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Perceived thickness and creaminess modulates the short-term satiating effects of high protein drinks.

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ABSTRACT

Previous research suggests that increasing beverage protein content enhances subsequent satiety, but whether this effect is entirely attributable to post-ingestive effects of protein or is partly caused by the distinct sensory characteristics imparted by the presence of protein remains unclear. To try and discriminate nutritive from sensory effects of added protein, we contrasted effects of three higher energy (c. 1.2MJ) and one lower energy (LE: 0.35MJ) drink preloads on subsequent appetite and lunch intake. Two higher energy drinks had 44% of energy from protein, one with the sensory characteristics of a juice drink (HP-) and the second thicker and more creamy (HP+). The high-carbohydrate preload (HC+) was matched for thickness and creaminess to the HP+ drink. Participants (healthy male volunteers, n=26) consumed significantly less at lunch after the HP+ (566g) and HC+ (572g) than after HP- (623g) and LE (668g) drinks, although the compensation for drink energy accounted for only 50% of extra energy at best. Appetite ratings indicated that participants felt significantly less hungry and more full immediately before lunch in HP+ and HC+ compared to LE, with HP- intermediate. The finding that protein generated stronger satiety in the context of a thicker creamier drink (HP+ but not HP-), and that an isoenergetic carbohydrate drink (HC+) matched in thickness and creaminess to the HP+ drink generated the same pattern of satiety as HP+ both suggest an important role for these sensory cues in the development of protein-based satiety.

Introduction

It has been widely reported that meals with a higher proportion of energy as protein are more satiating than isoenergetic meals lower in protein content both in acute tests of satiety using short-term measures of rated appetite and/or intake[1-10] and longer-term studies on manipulated protein content of the diet[11-14]. However, there remains some uncertainty about the mechanisms underlying the enhanced satiating efficiency of protein-based foods and drinks. Although there is clear evidence that protein ingestion results in a different profile of satiety-related hormonal signals compared to other macronutrients[15-17] that has been interpreted as the basis of protein-based satiety[18], a confounding issue in interpretation of many short-term studies of protein-based satiety is the difficulty in fully disguising the addition of protein. This often results in orosensory differences between protein and control conditions that could also contribute to the behavioural effects of these foods and drinks. It is well established that orosensory cues are an important component of short-term satiety. For example, high-energy preloads have been shown to be more satiating when ingested by the participant than when infused directly into the stomach or intestine [19]. Observations like this add weight to the satiety-cascade model [20], where learned and sensory cues from food are suggested to be critical components of the short-term satiating effects of nutrients. Several recent studies provide additional evidence to support this view. Firstly, sensory characteristics that were consonant with the presence of energy (thickness and creaminess) enhanced the satiating effects of energy in a drink context [21]. Secondly, the sensory characteristics, but not protein content, of a snack preload altered subsequent selection of protein-rich foods [22]. The present study extends these findings to ask whether perceived thickness and creaminess imparted by addition of protein in a beverage may at least in part explain why protein-enriched foods and drinks are found to be more satiating than are other macronutrients in short-term tests of satiety.

A key driver for the present study was an earlier investigation in our laboratory that found that a drink preload containing 50% of additional energy as protein was more satiating than an isoenergetic drink enriched with carbohydrate only[23]. Indeed in that study there was no evidence of satiety, either through reduced intake at a test lunch or in altered appetite ratings, after the high-energy (1250 kJ) carbohydrate-enriched drink compared to the low-energy (327 kJ) control drink. This finding is consistent with broader suggestions that energy consumed in beverage form generates weak satiety[24]. In this previous study we attempted to disguise the nutritional differences between the two high-energy drinks, however evaluations by participants clearly reported subtle sensory differences, with the high-protein drink rated as slightly more creamy, slightly thicker in texture and less pleasant than the carbohydrate drink. Therefore, sensory differences may have contributed to the short-term satiating effects of the protein drink rather than simply post-ingestive effects. More recent studies suggest a key role for sensory characteristics in determining the satiating effects of beverages[21].

The present study directly assessed the importance of sensory properties by contrasting the satiating effects of three isocaloric high energy drinks relative to a low energy control. Two versions of the high-energy drinks were enriched with protein but differed sensorially: one high-sensory protein drink (HP+) was created to taste slightly thicker and creamier than the other (HP-). The third high energy drink (HC+) was enriched purely by carbohydrate and had its flavour adjusted to match that of the high-sensory (HP+) protein drink. Since the same high carbohydrate formulation in the absence of sensory cues was not satiating in our previous study[23], any evidence that the sensory-enhanced HC+ drink resulted in satiety would be clear evidence that sensory characteristics such as thicker texture and creamy flavour may be a key element of the generation of satiety by nutrients in a beverage context. Thus, if the enhanced satiating effects of addition of protein are only a consequence of post-ingestive actions, the prediction would be that the HP- and HP+ drinks would have similar effects on subsequent

101 rated appetite and intake at a test meal. In contrast, if protein-induced satiety is dependent on
102 the sensory characteristics imparted by the added protein, then the two sensory-enhanced drinks
103 (HP+ and HC+) would be predicted to be more satiating than the high-protein low-sensory (HP-
104) drink. Thus the present design provided a clear means of dissociating the potential roles of
105 sensory and post-ingestive effects of the satiating effects of protein.
106
107

108 **Method**

109

110 ***Design***

111 A repeated measures design contrasted satiety (changes in rated appetite and test lunch intake)
112 following consumption of four preload drinks. Three preloads had a higher energy content, two
113 with 44% of energy added as protein either with (HP+) or without (HP-) enhanced creaminess
114 and thickness, and the third (HC+) had energy added as carbohydrate but thickness and
115 creaminess matched to the HP+ condition. The fourth preload was a low-energy control (LE).

