Snacks containing whey protein and polydextrose induce a sustained reduction in daily energy intake over 2 wk under free-living conditions1–3

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ABSTRACT

Background: The manipulation of the composition of foods consumed as between-meal snacks may aid daily energy restriction. Objectives: We compared the effects of the consumption of 2 energy-matched snack bars on appetite, energy intake (EI), and metabolic and endocrine responses. In addition, we investigated whether the acute effects of the consumption of snacks were maintained under free-living conditions and whether the habitual daily consumption of the snack over 14 d influenced these effects.

Design: Ten lean men [mean ± 5 age: 30.7 ± 9.7 y; body mass index (in kg/m²): 23.2 ± 2.8] consumed a whey protein and polydextrose (PPX) snack bar or an isoenergetic control snack bar as a midmorning, between-meal snack for 14 consecutive days in a double-blind, randomized, crossover design. The two 14-d intervention phases were separated by a 14-d washout period. On the first (day 1) and last (day 15) days of each intervention phase, appetite, food intake, and blood metabolite and endocrine responses were assessed under laboratory conditions. Free-living EI was recorded on days 4, 8, and 12 of interventions.

Results: Total daily EI was significantly lower when the PPX snack was consumed during experimental days (10,149 ± 831 compared with 9041 ± 610 kJ; P < 0.01), and daily EI remained lower when the PPX snack was consumed during the free-living part of the intervention (7904 ± 610 compared with 9041 ± 928 kJ; P < 0.05). The PPX snack was associated with lower glucose and ghrelin and higher glucagon-like peptide 1 and peptide tyrosine-tyrosine responses.

Conclusion: The manipulation of the composition of foods consumed as snacks is an effective way to limit subsequent EI. This trial was registered at clinicaltrials.gov as NCT01927926. Am J Clin Nutr 2014;99:1131–40.

INTRODUCTION

The development of functional food products that enhance satiety, suppress appetite, and reduce subsequent voluntary food intake to a greater extent than a similar energy-matched food product may be useful to help consumers adhere to energy-restricted diets and optimize successful body weight management. A range of foods and food constituents have been reported to have the potential to produce short-term changes in satiety (1–5). However, these studies tend to have been limited to investigations of subjective appetite sensations (eg, hunger, fullness, and desire to eat) or energy intake (EI) at a single test meal and usually conducted in the laboratory over the course of a single day. However, for a food that influences short-term satiety to be useful in successful body weight management, studies must be able to show that, under free-living conditions, the exchange of usual for functional foods results in reduced daily EI. Furthermore, reductions in daily EI must be sustained when the food is consumed on a daily basis.

Two ingredients that have a substantial body of evidence to support their effects in enhancing short-term satiety are whey protein (6–8) and polydextrose (9–13) (PPX). It is likely that including PPX in foods produces changes in postprandial metabolic and gut hormone responses that are associated with suppressed appetite and reduced subsequent EI (10, 14). However, effects of foods that combine PPX on appetite and EI, metabolic and gut hormone responses remain unclear.

We hypothesized that the consumption of a snack bar containing a combination of PPX would help limit voluntary food intake at a subsequent meal, and in turn, this reduction in EI may have significant nutritional consequences on overall daily EI.

Primary aims of this study were to 1) investigate whether the acute effects on EI observed previously by using liquid preloads that contained PPX can be replicated by using solid snack bars, 2) explore whether the effect on EI translates into a reduction in total daily intake under free-living conditions, and 3) determine whether the acute effects on EI can be sustained when snacks are consumed on a daily basis over 14 d. Secondary aims were to 1) investigate the effects of the consumption of snack bars on subjective appetite ratings and 2) determine blood metabolite.
and endocrine responses to snacks that might help explain any differences in EI.

**SUBJECTS AND METHODS**

**Participants**

Ten nonsmoking men [age: 18–45 y; BMI (in kg/m²): 19–25] (Table 1) with no history of serious disease or currently taking any medications were recruited from the staff and student population of Queen’s Medical Centre and University of Nottingham via a poster advertisement. Participants were excluded if they reported to be dieting or had experienced a weight loss or gain (≥3 kg in the past 6 mo).

