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ORIGINAL CONTRIBUTION

Polydextrose: its impact on short-term food intake and subjective feelings of satiety in males—a randomized controlled cross-over study

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Abstract

Purpose Polydextrose is a low-calorie highly branched-chain glucose polymer that is poorly digested in the upper gastrointestinal tract and therefore demonstrates fibre-like properties. Fibre has been shown to increase satiety and possibly reduce food intake. Therefore, the objective of the current study was to examine the effects of polydextrose on short-term satiety and energy intake.

Methods In a repeated-measures randomized blind cross-over design, 26 healthy males consumed a 400-g fruit smoothie containing 12 g (3 %) of polydextrose, and a buffet lunch 60 min after the smoothie. Motivational ratings for satiety and palatability and lunch energy intake were measured. The effects of the polydextrose-containing smoothie were compared against a polydextrose-free control smoothie.

Results Polydextrose did not significantly alter the taste and palatability of the fruit smoothie. Consuming the polydextrose-containing smoothie resulted in a significantly lower energy intake at lunch (102 kcal less) compared to the control.

Conclusion Polydextrose may be a good fortificant for reducing short-term food intake.

Keywords Satiety · Food intake · Appetite · Hunger · Polydextrose · Short-term · Fibre

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Introduction

Polydextrose is a glucose polymer with a degree of polymerization of approximately 12 [1]. Developed in the 1960s, it has randomly polymerized branched chains and varied types of glycosidic bonds that are not digested by human digestive enzymes [2]. It therefore has a low calorific value (1 kcal/g) and demonstrates physiological effects associated with dietary fibre [2–5]. Polydextrose increases faecal bulking and short-chain fatty acid production in the colon, reduces transit time, softens stools, lowers faecal pH, induces prebiotic effects, reduces concentrations of putrefactive and carcinogenic substances in the colon and reduces serum triglycerides [2–5]. Polydextrose is widely used in commercial foods for calorie reduction, bulking, stabilizing, as a sugar replacement, and as a humectant [4, 6].

Numerous studies have shown that fibre increases satiety of food and decreases short-term energy intake [7]. Foods containing fibre have been shown to suppress hunger pangs for longer following their consumption [8]. Therefore, the addition of polydextrose to foods may increase the satiating properties of food. Limited research has investigated this aspect, and they too report conflicting results. Whilst some studies have shown a significant effect of polydextrose on satiety [9], others have not [10, 11]. These equivocal findings highlight the need for more research before firm conclusions can be reached.

The current study was initiated to further investigate the effect of polydextrose on satiety and short-term energy intake. Using a fruit smoothie as the test medium, the specific objective of the study was to observe the impact of polydextrose on subjective feelings of satiety and subsequent energy intake. The effects of the polydextrose smoothie were compared against a polydextrose-free control smoothie. The study was designed to test two hypotheses that the polydextrose smoothie would elicit a significantly greater degree of subjective satiety, and secondly, significantly reduce energy intake at the subsequent meal (consumed 60 min later) compared to the control smoothie.

Subjects and methods

Study participants

Twenty-eight healthy male participants were recruited for the study by means of advertisement, flyers and personal communications. Two participants withdrew from the study after completion of one session for personal reasons unrelated to the study. Therefore, the complete data sets of 26 were obtained at the end of the study for statistical analyses. Before inclusion in the study, potential participants were briefed on all aspects of the experiments and given the opportunity to ask questions. They then signed a consent form in the presence of the researcher.

The inclusion criteria for the study were as follows: males, body mass index (BMI) between 18.5 and 30.0 kg/m^2, age between 18 and 45 years, not partaking in sports at the competitive and endurance levels, having no eating disorders or conscious restriction of food intake, and habitually consuming breakfast and snacks between meals (Table 1). The exclusion criteria were as follows: having metabolic diseases (diabetes, hypertension and the metabolic syndrome), having allergies/intolerances to the foods presented in the study, smoking, and having medical conditions requiring prescription medication and taking medications known to affect appetite (steroids, sulphonylureas, antihistamines, antidepressants, amphetamines, hypoglycaemic agents and hormones).