116

117 ***Participants***

118 Potential participants were recruited from participant databases held by the School of
119 Psychology, University of Sussex, on the basis that they were participating in a study about
120 mood and food. Inclusion criteria were young men aged 18-35 years of age whose body mass
121 index (BMI) was within the normal range (18-25 kg/m^2). Healthy normal weight men were
122 tested to minimise demand effects generated by the laboratory testing setting. Exclusion
123 criteria included smoking more than 5 cigarettes a week, an eating, metabolic or respiratory
124 disorder, any athletes in training, and those having a restrained eating style defined as
125 individuals scoring seven or more on the restraint scale score from the Three Factor Eating
126 Questionnaire (TFEQ) [(25)]. Participants gave written informed consent and the protocol was
127 approved by the Sussex University Ethics Committee. Two participants failed to attend all
128 sessions and their data were excluded. The 26 male participants who completed all sessions
129 had a mean age of 21.1 years (SD: 2.3), a mean TFEQ restraint of 2.7 (SD:2.4) and normal BMI
130 of 21.9 kg/m^2 (SD:1.6). Participants received £40 for participation.

131

132

133

134 ***Test preload drinks***

135 Drinks were developed iteratively using taste tests with volunteers to create two high protein
136 drinks (HP+ and HP-) with similar energy content, one resembling a juice drink, and the other
137 perceived by volunteers to be a creamy drink. The HC+ drink was developed to match the HP+
138 in terms of perceived thickness and creaminess but with the additional energy added as
139 carbohydrate only. The final prototype drinks were assessed by an untrained panel of 10 male
140 volunteers who were provided with 20ml samples of each of the high-energy preloads, served
141 in 50ml containers covered in foil to obscure visual cues. They were instructed to take a
142 sufficient mouthful to allow completion of a series of sensory ratings, and were provided with
143 water to cleanse the palate between mouthfuls. Sensory evaluations were made using 100mm
144 pen and paper visual analogue scales (VAS). Ratings confirmed that the two high-energy high-
145 sensory drinks (HP+ and HC+) were significantly thicker [$F(1.1, 8.8) = 9.74$, $p<0.05$] (HP+: 73
146 ± 6; HC+: 72 ± 5), and had higher "dairy-like" characteristics [$F(1.1, 9.1) = 8.16$, $p<0.05$]
147 (HP+: 59 ± 8; HC+: 66 ± 8) than the HP- beverage (dairy: 32 ± 9; thickness: 38 ± 10). HP+ and
148 HC+ also tended [$F(2,16)=2.42$, *NS*] to be perceived as creamier (HP+: 59 ± 8; HC+: 66 ± 8)
149 than the HP- drink (32 ±9). The overall pattern of data confirmed that HP+ and HC+ were
150 reasonably well matched on the sensory characteristics we were interested in, and both were
151 perceived as thicker and more creamy than was HP-.

152

153 The composition of the preloads is summarised in Table 1, and all were prepared from a base of
154 low-energy fruit-yoghurt drink (Apricot and Peach drink Danao®, Danone). HP+ and HP-
155 were developed to provide 44% of energy as protein and HC+ contained 87% of added energy
156 as carbohydrate and 13% as protein. Protein content was varied through use of different
157 amounts of virtually fat free fromage-frais (Waitrose brand) and a whey isolate (CMC Whey®,
158 Fast Research, Staffordshire, UK), which at the concentrations used had reduced bitterness
159 compared with other whey sources and so was easier to disguise. Carbohydrate was added as a

160 combination of maltodextrin (Cerostar) and sucrose. HP+ and HC+ had added yoghurt and
161 vanilla flavours (IFF) to enhance perceived creaminess and a small amount of guar gum
162 (Meyprodor, a water soluble fibre) to enhance perceived thickness. The LE condition used the
163 base drink diluted with water.
164
165 ***Test meals***
166 Participants consumed a standardised breakfast in the laboratory on each test day consisting of
167 breakfast cereal (either Crunchy-nut cornflakes or Special K cereal, both Kellogg's UK),
168 orange juice and semi-skimmed milk (1710.2 KJ). The test lunch comprised *ad libitum*
169 consumption of pasta (fusilli variety, Sainsbury's UK) mixed with commercial tomato-based
170 herb sauce (Napoletana, Sainsbury's UK) and served in bowls at a ratio of 250g cooked pasta to
171 250g sauce. The test meal provided 500KJ (3.7g protein; 19.8g carbohydrate; 1.5g fat) per
172 100g.
173
174 ***Assessment of rated appetite, mood and food intake at the test lunch***
175 Data were collected using the Sussex Ingestion Pattern Monitor (SIPM: University of Sussex),
176 a computer-based Universal Eating Monitor [(26)] for measuring food intake and recording rated
177 appetite [(27)]. This ensured minimal monitoring or disturbance from the experimenter. SIPM
178 consisted of a disguised electronic balance (Sartorius BP 4100-S, Sartorius, Goettingen,
179 Germany) fitted into the desktop and connected to an Apple Macintosh G3 computer, with the
180 balance surface obscured by a placemat. The system was custom programmed using
181 FutureBasic (Staz Software) to read the balance weight on stability to 0.1g accuracy during the
182 test meal. At the start of the lunch session a 500g plate of pasta was placed on the balance and
183 the experimenter left the cubicle. The computer instructions were to "Eat as much as you
184 want". A separate side plate was provided to place cutlery on when not eating so that the
185 weight of cutlery did not interfere with weighing. The SIPM system prompted participants to