All participants had normal clinical biochemistry and hematologic test results. Restrained eaters [defined by a score >7 for the restraint factor on the Three-Factor Eating Questionnaire (15)] and subjects who presented with symptoms of clinical depression [defined by a score >10 on Beck Depression Inventory (16)] were excluded from the study. The daily energy requirement and habitual EI were assessed during the screening process as described previously (8, 17). All participants were recruited and studied between May and September 2008 and received financial compensation for taking part in the study. Ethical approval for the study was granted by the University of Nottingham Medical School Research Ethics Committee.

**Design**

This study was a double-blind, randomized, crossover trial that spanned a total of 42 d. Two 14-d intervention phases were separated by a 14-d washout period. Participants made 4 experimental visits to the laboratory, which were scheduled on the first (day 1) and last (day 15) days of each intervention phase (see Supplementary Figure 1 under “Supplemental data” in the online issue).

**Free-living protocol**

During phase 1, participants remained free-living, and the diet content was self-selected; however, subjects were instructed to consume 1 of 2 snack bars each day as a between-meal, midmorning snack. After participants had completed the first intervention phase, they were instructed to consume their regular diet for 14 d (no snack bars were provided for consumption) as a wash-out phase. During the second intervention phase (14 d), participants were provided with the alternative snack bar. The order in which participants received snack bars was randomized and counterbalanced. On the 4th, 8th, and 12th days of each intervention phase, participants were asked to record all foods and drinks consumed for a 24-h period in a food diary.

**Experimental laboratory protocol**

Participants were advised to refrain from undertaking vigorous physical activities and the consumption of alcohol for a 24-h period before each experimental day (days 1 and 15 of each intervention phase).

Participants were instructed to consume a standardized meal at 2000 the evening before each study day. The meal was equivalent to 30% of estimated energy requirements with 48%, 36%, and 16% of energy from carbohydrate, fat, and protein, respectively (see reference 8 for details). Once subjects had consumed the meal, participants were instructed to consume no other foods or drinks (apart from water, which was available ad libitum) until they arrived at the laboratory at 0745 the next morning. On arrival, participants placed one hand in a hot-air ventilated perspex box (50–55°C) so that arterialized venous blood samples could be collected (18). A cannula was inserted retrograde into a dorsal hand vein under local anesthetic and was attached to a slow-running infusion of sterile saline (0.9%) to maintain patency. A fasting blood sample was collected, and participants completed baseline ratings of subjective appetite sensations by using paper-based visual analog scales (VASs). Subjects were provided with a standardized breakfast that they had 15 min to consume and then rested in the laboratory. After 150 min, an additional blood sample was collected, and participants completed appetite VASs before being provided with 1 of 2 isoenergetic 1067-kJ snack bars, which they had 15 min to consume. The snack bars contained PPX or minimal amounts of protein and no polydextrose (control) (Table 2). Additional appetite ratings were completed immediately after subjects had consumed the snack bar and 30, 60, and 90 min later. Blood samples were collected immediately (0 min) and at 5, 10, 15, 30, 45, 60, 75, and 90 min later. After 90 min, participants were provided with a pasta-based test meal to consume ad libitum. Participants were instructed to eat as much food as they wished and to stop eating when they felt comfortably full. Once participants indicated to the experimenter that they had finished eating, the meal was terminated. Appetite ratings were completed immediately (0 min) and at 30 and 60 min later. Blood samples were collected at 15, 30, and 60 min. The cannula was removed, and participants were free to leave the laboratory. They were asked to record all foods and drinks consumed during the remainder of the day in a food diary provided.

**TABLE 1**

<table>
<thead>
<tr>
<th>Participant characteristics (n = 10)</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (y)</td>
<td>30.7 ± 9.7</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>71.2 ± 9.5</td>
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<tr>
<td>BMI (kg/m²)</td>
<td>23.2 ± 2.8</td>
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<tr>
<td>Daily energy requirement (kJ)</td>
<td>12,484 ± 1907</td>
</tr>
<tr>
<td>Habitual energy intake (kJ)</td>
<td>12,870 ± 2428</td>
</tr>
<tr>
<td>Protein (% of energy)</td>
<td>15.9 ± 2.8</td>
</tr>
<tr>
<td>Fat (% of energy)</td>
<td>36.8 ± 7.9</td>
</tr>
<tr>
<td>Carbohydrate (% of energy)</td>
<td>43.0 ± 8.6</td>
</tr>
<tr>
<td>Restrained score</td>
<td>3.5 ± 1.7</td>
</tr>
<tr>
<td>Depression score</td>
<td>0.9 ± 0.8</td>
</tr>
</tbody>
</table>

1 All values are means ± SDs.

2 Daily energy requirement was assessed during screening as described previously (8, 12, 17).

3 Habitual energy intake and macronutrient composition were estimated during screening by using a self-reported food diary as described in detail elsewhere (8, 12, 17).

