in a thicker, creamier flavored drink. This outcome suggests that future studies need to consider carefully the possible effects of subtle differences in orosensory cues on the outcome of preload-style studies of satiety.

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