Table 1 Baseline characteristics of the study participants

Number of participants	26
Age (years)	28 ± 7
Height (m)	1.8 ± 0.1
Weight (kg)	76.7 ± 12.3
Body mass index (kg/m^2)	24.1 ± 3.2
Waist circumference (inches)	33.5 ± 3.0
Mid-upper arm circumference (cm)	12.1 ± 1.0
Body fat content (%)	17.9 ± 5.4
Habitual physical activity score	8.1 ± 1.5
Eating behaviour score	2.3 ± 0.5

Values are means ± standard deviations. Habitual physical activity was measured using Baecke's habitual activity questionnaire—a value below 9 denotes the absence of physical activity at the competitive and endurance levels. Eating behaviour was measured using the Dutch eating behaviour questionnaire—a value below 2.8 indicates the absence of intentional food restriction

General health status was assessed by means of a questionnaire (food allergies/intolerances, metabolic diseases, special dietary needs, prescription medication and smoking habits). Physical activity was quantified using the questionnaire of Baecke et al. [12]. Eating behaviour was determined using the Dutch eating behaviour questionnaire [13] (Table 1). Only those who did not consciously restrain their food intake due to psychological reasons, weight concerns and external stimuli were included in the study.

Anthropometric measurements were obtained in the fasting state with the participant wearing light clothes. Height was measured to the nearest centimetre using a free-standing stadiometer (Seca 217, Birmingham, UK) with the subject standing erect and the head in the Frankfurt plain. Body weight was measured to the nearest 0.05 kg using calibrated anthropometric weighing scales (Seca 877, Birmingham, UK). BMI was calculated as weight (kg)/height^2 (m). Waist circumference was measured to the nearest centimetre using an anthropometric measuring tape (Seca 201, Birmingham, UK) at the mid-point between the coastal margins of the ribs and upper margin of the iliac crest. Mid-upper arm circumference was measured at the mid-point between the tip of the shoulder and the tip of the elbow using an anthropometric measuring tape (Seca 201, Birmingham, UK). Body composition was measured using a bio-electrical impedance segmental body composition analyser (Model BC-418 MA, Tanita UK Ltd., Yiewsley, UK).

Breakfasting and snacking habits were determined using a pretested questionnaire developed by our research group and used previously [14]. Only those who habitually breakfasted ≥5 days/week and snacked between main meals on ≥ 5days of the week were included.

On the evening before each test day, participants were asked to restrict their intake of alcohol and caffeine-containing drinks and to restrict their participation in intense physical activity. They were also encouraged to keep physical activity to a minimum on the morning of and during testing. The participants were advised to eat a meal of similar size and composition for dinner on the evenings prior to both test days.

Study design and ethics

A repeated-measures single-blind randomized cross-over design was adopted with each participant returning on two separate days. A gap of at least 2 days was maintained between the two sessions to minimize cross-over effects. Each preload was tested once by each participant. The study was conducted according to the guidelines laid down in the Declaration of Helsinki, and the protocol was approved by the Oxford Brookes University research ethics committee. Ethical approval covered all methodological aspects of the study, participant recruitment, data confidentiality and storage.

Preloads

The preload beverage used in the study was a commercial peach and passion fruit smoothie widely consumed in the UK. Ingredients in the smoothie were apples, peaches, banana, passion fruit, orange and lime. Its compositions (per 100 ml) were energy 52 kcal, protein 0.7 %, carbohydrates 12 %, fibre 0.7 % and trace amounts of fat.

The control drink consisted of 400 g of the smoothie. A serving size of 400 g was based on the current average serving volume of soft drinks [15]. The treatment drink consisted of 383 g of the smoothie and 17 g of Litesse® (containing 12 g of polydextrose). For preparing the treatment drink, the Litesse® was weighed directly into the serving glass, followed by the smoothie and the contents were stirred vigorously for 1 min to ensure homogenization. The energy content of the control and treatment were 208 and 211 kcal, respectively. Both preloads were presented chilled to the participants.