call the experimenter for a refill after the sixth interruption to their meal, by which time 300-400g had been consumed, which ensured that participants could not use an empty bowl as an external cue to end their meal. This process was repeated until the participants indicated that they had "finished" their meal.

Before and after each preload and meal, participants completed computerised ratings of hunger, fullness, thirst, clear-headed, happy, friendly, jittery, nauseous, energetic, relaxed, presented in the form "How <descriptor> do you feel?". Mood ratings were included as distractors. Ratings were made by electronic VAS end-anchored with "Not at all" (scored zero) and "Extremely" (scored 100). Sensory and hedonic ratings (familiar, sweet, pleasant, sour, bitter, creamy, fruity, refreshing, thick, novel, dairy, fatty) of the preload were made using the same style of VAS when the drink was first tasted and once it had been consumed in full, and participants also rated the lunch when first tasted and at the end of the meal. Polarity of all computerised ratings was randomised to minimise carry-over effects.

Procedure

Participants were instructed to eat as normal on the day before testing, but consume only water from 11pm the prior evening. On each test day, breakfast was served between 08.30 and 10.00h, and participants left the laboratory after breakfast before returning for their later appointments, but were restricted to drinking water only during this period. A 500ml bottle of water was provided to encourage water consumption throughout the morning. To encourage compliance with instructions not to eat or drink anything other than water, participants were warned that random samples of saliva could be collected at any time during the study (this was not followed up). Participants returned to the laboratory 180 minutes after breakfast and consumed the relevant preload in a small, ventilated cubicle where they also completed the mood and appetite ratings. Preloads were served in a 400ml polystyrene cup with an opaque lid

212 and straw, and participants were instructed to consume all the drink within 10 minutes. To
213 monitor compliance, each preload was weighed before and after consumption and preload
214 session duration recorded. Once they had consumed the preload and completed the associated
215 ratings they rested in an adjacent waiting room until lunch, which was served 30 minutes after
216 the preload session began. The delay between preload and lunch was selected based on an
217 earlier study, where similar drinks had the same impact on subsequent appetite regardless of
218 whether they were consumed 30 or 120 minutes prior to the test meal[23]. Once they had
219 consumed as much of the lunch as they wanted and had completed all ratings, they were free to
220 leave except on the final session, when they had a structured debriefing where they were asked
221 about the purpose of the study. Participants were also asked if they had noticed differences
222 between the preloads, breakfast or lunch meals across the test days and were asked: "Have you
223 ever tasted a high protein shake – otherwise known as body building drinks?" to judge
224 familiarity with products like the drinks under test.
225
226 ***Data analysis***
227 Intake data were contrasted between the four preload conditions using one-way repeated
228 measures ANOVA, with the prediction that all three higher energy preloads would reduce
229 intake but that HP+ and HC+ would have a larger effect than HP-. Total energy intake was
230 calculated as the sum of energy consumed at breakfast, preload and test meal, and these were
231 contrasted using ANOVA. The degree of compensation at the *ad libitum* meal for the energy
232 consumed in the preloads was calculated as the energy difference between each high energy test
233 preload and the LE, expressed as a fraction of the reduction [28, 29]. Computer failure meant all
234 rating data were lost for one participant on one day, and initial analysis of changes in hunger
235 after preload consumption identified one participant as a significant outlier (data more than 2
236 standard deviations from the mean) in two preload conditions and his data were excluded from
237 further analysis. After confirming there were no spurious baselines differences, changes in