4 Restrained was assessed by using the restraint factor of the Three-Factor Eating Questionnaire (15).

5 Depression was assessed by using the Beck Depression Inventory (16).
### TABLE 2
Composition of snack bars

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>PPX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (kcal)</td>
<td>250</td>
<td>248</td>
</tr>
<tr>
<td>Energy (kJ)</td>
<td>1047</td>
<td>1038</td>
</tr>
<tr>
<td>Protein (g)</td>
<td>0.6</td>
<td>12.9</td>
</tr>
<tr>
<td>Protein (% of energy)</td>
<td>1</td>
<td>21</td>
</tr>
<tr>
<td>Total carbohydrate (g)</td>
<td>31.3</td>
<td>16.9</td>
</tr>
<tr>
<td>Total carbohydrate (% of energy)</td>
<td>50</td>
<td>27</td>
</tr>
<tr>
<td>Including disaccharides (g)</td>
<td>27.4</td>
<td>10.8</td>
</tr>
<tr>
<td>Including disaccharides (% of energy)</td>
<td>44</td>
<td>17</td>
</tr>
<tr>
<td>Fat (g)</td>
<td>13.6</td>
<td>13.7</td>
</tr>
<tr>
<td>Fat (% of energy)</td>
<td>13.7</td>
<td>13.7</td>
</tr>
<tr>
<td>Polydextrose (g)</td>
<td>49</td>
<td>50</td>
</tr>
<tr>
<td>Polydextrose (% of energy)</td>
<td>0.6</td>
<td>6.2</td>
</tr>
<tr>
<td>Polydextrose (g)</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

1 C, control snack bar; PPX, whey protein and polydextrose snack bar.
2 For polydextrose, 4.2 kJ/g was used as the energy value.

### Test meals

#### Breakfast

The breakfast supplied to participants consisted of crispy rice cereal (Rice Krispies; Kelloggs) and semiskimmed milk (1.7% fat) and was equivalent to ~10% of the daily energy requirement of participants. Each breakfast contained 14%, 14%, and 72% of energy from protein, fat, and carbohydrate, respectively. The cereal:milk ratio was 30 g:125 mL.

#### Snack bars

Snack bars were prepared by Mars R&D. The bars were produced in batches and packaged in opaque wrappers labeled with the randomly assigned batch code to represent the nature of the snack contained within. The investigator was blinded to the nature of these codes, and this information was only revealed to the investigator when the study had been completed and data analyzed.

#### Lunchtime test meal

The ad libitum lunchtime test meal consisted of pasta in a cheese and tomato sauce (see references 8 and 17 for details). The meal was homogeneous in nature so that energy and macronutrient intakes could be easily determined by the weight of food consumed. Each 100 g of the test meal provided 657 kJ, with 13%, 38%, and 49% from protein, fat, and carbohydrate, respectively. Portions were prepared in advance and heated when required. Participants were instructed to consume as much as they wished until they felt comfortably full.

### Appetite and hedonic ratings

Subjective ratings of hunger, fullness, desire to eat, thirst, and nausea were collected by using paper-based 100-mm VASs as described previously (17). Hedonic ratings of creamy, pleasant, fruity, salty, strong, and sweet were made after completing the snack bar and were in the same format as appetite questions.