Test meals

At each study session, the participants were provided with a standard breakfast and a buffet lunch. Breakfast consisted of a choice of granary bread (fresh or toasted), corn flakes, bran flakes, special K cereal, fat spread, strawberry conserve, marmalade, milk, tea and coffee (Table 2). On the first day of testing, the participants were informed that they could select any combination and quantity of these foods for breakfast. This was then kept standard for each individual for both test sessions. Mean energy intake at breakfast was 393 ± 139 kcal.

Lunch was a buffet of sandwiches, yoghurt and fruit (Table 3). Of the eight sandwiches, the participants were instructed to select their favourite three and these were then served for them at lunch. A choice of three (instead of providing all eight types) sandwiches was presented to

Table 2 Nutrient and energy profiles of foods served at breakfast

	Portion size (g)	Protein (g)	Carbohydrates (g)	Fat (g)	Fibre (g)	Energy (kcal)
Bread	44	4.5	20.4	1	1.6	113
Corn flakes	40	2.8	34	0.4	1.2	151
Bran flakes	42	4.2	28	0.8	6.3	150
Special K cereal	40	5.6	30.4	0.6	1	152
Fat spread	10	0.05	0.05	6	0	54.4
Strawberry conserve	15	0	9.6	0	0	39
Marmalade	15	0.03	9.4	0	–	38
Milk	210	8	10	4	0	105
Tea	3	0	0	0	0	–
Coffee	5	0.35	1.8	0.01	1.4	3

Macronutrient, fibre and energy values are amounts per portion

Table 3 Nutrient and energy profiles of foods served at lunch

	Protein (g)	Carbohydrate (g)	Fat (g)	Fibre (g)	Energy (kcal)
Egg mayonnaise sandwiches	8	21	11	2	202
Cheese and tomato sandwiches	10	21	10	2	203
Cheese and pickle sandwiches	9	25	9	2	204
Houmous salad sandwiches	6	23	10	4	197
Tuna mayonnaise sandwiches	9	21	10	2	202
Chicken salad sandwiches	10	22	9	3	202
Roast beef and tomato sandwiches	13	22	8	2	201
Ham and cheese	12	21	9	2	202
Yoghurt	7	13	0.1	1	71
Apple	1	16	0.1	2	70
Pear	0.4	13	0.1	3	60
Orange	2	17	0.2	3	80

Values are amounts per portion. A sandwich portion was defined as half of a two-bread-slice sandwich avoid wastage and excess expenditure. From each type, two sandwiches (one sandwich equates to a unit made from two slices of bread) were initially provided, resulting in a total of six sandwiches for each participant. The sandwich recipes were formulated so that all the types contained approximately the same energy content per portion (Table 3). The accompanying foods (fruit and yoghurt) also contained an approximately similar amount of energy. Participants were informed that they could eat ad libitum, and the buffet was continuously replenished to ensure excess food was available. Only still water was provided as a beverage during lunch.

Study protocol

The protocol adopted was the classical preload paradigm typically used in satiety studies [16, 17]. Each test session included a standard breakfast, the smoothie preload and an ad libitum buffet lunch. The time interval between breakfast and the preload was 3 h and between the preload and lunch was 1 h. Previous studies have observed significant levels of compensation 60 min after an energy preload (ranging from 30 to 300 kcal) [14, 18, 19]. Therefore, the same time interval between the preload and lunch was used in the current study. The objective of the study was stated to the participants as being 'to examine the palatability of the smoothies and effect on feelings of satiety'. They were told that the only data obtained in the study were those from the visual analogue scales (VAS). However, the primary study outcome was food intake at the buffet lunch, and the participants were not told of its measurement until they had completed the study.

The participants arrived at the lab between 07:00 and 08:30 h following a 10 h overnight fast. Breakfast was served 5 min after the participants' arrival at the laboratory. Participants were instructed to consume their breakfast within 20 min. Upon completing breakfast, participants were given in writing the times they would have to return to the laboratory for the smoothie and lunch. Participants were instructed not to consume anything between breakfast and the test drink except for 250 ml of water.