238 hunger and fullness immediately after consuming the preload and at the start of lunch were
239 calculated and contrasted using 2-way ANOVA. Similarly, sensory and hedonic ratings before
240 and after preload consumption were contrasted between preloads to confirm the expected
241 sensory differences were evident and that these did not generate confounding differences in
242 liking. Within-subjects contrasts were used to test specific predictions and Bonferonni post hoc
243 corrections applied when making post-hoc comparisons. Data were analysed using SPSS 18 for
244 Macintosh.
245
246
247 **Results**
248 ***Intake***
249 Lunch intake varied significantly between preload conditions ($F(3,75) = 6.26$, $p<0.01$: Figure
250 1a), with intake following the two thicker and more creamy drinks (HP+ and HC+)
251 significantly less than after the LE control ($p<0.01$, $p<0.001$ respectively). Critically, intake
252 after the thick/creamy high protein HP+ drink was significantly less than after the high protein
253 drink without thick/creamy sensory characteristics (HP-, $p<0.05$), and intake after the HP- drink
254 did not different significantly from that after LE (Figure 1a). Short-term total energy intake
255 (Figure 1b) also differed significantly between conditions ($F(3,75)=11.13$, $p<0.001$), with
256 significantly greater energy intake in all three high-energy conditions compared to LE although
257 total energy intake was significantly lower in the HP+ than HP- condition ($F(1,25)=5.46$,
258 $p<0.05$). Overall compensation for preload energy was 22.4% in the HP- condition compared
259 with 50.2% in the HC+ and 52.6% in HP+ conditions.
260
261 ***Rated hunger and fullness***
262 Rated hunger and fullness immediately before preload consumption did not differ significantly
263 between preload conditions [hunger: $F(3,72) = 2.23$, NS; fullness $F(3,72) = 2.48$, NS]. As

264 expected, changes in hunger depended on time of rating [$F(1,72) = 14.07$, $p<0.001$], with a
265 larger initial decrease in hunger immediately after preload consumption and some recovery of
266 hunger by the lunch test. There was a trend for a significant overall effect of preload [$F(3,72) =$
267 2.67, $p=0.056$], but the interaction between time and preload was not significant [$F(3,72) =$
268 0.86, NS]. As can be seen (Table 2), hunger decreased immediately after consuming all four
269 preloads but this decrease was only sustained in the HP+ and HC+ conditions. The decrease in
270 hunger in both the HP+ and HC+ conditions immediately before lunch was significantly greater
271 than that in the LE control condition (both $p<0.05$) with changes after HP- intermediate and not
272 significantly different from other preloads. A similar pattern was seen with fullness ratings
273 (Table 2), and here the effects of time [$F(1,72) = 14.87$, $p<0.001$], preload [$F(2,72 = 8.37$,
274 $p<0.001$) and the preload x time interaction [$F(3,72) = 3.09$, $p<0.05$], were all significant.
275 Rated fullness increased in all four conditions immediately after consuming the drinks,
276 although this increase was significantly greater in the HC+ than in the other three conditions
277 (LE $p<0.001$, HP- $p<0.05$, HP+ $p<0.01$). However, the initial increase in fullness was not
278 sustained in the LE condition, and immediately before lunch the largest increases in fullness
279 were seen in the HP+ and HC+ conditions.
280
281 ***Rated thirst and nausea***
282 Protein-elicited thirst presented a possible confound for interpretation of this study (Table 2).
283 As baseline first did not differ significantly between conditions, change data were used to
284 contrast effects of preloads. Thirst varied with time ($F(1,72) = 6.88$, $p<0.05$), with the expected
285 large decrease immediately after drink consumption, but although the main effect of preload
286 condition was not significant ($F(3,72) = 1.33$, NS) there was a significant interaction between
287 Preload and Time ($F(3,72) = 3.22$, $p<0.05$). Surprisingly thirst was reduced more after the two
288 high protein preloads relative to the LE control and HC+ preloads prior to lunch.
289

290 Differences in lunch intake could also have been confounded by any gastric discomfort from
291 consuming these drinks. However, if so then we would have expected differences in nausea
292 ratings between preloads however there was no significant difference in baseline nausea
293 [F(3,72) = 1.66, NS], and no significant effects of preload [F(3,72) = 0.29, NS], time [F(1,72) =
294 1.43, NS] or time x preload interaction [F(3,72) = 2.39, NS) for changes in nausea immediately
295 and 30 minutes after preload ingestion.
296
297 ***Sensory and hedonic ratings of the test meal and preloads***
298 To assess whether the sensory differences evident during pilot work were detectable during the
299 satiety tests, evaluations of the four preloads at the start and end of ingestion were examined.
300 To allow comparisons between pilot and test data, only ratings at the initial taste test are shown
301 (Table 3). As expected, preloads differed significantly in perceived creaminess [F(3,75) =
302 37.00, p<0.001], thickness [F(3,75) = 23.82, p<0.001], fattiness, [F(3,75) = 16.39, p<0.001]
303 and perceptions of dairy [F(3,75) = 17.01, p<0.001]. HP- was rated as significantly less thick
304 and less fatty than were the HP+ and HC+, but (in contrast to pilot data) was rated similarly on
305 creaminess and dairy-like characteristics. Sensory ratings did not differ between the start and
306 end of preload ingestion, with only one significant interaction arising from evaluation of ratings
307 of the "dairy-like" characteristics [F(2.0,47.6) = 2.80, *p*<0.05], although within-subjects
308 contrasts did not identify the cause of that interaction which may be spurious. The drinks did
309 not differ significantly in sweetness [F(3,75) = 1.10, NS], bitterness [F(3,75) = 0.47, NS] or
310 novelty (F(3,75) = 1.93, NS). As expected, rated novelty declined significantly between the
311 start and end of ingestion [F(1,25) = 10.48, p<0.01].
312
313 There were no overall significant differences in rated pleasantness of the four preloads
314 [F(3,75)=2.70, NS], but there was a significant interaction between preload and rating time
315 [F(3,75)=6.27, p<0.001]. Ratings before ingestion did not differ significantly between

