No difference in compensation for sugar in a drink versus sugar in semi-solid and solid foods

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HIGHLIGHTS

• We hypothesised that sugar would be better compensated for in a food than in a drink.
• We used a parallel group design, with a 20-minute inter-meal interval.
• If anything, energy compensation was greater for the drink preload and in men.
• This could not be explained by differences in pre-meal blood-glucose concentration.
• Energy compensation differs little across realistic food and drink stimuli.

ABSTRACT

It is claimed that sugar consumed in a drink is poorly compensated for by a reduction in subsequent energy intake, however very little research has tested directly the effect on appetite of adding sugar to a drink versus food. In this between subjects study, 144 participants (72 men) consumed preloads sweetened with either sucrose or the low-energy sweetener, sucralose (preload energy difference 162 kcal) in the form of a blackcurrant drink, jelly or candy. The different preload viscosities were achieved by varying the amount of thickener (carrageenan) and water in the recipes. Participants completed hunger ratings before and 5, 10 and 20 min after consuming their preload. After the 20-minute rating they were served a test-meal comprising an excess of bite-sized sandwiches and a sweet dessert. Energy intake measured for the same meal consumed the previous day (baseline day, no preload consumed) was used in the data analyses to control for individual differences in energy intake. Overall, there was 36% compensation for the energy difference in the preloads, but this did not vary with preload viscosity — if anything compensation was greater for the drink preload, and greater in men. The drink preload also showed an effect of sucrose versus sucralose for hunger. The lack of the predicted effect of viscosity on compensation could not be explained by differences in blood-glucose concentration 20 min after consuming their preload. After the 20-minute rating they were served a test-meal comprising an excess of bite-sized sandwiches and a sweet dessert. Energy intake measured for the same meal consumed the previous day (baseline day, no preload consumed) was used in the data analyses to control for individual differences in energy intake. Overall, there was 36% compensation for the energy difference in the preloads, but this did not vary with preload viscosity — if anything compensation was greater for the drink preload, and greater in men. The drink preload also showed an effect of sucrose versus sucralose for hunger. The lack of the predicted effect of viscosity on compensation could not be explained by differences in blood-glucose concentration 20 min after consuming their preload. After the 20-minute rating they were served a test-meal comprising an excess of bite-sized sandwiches and a sweet dessert. Energy intake measured for the same meal consumed the previous day (baseline day, no preload consumed) was used in the data analyses to control for individual differences in energy intake.

Comparison of baseline and test-meal food intakes indicated that, irrespective of energy content, the sweet drinks reduced the relative intake of sweet food. In conclusion, short-term energy compensation did not differ across a set of realistic drink and food stimuli.

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1. Introduction

Many studies have investigated the short-term effects on appetite of consuming sugar-sweetened drinks. We reviewed these studies recently [1]. They have typically used the preload, test-meal procedure in which the participant consumes a fixed amount of the drink and the amount of food they then eat in the ‘ad libitum’ test-meal (food is served in amounts in excess of what would usually be eaten) is measured. The interval between preload and test-meal varied between studies, ranging mostly between 20 and 90 min, although in some studies the drink was consumed with the meal (e.g., [2]). A common finding was that test-meal energy intake was lower after the sugar-sweetened drink compared with a zero-energy control — water, or a drink of equal sweetness sweetened with a low-energy sweetener. Rarely, however, did the reduction in test-meal energy intake fully compensate for the difference in energy content between the sugar-sweetened drink and its comparison drink. Indeed, in many individual studies the difference in energy intake after the sugar-sweetened drink versus control was not statistically significant, whereas sometimes cumulative energy intake (drink plus test-meal intake) was significantly higher after the
sugar-sweetened drink. This may have contributed to the impression that sugar or ‘calories’ in a drink are at best weakly compensated for (see [3,4]). Across these many studies in children and adults, however, the cumulative evidence from meta-analysis showed 50% compensation, which was highly significantly different from both zero (no compensation) and 100% (complete compensation), and not altered much by preload to test-meal interval or participant gender or weight status ([11]; see also [5]). In turn, this is consistent with the evidence showing that consumption of sugar-sweetened drinks contributes over the longer term to increases in energy intake and risk of overweight and obesity (e.g., [6,7,8,9]). This is most likely primarily because sugar-sweetened drinks provide an opportunity for energy intake, and not because sugars differ from other carbohydrates (nor probably much from fat) in respect of effects on energy intake or body weight (e.g., [8,9]).