Participants were instructed to drink the smoothie within 10 min. This did not prove to be difficult for any of the subjects. Lunch was served as individual buffets for each person. The individual buffet consisted of the sandwich platters, yogurt, fruit bowl and table water. To minimize social interactions and its effects on food intake, participants sat alone whilst having lunch. Previous studies have shown that talking, the social setting and the familiarity of others present all influence individuals' food intake [20]. Participants were instructed to eat until they were comfortably full. To avoid potential overeating, they were told that they could take home any leftovers. Sandwich choice and quantity eaten by each participant was unobtrusively observed and recorded whilst participants had lunch. The eating area was located in an open-plan room and the buffet and seating was arranged facing away in a manner that allowed the investigators to observe and record participants' food choice, and quantity unobtrusively and without their knowledge from an ante-room located behind them. Plate waste was measured once the participant had finished and left the laboratory. This was carried out by weighing the individual food types in the plate waste (sandwich type, fruit and yoghurt) and calculating the energy and nutrient content in each individual type using the values in Table 3.

Subjective motivational ratings for hunger, fullness, desire to eat and prospective food consumption were obtained before and after breakfast, 1 h after breakfast, before drinking the smoothie, 15, 30 and 45 min after the smoothie, before and after lunch. The participants also rated the palatability of the preload (how pleasant and how tasty) immediately following the consumption of the smoothie.

In order to minimize climatic effects, participants completed both test sessions within 2 consecutive weeks. Testing was carried out in a climate controlled food lab (ambient temperature: 22 ± 2 °C).

At the completion of the study, the participants were debriefed and compensated for their time with book tokens.

Measurement of subjective motivational ratings

One-hundred-millimetre continuous line VAS were utilized to measure subjective feelings of hunger, fullness and desire to eat. The lines were anchored at the left and right ends with opposing statements for feelings of hunger, fullness, desire to eat and prospective food consumption. The specific questions asked were, 'How hungry do you feel?', 'How full do you feel?', 'How strong is your desire to eat?' and 'How much food do you think you can eat?' Two VAS were additionally used immediately after the consumption of the smoothie to record the palatability of the beverage. The specific questions asked were, 'How tasty was the drink?' and, 'How pleasant was the drink?' The VAS was provided in the form of a booklet for each test session, and the participants were instructed on how to complete the scales at the pre-study briefing.

Data analyses

Data were analysed using the Statistical Package for the Social Sciences (SPSS) version 17 (SPSS Inc., Chicago, IL, USA). Descriptive statistics (mean, SD, standard error [SE]) were calculated for all data. Data manipulations and figure constructions were carried out on a Microsoft Excel worksheet (2006, Reading, UK).

VAS ratings were quantified by measuring in millimetres the distance between the left end of the scale and the marked point. The change from baseline values was used for all analyses (the data used for analysis were therefore corrected for baseline values). The incremental area under the curve (IAUC) for subjective feelings following the drink until the initiation of lunch was calculated geometrically using the trapezoidal rule [21]. Nutrient intakes were calculated using compositional data provided by the manufacturers and published values [22]. The protein, carbohydrate, fat, fibre and energy content per gram basis was calculated for each food item, and the nutrient intake by each participant at each session was calculated based on the quantity eaten.

Differences in energy intake at lunch and the IAUC for the VAS between the treatment and control were compared using the paired t test procedure. Differences in nutrient intake were also compared with the paired t test procedure. Alpha (α) was set at 0.05 for all statistical analyses. Normality of data was tested using the Kolmogorov–Smirnov statistic. With a calculated effect size of 0.52 (Cohen's d) and a sample size of 26, the design had a statistical power (for data analysed using the paired t test procedure) of 83.1 %.