316 conditions (F(3,75) = 0.86, NS). However, pleasantness decreased significantly for the HP+
317 and HP- preloads but did not change in HC+ or LE conditions (Figure 2).
318
319 There were no significant differences in overall rated pleasantness of the pasta between
320 conditions [F(3,75)=1.92, NS] nor any interaction between Preload and Taste
321 [F(2.4,59.7)=1.59, NS]. Rated pleasantness of the pasta declined significantly from start to end
322 of the meal in all conditions [F(1,25)=26.60, $p<0.001$].
323
324 **Participant awareness**
325 The majority of participants (20/26) believed the experiment was investigating "food and
326 mood" in line with the explanation provided during recruitment. Two participants correctly
327 identified: "effects of the drink upon appetite/the meal". Ten participants correctly said they
328 received different drinks each test day, while nine participants recalled noticing only two
329 different drinks. Overall these responses indicate that many participants were not overtly aware
330 of the purpose of the experiment. None of the participants reported regularly consuming
331 commercially available protein drinks.
332
333
334 **Discussion**
335
336 In this study the addition of protein to a beverage only resulted in short-term satiety when the
337 addition of protein was combined with small increases in thickness and creamy flavour. Thus
338 the sensory-enhanced HP+ drink was more satiating than the same level of protein added in the
339 absence of sensory cues (HP-). Moreover, whereas the addition of extra energy purely as
340 carbohydrate was previously found to be ineffective at generating satiety in this context[23],
341 when the same carbohydrate was added alongside increased creamy flavour and thickness (the

342 HC+ preload), the drink was as satiating as was the HP+ drink. Together both the difference in
343 satiety response between protein drinks which differed in sensory characteristics and similarity
344 of response to drinks that were perceived as similarly thick and creamy but which differed in
345 macronutrient content (HP+ and HC+) suggest that the sensory characteristics of beverages are
346 critical in determining short-term satiety.
347
348 The key question is what explains the difference in satiety between HP+ and HP- conditions.
349 This effect cannot easily be attributed to nutritional differences since these preloads had similar
350 amounts of added protein, both chiefly through different extracted versions of whey protein.
351 Many studies suggest that whey protein is more satiating than other forms of protein based on
352 both greater compensatory eating responses[30], greater suppression of rated appetite[17, 31] and
353 increased release of satiety hormones[17, 31] after consuming preloads enriched in whey protein,
354 although some studies failed to confirm whey as more satiating than other protein sources[16].
355 However, as HP+ and HP- had similar levels of whey protein, it is difficult to attribute the
356 difference in effects on appetite to small differences in the type of protein. A more consistent
357 finding in the literature is that preloads enriched with carbohydrate are less satiating than are
358 energy-matched protein preloads[2, 4, 23, 32, 33]. Thus the prediction, based on nutrient
359 composition would be that the HC+ preload would have been less satiating than the HP+
360 preload. The finding that altering the thickness and creamy flavour of the HC+ preload to make
361 it more similar to the HP+ preload resulted in similar satiety responses to the two drinks implies
362 that may be sensory rather than macronutrient differences which are critical in determining
363 different short-term satiety responses between carbohydrate and protein-enriched beverages.
364 This finding fits well with a recent study in our laboratory that also found that making drinks
365 thicker in texture and creamier in flavour enhanced the degree to which added protein was
366 satiating[21]. In relation to the present study, the HC+ drink was more satiating than was a
367 similar carbohydrate drink without added thickness or creaminess in an earlier study[23]. It

368 would have been useful to have included this HC- (the high carbohydrate without added
369 sensory quality) in the present study. However, conditions equivalent to the HC+/HC- contrasts
370 were included in our recent study[21], and again altering thickness and creamy flavour enhanced
371 satiety.
372
373 How then might altering the thickness and creaminess of a drink enhance the satiating
374 efficiency of ingested nutrients? In line with recent ideas about sensory-nutrient interactions in
375 satiety(34), we hypothesised that products with higher protein content, particularly in a dairy
376 context, have some sensory characteristics in common, including both a thicker texture and
377 creamy flavour. Past experience of both these sensory characteristics and consequent effects of
378 ingestion on appetite of such products should lead to an expectation that drinks with these
379 sensory characteristics would be more filling, so facilitating the consumer to respond to actual
380 nutrient ingestion. Several lines of evidence support this suggestion. Firstly, differences in the
381 profile of release of satiety hormones have been shown between protein and carbohydrate
382 preloads[16, 35]. Many of these studies do not report the sensory analysis of the preloads, but it is
383 likely that subtle sensory differences would have existed. It is established that orosensory cues
384 can solicit release of hormones related to appetite control[36, 37] probably as part of learned
385 preparatory responses which prepare the body to process nutrients[38]. Thus subtle sensory
386 differences between beverages such in thickness and creaminess could modify post-ingestive
387 processing of nutrients by facilitating anticipatory hormone release. Sensory cues also generate
388 explicit expectations about how satiating foods will be[39], and recent data from our laboratory
389 confirm that the subtle differences in sensory characteristics between preloads in the present
390 study would have resulted in explicit expectations of satiety(40). This interpretation of the
391 differences in response to the three high energy preloads in the present study relies on subtle
392 sensory differences between stimuli. The analysis of participants' evaluations of the drinks
393 during testing suggest which of these sensory features were most important, but it is possible