With respect to energy-containing drinks and the possibility that there might be something special about ‘fluid calories,’ there seems to us to be two somewhat separate questions. The first concerns whether drinks are less satiating per se than foods. As Akhavan et al. [10] discuss, the evidence is mixed on this. Whilst solids might be expected to be more satiating than liquids, soup for example is highly satiating [11]. The second, more specific, question is whether the same amount of a nutrient, in the present case sugar, is more satiating when consumed in a solid than in a liquid? In other words, is there a nutrient × viscosity effect for energy compensation? This question has received relatively very little direct attention. In one study liquid and solid sucrose-sweetened preloads, equal in volume and energy content, were compared against a zero-energy sweet control (liquid and sweetened with sucralose). Energy compensation did not differ at all between the liquid and solid versions, being 35% and 32%, respectively [10]. At the other extreme, in a series of three studies Yeomans and colleagues [12,13,14] found consistently greater energy compensation as drink thickness increased (e.g., 6% and 70%, respectively, for the thinnest and thickest drinks in the ‘no information’ conditions in McCrickard et al. [14]). The explanation for these different results is unclear, at least to us. The preloads differed between the different studies—highly sweet, lemon flavour and unusual [10], and sweet drinks based on fromage frais and fruit squashes [12,13,14]. In the latter studies the drinks differed in both added protein and carbohydrate content (maltodextrin) between high and low energy versions and in ‘creaminess’ as well as thickness between thinner (‘low sensory’) and thicker (‘high sensory’) versions [12,13,14]. In their systematic review of energy compensation in preload, test-meal studies Almiron-Roig et al. [5] found greater energy compensation for solid and semisolid preloads than for liquid preloads, but this is based mainly on comparisons across different studies, in which the preloads differed in various characteristics in addition to viscosity. For example, nutrient content and the extent to which the manipulation of nutrient content was disguised also differed between the studies. Moreover, energy compensation was found not to differ between liquid preloads and composite meals (i.e., solid or semisolid food with a drink). Therefore, the question of a nutrient × viscosity effect for energy compensation was not addressed directly in this review.

Uncertainty remains, therefore, about energy compensation in drinks versus semi-solid and solid foods. Accordingly, in the present study we devised preload stimuli that differed in viscosity, and at each level of viscosity compared an identical manipulation of energy (sucrose) content. The manipulation of energy content was disguised using the low-energy sweetener sucralose. It is worth noting that sucrose is the main ‘caloric’ sweetener used in soft-drinks (sodas, squashes, etc.) consumed in the UK. Our aim in devising the preloads was to be able to present them as credible drinks and foods. Using the thickening agent carrageenan and varying the volume of water we produced a sweet blackcurrant drink, a sweet blackcurrant jelly (semi-solid) and a sweet blackcurrant soft ‘candy’ (chewable solid). The difference in the low (3–7 kcal) and high (165–169 kcal) energy versions at each of these three levels of viscosity was 162 kcal. The test-meal comprised cheese sandwiches, ham sandwiches and a sweet creamy-yogurt dessert, served with water. We based our power calculation for this study on this preload energy difference and previous results for energy compensation from studies using the same drink preload and a similar test-meal [15].