Results

Palatability of the preloads

Participants rated both the treatment and control as equally tasty [M = −3.58; $t(25) = -1.74$; $P = 0.094$] and pleasant [M = −0.69; $t(25) = -0.35$; $P = 0.73$]. Therefore, the addition of polydextrose did not significantly affect the palatability of the smoothie. When enquired at the post-study debriefing, all the participants said that they were unable to distinguish between the treatment and control. Mean (±SE) taste and pleasantness scores (with 100 being extremely tasty and pleasant) for the control and treatment were 75 ± 2.7, 79 ± 2.8, 76 ± 2.5 and 77 ± 2.5, respectively.

Energy and nutrient intakes

Energy intake at lunch differed between the control and treatment. A significantly lower food intake was observed at lunch following the treatment compared to the control [M = 102.12; $t(25) = 2.67$; $P = 0.007$] (Table 4). The treatment resulted in a calorie reduction of approximately 100 kcal compared to the control. This equated to an energy compensation of 10 % following the treatment compared to the control.

The participants consumed significantly different carbohydrate, fat and fibre quantities at lunch [M = 9.78; $t(25) = 2.47$; $P = 0.011$; M = 2.93; $t(25) = 1.90$; $P = 0.035$ and M = 1.13; $t(25) = 2.27$; $P = 0.016$, respectively] (Table 4). The protein content did not differ significantly between the treatment and control conditions [M = 2.95; $t(25) = 1.67$; $P = 0.054$]. All four nutrients were consumed in greater amounts in the control condition compared to the treatment condition.

Subjective motivational ratings

The temporal changes in the subjective ratings for hunger, fullness, desire to eat and prospective eating were comparable for both the control and treatment (Fig. 1). The pattern of change was similar for both beverages for all four subjective feelings. Maximum satiety for both beverages following the preload was observed 15 min after consumption. Satiety progressively decreased thereafter for both beverages.

The VAS IAUC for the time period from before consuming the preload until the initiation of lunch was not significantly different between the control and treatment (hunger M = −288.43; $t(25) = -1.32$; $P = 0.20$, fullness M = 8.45; $t(25) = 0.04$; $P = 0.97$, desire to eat M = −49.30; $t(26) = -0.22$; $P = 0.83$ and prospective food consumption M = −143.34; $t(25) = -0.70$; $P = 0.50$) (Table 5). The control and treatment produced similar degrees of subjective hunger, fullness, desire to eat and prospective food consumption sensations.

Discussion

The results are applicable to healthy adult males who do not intentionally restrict food intake, partake in competitive level sports or have metabolic diseases. Previous studies have suggested that males are better able to demonstrate

Table 4 Nutrient and energy intakes at lunch

	Energy (g)	Protein (g)	Carbohydrate (g)	Fat (g)	Fibre (g)
Control	1,095 ± 64*	56 ± 3*	126 ± 7*	46 ± 3*	13 ± 1*
Treatment	993 ± 75#	53 ± 4*	117 ± 7#	43 ± 3#	12 ± 1#

Values are mean ± SE. Values represent the amount of each nutrient consumed at lunch. Values with different superscript symbols within a column are significantly different ($P < 0.05$, paired t test)