394 that preloads varied on other dimensions that were not captured by the evaluations used here.
395 HP+ and HP- preloads differed significantly in rated thickness only, with non-significant trends
396 for greater creaminess, fattiness and dairy-like qualities. Although there was a trend for higher
397 creaminess in both HP+ and HC+ conditions relative to HP-, all of these were rated as creamier
398 than was the control. Differences between high energy conditions were less clear in the main
399 study than in the pilot studies, possibly due to contrast effects making this more evident when
400 products were rated alongside each other in the absence of the LE condition, an effect we have
401 seen in other studies[21], and which fits with more general contrast effects in sensory
402 evaluation[41]. Importantly HC+ and HP+ appeared well matched in terms of thickness and
403 creaminess, with only a trend for HC+ having less dairy-like qualities than HP+. The finding
404 that perceived thickness was important fits with other studies that suggest this characteristic is
405 an important orosensory satiety cue[42-44]. Studies also suggest viscosity is an important
406 component of the satiating efficiency of beverages, with greater satiety from more viscous
407 drinks[45-48], and texture appearing to be more important than flavour in determining satiation in
408 a dairy-context[49]. The current literature implies that textural differences, probably viscosity,
409 may be the most likely explanation for why HC+ was more satiating here than would be
410 expected based on nutrient content alone and why HP- was less satiating than HP+.
411
412 An alternative explanation for differences between preloads, however, could be the small
413 differences in soluble fibre content generated by the use of guar gum as thickening agent.
414 Increased viscosity generated by the addition of insoluble fibres has been shown to enhance
415 satiety[50, 51], increase release of satiety-related gastric hormones[52], and modify gastric
416 emptying[53]. In all of these studies differences in post-ingestive effects of fibre were
417 confounded by likely differences in sensory characteristics through changed viscosity, and the
418 present literature does not allow easy separation of orosensory and post-ingestive effects.
419 However, it has been suggested that the dilution effects of small amounts of added fibre on

420 viscosity in the stomach make orosensory explanations more likely[54]. Most studies exploring
421 effects of fibre use much greater quantities than was used to subtly thicken HP+ and HC+: for
422 example 12g of guar gum was added to explore effects on gastric emptying[53], and enhanced
423 satiety was reported after addition of 12g of inulin in a protein-rich beverage[55], compared with
424 1.2g guar gum used here. No study that we aware of has demonstrated enhanced satiety or
425 physiological response to such small quantities, however the only way to truly isolate sensory
426 versus post-ingestive effects would be to contrast the same preloads when infused into the
427 stomach relative to see whether the apparent sensory/nutrient interactions suggested here persist
428 in the absence of orosensory cues. However, past research suggests that orosensory cues are
429 necessary for the full expression of satiety, with reduced satiety when the same foods are
430 infused into the stomach or intestine than when ingested[19], and although a nutrient effect of the
431 added guar gum or very small differences in fat content between preload cannot be excluded,
432 such explanations are less plausible than would be effects through sensory-nutrient interactions.
433
434 In this study there was a relatively short delay between beverage consumption and the test meal
435 (minimum of 20 minutes), and this may have exaggerated the effects of sensory quality and
436 reduced the impact of post-ingestive satiety cues. However, the delay we used was chosen
437 since an earlier study found no difference in effect of protein preloads between 30 minute and
438 120 minute delays[23], and other preload studies suggest that short delays are most effective[28].
439 However, it may be that some participants treated the drink as a course of the test meal
440 implying the responses were more related to satiation than satiety.
441
442 We did find a decrease in the rated pleasantness of the preload after ingestion in both protein
443 conditions, but not the HC+ or control conditions. This finding is consistent with previous
444 research suggesting that protein foods produce greater sensory-specific satiety (SSS) than do
445 other macronutrients[56], although SSS effects did not emerge in previous experiments in our

446 laboratory[1, 23]. This difference between protein and non-protein preloads cannot readily
447 explain the differences in intake and appetite at the test lunch since intake and appetite after
448 HC+ and HP+ preloads was similar, and significantly different from that after HP-.
449
450 Overall the critical finding in the present study was that matching high protein and
451 carbohydrate preloads in terms of perceived thickness and creaminess resulted in very similar
452 satiety responses to these drinks, whereas normally protein has been found to be more satiating
453 than carbohydrate. In contrast, there were significant differences in satiety following
454 consumption of protein preloads that were matched in nutritional content but which differed in
455 thickness and creaminess, with the less thick and creamy version (HP-) less satiating. These
456 findings have implications both for the future conduct of human preload studies, where greater
457 care is needed to match stimuli at a sensory level, and in terms of our understanding of the
458 nature of satiety. In particular differences in the satiating effects of different types of foods,
459 such as liquid versus solid etc, may be in part attributed to the role of sensory cues in
460 facilitating post-ingestive satiety.
461