### Blood sampling and analysis

Blood samples were collected from a 3-way tap connected to the cannula. The first 2 mL of each sample was discarded to avoid contamination with saline. Blood glucose was measured immediately by using a β-Glucose Analyzer (Haemacue). The first 4 mL whole blood was dispensed into a serum-separating tube and allowed to clot for 30 min at room temperature. The next 4 mL was dispensed into a lithium heparin coated tube containing 50 μL EGTA. The remaining 8 mL whole blood was dispensed into an EDTA-coated tube that contained 75 μL aprotinin (Trasylo; Bayer AG). Plasma and serum was obtained by centrifugation of these tubes for a period of 10 min at 3000 × g at 4°C. The plasma or serum was removed, divided into aliquots, and stored at –80°C for later analysis.

The plasma obtained from lithium heparin tubes was analyzed for nonesterified fatty acids (NEFAs) (Acyl-CoA synthetase, Acyl-CoA oxidase method, Wako NEFA C; Wako) (intraassay CV: 1.4%; interassay CV: 2.8%), glucagon-like peptide 1 (GLP-1) (intraassay CV: 4.6%; interassay CV: 5.0%), and peptide tyrosine-tyrosine (PYY) (intraassay CV: 5.8%; interassay CV: 6.8%) by previously established, sensitive methods (19, 20). Plasma obtained from EDTA-coated tubes was analyzed for ghrelin (LINCO Research) by using a radioimmunoassay (intraassay CV: 6.7%; interassay CV: 16.3%). Serum was analyzed for insulin by using a radioimmunoassay (Coat-A-Count Insulin; Euro Diagnostic Products Corp) (intraassay CV: 8.4%; interassay CV: 107%).

### Sample-size estimate and power

An a priori sample-size estimate was conducted on the basis of the ability to detect a difference in ad libitum EI at a lunchtime test meal between a PPX snack and an energy-matched control snack by using a crossover design (2-tailed paired t test) (G*Power 3.1.7 software; Heinrich-Heine-Universitat Dusseldorf) (21). To detect a difference in ad libitum EI at α = 0.05 and β = 0.2 with an effect size of 0.96 [on the basis of the mean and variance (SD) of EI in subjects at a lunchtime test meal after a liquid preload that contained PPX (mean ± SEM: 6093 ± 1565 kJ) and an energy-matched control (7007 ± 1589 kJ) and the correlation between variables of r = 0.82, as reported in a previous study (12)], the minimum sample size required was n = 9.

### Statistical analysis

SPSS software (version 13; SPSS) was used for data entry and analysis. All data are presented as means ± SEMs unless otherwise stated.

Repeated-measures ANOVA on 2 factors (snack × day) were conducted for ad libitum lunchtime EI and total EI on experimental days, total daily EI when free living, and hedonic rating variables. Planned post hoc analyses were conducted by using a 2-tailed paired Student’s t test to compare differences in these variables between snacks and between study days.

VASs and blood metabolite responses were calculated as the AUC above or below baseline [incremental AUC (iAUC)] and analyzed by using repeated-measures ANOVA on 2 factors (snack × day). Planned post hoc analyses were conducted by using 2-tailed paired t tests to compare time-averaged responses (the iAUC) between snacks and study days. Differences were considered significant at P < 0.05.
RESULTS

Ten men were enrolled onto the study (Table 1). No adverse events were reported during the study, and there were no dropouts or exclusions; thus, data were analyzed from all participants (n = 10).

EI at the test meal

There were significant main effects of the day (P < 0.05) and snack (P < 0.05) for ad libitum EI at the test meal. On day 1, ad libitum EI at lunch was significantly lower after the PPX snack (4085 ± 365 kJ) than the control snack (4880 ± 459 kJ) (P < 0.05). EI after the control snack on day 1 was significantly lower than intake on day 15 (P < 0.05), but there was no difference between ad libitum EI on days 1 and 15 after the PPX snack. Nevertheless, ad libitum EI at the lunchtime test meal on day 15 remained significantly lower after the consumption of the PPX snack (4330 ± 359 kJ) than the control snack (5344 ± 424 kJ) (P < 0.05) (Figure 1).

Total daily EI on experimental days

Total daily EI during experimental days was calculated from the sum of energy consumed at breakfast, the energy provided by the snack, EI at the ad libitum test meal, and self-reported intake for the remainder of the day.