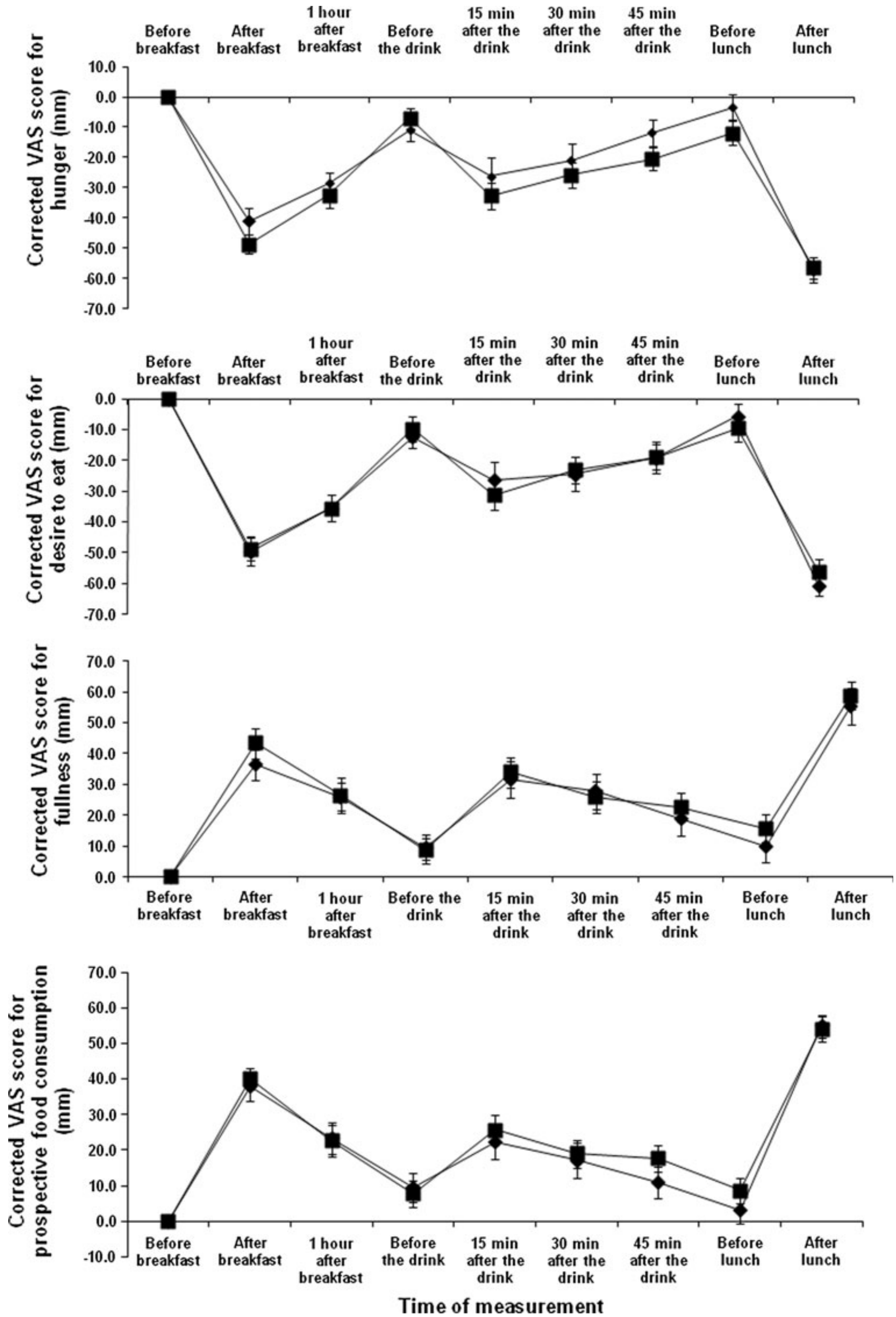

Fig. 1 Temporal visual analogue *scale curves* for hunger, desire to eat, fullness and prospective food consumption for the control (*filled diamond*) and treatment (*filled square*) smoothies. Values represent the change from baseline (corrected for baseline value). Feelings of hunger and desire to eat decreases towards the *negative* end of the *y* axis. Feelings of fullness and prospective food consumption increases towards the *positive* end of the *y* axis. *Error bars* are standard errors

physiological energy compensation [14, 23]. Females appear to show relatively weaker energy compensatory responses [14, 23] possibly due to effects of the menstrual cycle [24–26] and differences in energy regulation mechanisms [27–32]. Furthermore, males consume more food (and hence energy) at meals than females [33]. Therefore, limiting the participants to one sex (and specifically males) reduced data variability and errors. However, from a public health perspective, it is important that the effects of polydextrose on short-term energy intake and satiety in females are also investigated.