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618
619

620 Table 1. Final nutritional composition of the four test preloads.

621

		Preload			
		LE	HP-	HC+	HP+
Protein	g per 300g serving	1.6	32.9	9.2	32.2
	% energy	7.9	44.1	12.8	44.0
Carbohydrate	g per 300g serving	18.5	34.9	58.2	34.9
	% energy	88.6	46.8	80.8	48.0
Fat	g per 300g serving	0.2	2.7	0.5	2.4
	% energy	1.86	8.4	1.6	7.4
Total energy (kJ)		350	1248	1205	1225
Fibre (g per 300g serving)		1.0	1.8	3.0	3.0

622 Table 2. Mean (±SE) changes in hunger, fullness, thirst and nausea immediately and 30

623 minutes after consuming the four test preload drinks.

624

625

Attribute rated	Time after preload ingestion (min)	Preload condition			
		LE	HP-	HC+	HP+
Hunger	0	-9 ± 3[a]	-10 ± 2[a]	-14 ± 4[a]	-17 ± 4[a]
	30	-2 ± 2[a]	-4 ± 3[ab]	-8 ± 3[b]	-10 ± 3[b]
Fullness	0	8 ± 3[a]	26 ± 4[b]	12 ± 3[a]	14 ± 3[a]
	30	0 ± 2[a]	7 ± 2[ab]	12 ± 3[b]	15 ± 3[b]
Thirst	0	-22 ± 5[a]	-19 ± 6[a]	-14 ± 6[ab]	-9 ± 6[b]
	30	-6 ± 3[a]	-16 ± 5[b]	-6 ± 4[a]	-11 ± 5[b]
Nausea	0	-2 ± 4[a]	2 ± 4[a]	3 ± 4[a]	2 ± 3[a]
	30	-1 ± 3[a]	-2 ± 4[a]	-4 ± 3[a]	-2 ± 4[a]

626

627 In each row, data marked with different superscripts differ significantly ($p<0.05$ or less using Bonferroni protected

628 contrasts).

629

630 Table 3. Mean (±SEM) sensory and hedonic evaluations of the preloads at the initial taste test.

	Preload condition			
Rating made	LE	HP-	HC+	HP+
Sweet	68 ± 2	72 ± 3	76 ± 2	68 ± 4
Thick	27 ± 4[a]	61 ± 5[b]	77 ± 3[c]	77 ± 4[c]
Creamy	32 ± 4[a]	63 ± 3[b]	72 ± 3[b]	69 ± 4[b]
Fatty	31 ± 4[a]	45 ± 4[ab]	50 ± 4[b]	53 ± 4[b]
Novel	39 ± 4	46 ± 5	46 ± 5	51 ± 5
Bitter	30 ± 4	28 ± 4	28 ± 4	26 ± 3
Dairy	31 ± 5[a]	61 ± 3[b]	58 ± 5[b]	68 ± 4[b]

631

632 For ratings which differed between conditions (thick, creamy and dairy), data marked with different superscripts

633 differ significantly ($p<0.05$ or less using Bonferroni protected contrasts).

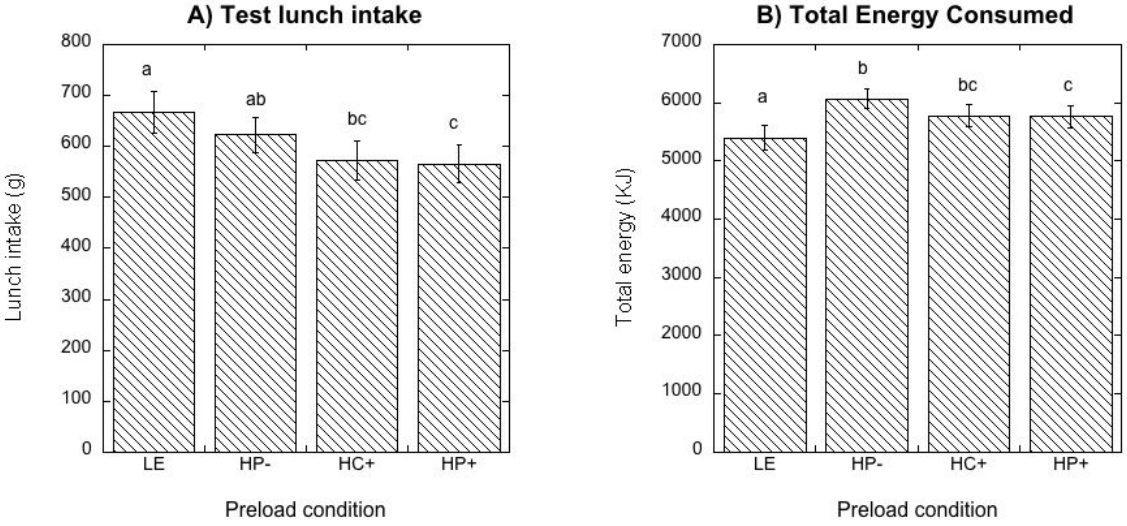
634 **Figure legend**

635

636 Figure 1. Test food intake at lunch (panel A) and total energy consumed in the laboratory
637 tests (panel B) in the four preload conditions: LE (low energy), HP- (low sensory protein),
638 HC+ (high sensory carbohydrate) and HP+ (high sensory protein). All data are mean ±SEM,
639 n=26. Letters above each bar indicate significance: within each panel, bars with different letters
640 are significantly different ($p<0.05$ or higher).