There was a significant main effect of the day (P < 0.05) and snack (P < 0.05) on total daily EI. On day 1, total EI was significantly lower after the consumption of the PPX snack (9248 ± 782 kJ) than the control snack (11,466 ± 738 kJ) (P < 0.05). Total daily EI on day 15 was significantly higher than EI on day 1 in both snack conditions (P < 0.05). As a consequence, total daily EI on day 15 remained significantly lower when the PPX snack was consumed (10,214 ± 954 kJ) than when the control snack was consumed (12080 ± 775 kJ) (P < 0.05) (Figure 1).

Free-living intake

There was a significant main effect of the snack (P < 0.05) with mean self-reported free-living daily EI over the 3 recorded days that was significantly lower during the consumption of the PPX snack (7904 ± 610 kJ) than the control snack (9041 ± 928 kJ) (P < 0.05).

Hedonic evaluation of snack bars

Snack ratings of creamy, pleasant, strong, and sweet displayed a significant main effect of the snack (P < 0.05). Pleasant was the only rating to display a main effect of the day (P < 0.05) (Figure 2). Planned comparisons revealed that the control snack was rated creamier than the PPX snack on days 1 and 15 (P < 0.05), and although creamy ratings did not change from days 1 to 15 for the PPX snack, participants rated the creaminess of the control snack higher on day 15 than they did on day 1 (P < 0.05).

On day 1, there was no difference in how pleasant participants rated snacks; however, participants rated the PPX snack less pleasant on day 15 than on day 1 (P < 0.05) but rated the control snack more pleasant on day 15 than on day 1 (P < 0.05). As a consequence, on day 15, the PPX snack was rated less pleasant than the control snack (P < 0.05). On day 1, there was no difference in how strong participants rated snacks. However, the PPX snack was rated less strong on day 15 than on day 1 (P < 0.05), which resulted in the control snack being rated stronger than the PPX snack on day 15 (P < 0.05). The PPX snack was rated less sweet than the control snack on days 1 and 15 (P < 0.05) with no difference in the sweetness rating of either snack from days 1 to 15.

Subjective appetite ratings

Hunger

There was a significant main effect of the snack for the iAUC for subjective hunger ratings (P < 0.05). On day 1 hunger iAUC values after the PPX snack were significantly lower than after the control snack (P < 0.05), which suggested that participants experienced reduced feelings of hunger in response to the PPX
snack than control snack bar. There was no change in \( i \text{AUC} \) hunger ratings in response to the control snack from days 1 to 15, but \( i \text{AUC} \) hunger ratings in response to the PPX snack tended to change from days 1 to 15 (\( P = 0.1 \)), and as a result, on day 15, there was no difference in \( i \text{AUC} \) hunger values between snack conditions (Figure 3).

**Fullness**

There was no effect of the snack but there was a significant main effect of the day (\( P < 0.05 \)) for \( i \text{AUC} \) fullness ratings. \( i \text{AUC} \) fullness ratings decreased from days 1 to 15 after the control and PPX snacks (\( P < 0.05 \)), which suggested that, although there was no difference in overall fullness ratings between snacks on either experimental visit days, snacks did not suppress fullness as much on day 15 compared with day 1.

**Blood glucose**

The blood glucose \( i \text{AUC} \) displayed significant main effects of the snack (\( P < 0.01 \)) and day (\( P < 0.05 \)) and a snack \( \times \) day interaction (\( P < 0.05 \)) (Figure 4). The mean blood glucose
AUC was significantly higher in response to the control snack than the PPX snack (mean difference: 13.3 ± 4.8 mmol/L over 90 min), and mean AUC blood glucose values on day 1 were significantly lower than those observed on day 15 (mean difference: 65.1 ± 10.4 mmol/L over 90 min).

**Serum insulin**

There was no significant effect of the snack or day on serum insulin iAUC; however, there was a trend for serum insulin iAUC concentrations to be higher with the control snack than with the PPX snack (mean difference: 175.8 ± 86.8 pmol/L; P = 0.06) (Figure 4).

**NEFAs**

The plasma NEFA iAUC displayed a main effect for the day (P < 0.01), with the plasma NEFA iAUC on day 1 higher than on day 15 (mean difference: 10.9 ± 3.7 U over 90 min), which suggested that plasma NEFA concentrations were suppressed to a greater extent on day 1 than day 15 despite no significant differences in NEFA responses between snack conditions (Figure 4).