The results showed that the addition of polydextrose at a concentration of 3 % did not noticeably affect the organoleptic properties of the smoothie and this agrees with previous work [10, 11]. It appears that energy intake at the subsequent meal significantly decreases (by 10 %) when a

Table 5 Incremental areas under the curve for subjective feelings

	Feeling of hunger (min. mm)	Feeling of fullness (min. mm)	Feeling of desire to eat (min. mm)	Feeling of prospective food consumption (min. mm)
Control	694 ± 175	985 ± 198	756 ± 211	610 ± 163
Treatment	982 ± 152	976 ± 132	806 ± 135	754 ± 146

Values are means (± SE). The incremental areas under the curve represent the time between consuming the test drink and the initiation of lunch. None of the subjective sensations was significantly different between the control and treatment ($P < 0.05$, paired t test)

smoothie containing 3 % polydextrose is consumed. King et al. [9] showed a similar effect using a larger dose of polydextrose (25 g–12.5 %) and by accounting for the energy content in the preload. In comparison, the current study demonstrated significant decreases in short-term food intake using iso-caloric preloads and a smaller dose of polydextrose. The small sample size ($n = 15$) used by King et al. [9] may not have provided adequate power to detect stronger differences between the treatments independent of the energy content in the preload [17].

The results of the study do not concur with those observed by Monsivais et al. [10] who observed a significant reduction in motivational ratings following a 24 g dose of polydextrose but no effect on subsequent meal energy compensation. Monsivais et al. maintained a 100-min gap between the preload and lunch compared to 60 min in the current study. Previous reports have indicated that physiological compensation to a preload occurs within a specific time window, the attributes of which depend on preload size and time interval between the preload and test meal [14, 34]. Monsivais et al. also appear to have pooled the lunch intake data of the two sexes for statistical analyses despite males eating significantly more at lunch. The type of polydextrose tested in the two studies was also different (Sta-lite III® by Monsivaise et al. and Litesse® in the current). These two types differ in terms of physico-chemical characteristics such as viscosity [35, 36], which incidentally has been shown to inversely correlate with hunger [37]. Previous studies comparing the effects of different (commercial) types of the same functional ingredient have also shown that physico-chemical differences between (commercial) types influence physical and physiological outcomes [38, 39].

The addition of polydextrose did not appear to significantly affect subjective ratings of hunger, fullness, desire to eat and prospective food consumption. This is in agreement with previous observations [9, 11]. As was evident in the current study and previous research [14, 40–42], motivational ratings do not always accurately reflect physiological energy needs and actual food intake levels [40, 43].

The findings of the current study open up a raft of future research possibilities. Whilst future studies need to confirm the findings of the current investigation, they also need to explore the physiological mechanisms responsible for the observed effects. It is possible that the satiating effects of polydextrose are through the slowing down of gastric emptying and transit time as a result of increased chyme viscosity [4]; however, this remains to be confirmed. Research to date has focused only on the short-term effects of polydextrose on energy intake and satiety. Long-term trials looking at the effects of repeated polydextrose supplementation on energy regulation are required in order to establish if the short-term effects translate into long-term weight loss. Furthermore, future studies should comparatively evaluate different brands of commercial polydextrose for their effects on physiology. Commercially available polydextrose formulations are physico-chemically different to each other, and it is important to determine whether all these forms impact on energy balance in the same manner.

A drawback of the current study was that food intake during the remainder of the day was not measured. Therefore, it is not known whether the reduced energy intake at lunch was or was not compensated for during the remainder of the day. Further, the use of a single concentration of polydextrose as a treatment precluded the observation of dose response effects. These aspects need to be considered in future studies.

In conclusion, the study suggests that polydextrose added to a beverage at a concentration of 3 % has the potential to reduce food intake in healthy male adults in the short term. It appears that polydextrose could be potentially used for appetite control, and this avenue of research justifies more attention. The results do not agree with the first study hypothesis that a polydextrose-containing smoothie significantly influences subjective satiety but agrees with the second hypothesis that it significantly reduces energy intake at the subsequent meal consumed 60 min later (compared to a polydextrose-free control).

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