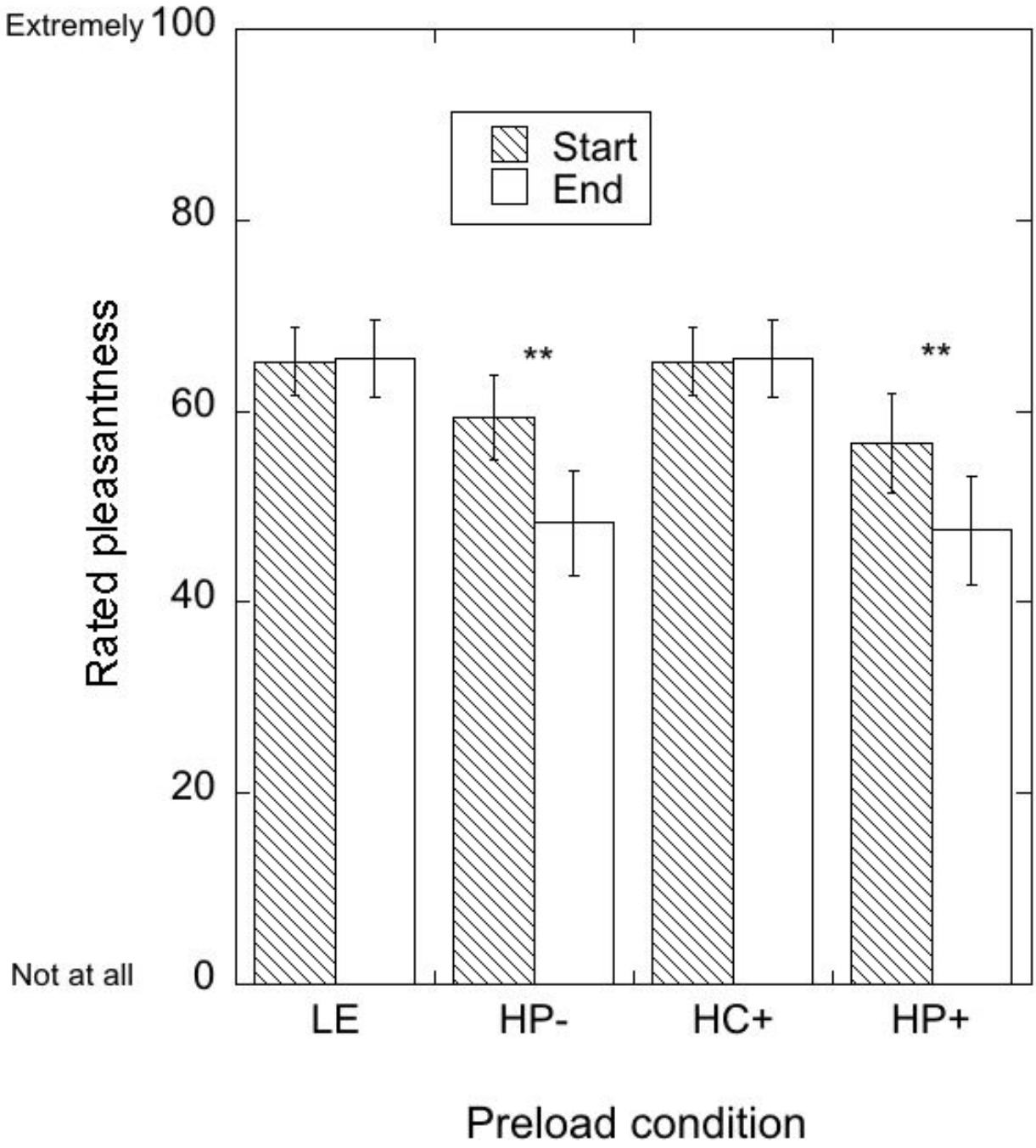
641

642 Figure 2. Rated pleasantness of the four test drinks before (Start) and after (End) they had
643 been consumed: LE (low energy), HP- (low sensory protein), HC+ (high sensory carbohydrate)
644 and HP+ (high sensory protein). All data are mean ±SEM, n=26. ** denotes significant change
645 between start and end ratings, $p<0.01$


A) Test lunch intake
Lunch intake (g)
800
700
600
500
400
300
200
100
0
a
ab
bc
c
LE
HP-
HC+
HP+
Preload condition
B) Total Energy Consumed
Total energy (KJ)
7000
6000
5000
4000
3000
2000
1000
0
a
b
bc
c
LE
HP-
HC+
HP+
Preload condition

646

647


Extremely
100
80
60
40
20
0
Not at all
Rated pleasantness
Start
End
**
**
LE
HP-
HC+
HP+
Preload condition

648