**GLP-1**

There was no significant main effect of the day for the plasma GLP-1 iAUC, and although plasma GLP-1 iAUC values did not show a significant main effect of the snack (P = 0.096), there was a trend for iAUC plasma GLP-1 values to be higher in response to the PPX snack than in response to the control snack (mean difference: 215.1 ± 123.0 pmol/L over 90 min) (Figure 5).

**PYY**

Although there was no significant main effect of the day, there was a significant main effect of the snack for the plasma PYY iAUC (P < 0.05). Plasma PYY iAUC values for the PPX snack were significantly higher than values observed in the control-snack condition (mean difference: 123.8 ± 48.2 pmol/L over 90 min; P < 0.05) (Figure 5).

**Ghrelin**

There was a significant main effect of the snack (P < 0.05) and a snack × day interaction for iAUC plasma ghrelin responses to snacks (P < 0.05). There was no significant difference in the plasma ghrelin iAUC between PPX (7864 ± 911.2 nmol/L over 90 min) and control (9198.4 ± 950.8 nmol/L over 90 min) snacks on day 1. There was no difference in the plasma ghrelin iAUC between days 1 and 15 with the control snack. However, plasma ghrelin iAUC values were significantly higher on day 15 than on day 1 in the PPX-snack condition (P < 0.01), which resulted in a trend for higher plasma ghrelin iAUC values on day 15 after the PPX snack (15,173.0 ± 2619.3 nmol/L over 90 min).
DISCUSSION

In this study, we showed that the consumption of a snack bar that contained PPX as a midmorning, between-meal snack reduced subsequent voluntary food intake at the next meal compared with after consumption of a control snack that contained an equivalent amount of energy but did not contain whey protein or polydextrose. Furthermore, self-reported EI during the remainder of the day was not different between snacks; hence, total EI was significantly lower on experimental days when the PPX snack was consumed. In addition, when snacks were consumed as part of an otherwise self-selected diet under free-living conditions, mean self-reported daily EI was

than the control snack (8677.1 ± 1091.6 nmol/L over 90 min) (P = 0.06) (Figure 5).

FIGURE 4. Mean (± SEM) blood glucose (A), serum insulin (B), and plasma NEFA (C) responses to the PPX and C when they were consumed on days 1 and 15 of the intervention phase (n = 10). Vertical, dashed lines indicate times that breakfast, snack, and ad libitum test meals were consumed. Repeated-measures ANOVA displayed a main effect of the snack (P < 0.01), day (P < 0.05), and a snack × day interaction (P < 0.05) for blood glucose AUC. There were no significant effects for serum insulin AUC (P-snack × day interaction = 0.69), and there was a main effect of week (P < 0.01) for plasma NEFA (P-snack × day interaction = 0.78). BL, baseline; C, control snack bar; NEFA, nonesterified fatty acid; PPX, whey protein and polydextrose snack bar.
significantly lower when PPX snacks were consumed than when the control snack was consumed.

Snacking is a common practice that is believed to increase risk of developing obesity because of the positive correlation between the incidence of snacking and daily EI (22). Results of the current study are in contrast with the belief that snacks consumed between meals are not detected and consequently do not affect satiety (23). In a series of studies, we have shown that snacks, which were defined for the purposes of these studies as foods consumed between the 3 main meals, were able to have an effect on satiety. The findings of the current study confirm and support findings of our previous studies that showed that liquid preloads (consumed as between-meal, midmorning snacks) that contained PPX influenced subsequent voluntary food intake (12, 17). Together, these findings suggest that making changes to the composition of foods consumed as between-meal snacks, without

**FIGURE 5.** Mean (±SEM) plasma GLP-1 (A), PYY (B), and ghrelin (C) responses to the consumption of the PPX and C when they were consumed on days 1 and 15 of the intervention (n = 10). Vertical, dashed lines indicate times that breakfast, snack, and ad libitum test meals were consumed. Repeated-measures ANOVA showed a main effect of the snack (P < 0.05) for plasma PYY AUC (snack × day interaction, P = 0.29), a main effect of day (P < 0.05), and a snack × day interaction (P < 0.05) for plasma ghrelin AUC. There were no significant effects for GLP-1 AUC (P-snack × day interaction = 0.26). BL, baseline; C, control snack bar; GLP-1, glucagon-like peptide 1; PPX, whey protein and polydextrose snack bar; PYY, peptide tyrosine-tyrosine.
changing the energy content, influences voluntary EI at a subsequent meal. Furthermore, these reductions in intake at a subsequent test meal manifested into lower daily EI, and these reductions in daily EIIs were maintained when the snack was consumed on a daily basis under free-living conditions.

Differences in hedonic ratings of the snack bars showed differences in palatability associated with changing the composition of the snack. We could not rule out the possibility that these differences in palatability could have influenced the findings in this study. Although we had baseline measurements of habitual EI, the study lacked a randomized, no-snack arm, in which participants were asked to abstain from the consumption of any between-meal midmorning snacks. Although we could infer that the consumption of PPX snack reduced total daily EI compared with the consumption of the energy-matched control snack, we could not conclusively determine whether total daily EI was lower than if no snack was consumed.

The focus of this study was on EI because it was not anticipated that, over a 2-wk period, meaningful changes in body weight would be observed. However, on the basis of the findings of this study, future studies that investigate effects of the consumption of between-meal snacks over longer periods of time, which would usefully include measures of body weight and body composition change, are warranted. Furthermore, future studies should also monitor the physical activity of participants during interventions so that any possible influence of differences in physical activity on outcomes can be excluded.

Note that self-reported intake during the free-living phase of the experiment was lower than the EI recorded on any experimental day. We believe that these differences in EI were attributable to the underreporting associated with self-reported measures of diet (24–26). During experimental days, the majority of EI was carefully measured and consumed under controlled laboratory conditions, with only the remainder of the day intake being self-reported and, thus, subject to underreporting. However, during the free-living phase of the study, 100% of total EI was determined by self-reported measures, and thus, total daily intake was subject to the error and underreporting associated with self-reporting.

Despite the consistent observation of significant differences in both EI at the ad libitum lunchtime test meal and self-reported EI during the free-living part of the study, this observation was not reflected by differences in subjective appetite ratings. Only hunger ratings were significantly different between snack conditions. Because the study was powered to detect a difference in ad libitum EI at the lunchtime test meal, the failure to detect differences in subjective appetite ratings may have been attributable to the study being underpowered for these variables. Alternatively, the failure could have reflected the inability of subjective appetite ratings to predict subsequent EI (27, 28).

Nevertheless, differences in EI were supported by differences in gut peptide responses to the snacks. Differences in glucose responses between snacks were not surprising to us because of the higher carbohydrate content of the control snack bar. However, serum insulin concentrations were similar between conditions, probably because, with the PPX snack, the stimulation of insulin secretion was achieved by a combination of carbohydrate and protein ingestion (29, 30). In contrast, there were differences in the gut hormone responses including lower ghrelin and higher GLP-1 and PYY responses in the PPX snack, which may help to explain why the PPX snack had more beneficial effects on subsequent EI than the control snack did. PYY has been shown to suppress ghrelin, and thus, the trend for lower ghrelin observed after the PPX snacks may have been a reflection of this phenomenon (31) or a direct response to the consumption of the snack. Furthermore, a greater suppression of ghrelin and higher postprandial plasma PYY and GLP-1 have been reported to be associated with lower subjective appetite ratings and reduced voluntary food intake at a subsequent test meal (32–36). These differences in gut hormone responses provide support to suggest the mechanism by which the PPX snack had more beneficial effects on subsequent EI than the control snack.

Furthermore, it appears that at least some of the metabolic and endocrine responses to the snacks changed with repeated daily exposure. We propose that, when a food is consumed on a daily basis, there may be a learning effect that manifests in physiologic differences in the response to that food. Despite these apparent adaptations, EI at the test meal was higher on day 15 in both snack conditions, which suggested that participants may have become less sensitive to gut peptide signals after 14 d of daily exposure.

In conclusion, the current findings suggest that manipulating the composition of foods consumed as between-meal snacks influences subsequent EI in lean, male participants. We conclude that replacing regular snacks with snacks that contain PPX has the potential to be helpful in a weight-management regimen. However, because the current study was only conducted in lean men, future studies should examine effects in females as well as in overweight and obese subjects who may benefit the most from limiting daily EI.

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