We based the preload to test-meal interval (20 min) on our previous studies [15] and Anderson and Woodend’s [16] demonstration of a clear difference in hunger present at 15 and 30 min after consumption of sucrose versus low-energy sweet control preloads. We used a between-subjects (parallel groups) design to address a concern that the extent of energy compensation is underestimated in within-subjects (cross-over) studies due to carry-over effects [15]. We included a baseline day in which we recorded participants’ test-meal intake without them consuming a preload, in order to control for individual differences in test-meal energy intake after consuming the preload during a subsequent test session, which took place on the following day. To increase generalisability of our findings, we tested equal numbers of male and female participants, but we excluded dieters and highly restrained eaters because of concern about insufficient intake in the test-meal.

After completing the main study we measured blood glucose concentration before and after consumption of the different sucrose preloads in six of the original participants (three male). This was done to investigate the extent to which increased preload viscosity might have delayed gastrointestinal processing of the sucrose.

Based on the balance of findings to date, we hypothesised that there would be greater energy compensation in participants receiving the jelly and candy preloads compared with the drink preload. We did, however, expect to see some compensation in the drink condition as well [1,5,15]. An additional hypothesis was that the ratio of sweet to total test-meal food intake would be lower on the test day compared with the baseline day because consumption of the sweet preload (which only occurred on the test day) would reduce appetite for the sweet food offered in the test-meal. In other words, we predicted a ‘sensory-specific satiety’ effect [17,18,19]. As far as we are aware this has not been tested previously in preload, test-meal studies.

2. Methods

2.1. Participants

Healthy men and women who were 18 to 65 years old were recruited via volunteer databases, membership of which consisted of members of the general public in Bristol and students and staff at the University of Bristol. Exclusion criteria were (1) currently dieting, (2) dieter >2 times in the past year, (3) score >2.9 on the restraint scale of the Dutch Eating Behaviour Questionnaire (DEBQ) [20], (4) vegetarian or vegan, (5) having a food ‘allergy’ or ‘sensitivity,’ (6) did not like the test foods, (7) smoked >5 cigarettes/week or equivalent, and (8) doing >225 min/week vigorous physical activity and/or >445 min/week moderate physical activity. Participants also had to be willing and available to complete two laboratory-based test sessions on consecutive days. Nine-hundred-and-fourteen people completed an online screening questionnaire to recruit the final, target sample of 72 men and 72 women. Participants were rewarded with £10 or two experimental hours credits (psychology students) for taking part.

After the completion of the main study, participants were selected randomly to be re-contacted with a view to completing the supplementary study measuring blood glucose. Three men and three women were recruited for this within-subjects study. This sample size was based on data collected in a separate pilot study.

All participants gave signed consent prior to starting the respective studies. The study protocols were approved by the University of Bristol, Faculty of Science Human Research Ethics Committee.

2.2. Design

The study design is summarised in Fig. 1. Within the constraint that there would be equal numbers of men and women in each treatment,
participants were assigned randomly to receive one of six preload treatments varying in sweetener (sucralose or sucrose) and viscosity (drink, jelly, candy). Each participant attended on two occasions, first to consume an ad libitum test-meal without having consumed a preload (baseline day) and second, on the following day, to consume their preload followed by the same test-meal. Primary outcomes were (1) total energy consumed in the test-meal on the test day adjusted for total energy consumed on the baseline day, and (2) hunger rated during the preload-test-meal interval, adjusted for hunger rated 5 min before consuming the preload.

In the supplementary study, blood glucose was measured 5 min before and on a further eight occasions after consumption of the sugar-sweetened preloads (no test-meal was consumed). Each participant received each of the three preloads, one per day on three consecutive days. Order of treatments was balanced as far as possible across participants.

2.3. Preloads

The drink preloads were based on supermarket brand, 'dilute to taste' blackcurrant squashes, namely Sainsbury’s no added sugar, double concentrate blackcurrant squash (sweetened with sucralose) and Sainsbury’s high juice blackcurrant squash (sweetened with sucrose) (Sainsbury’s Supermarkets Ltd., London, UK). These were diluted as shown in Table 1, and small amounts of black food dye and thickener were added to the sucralose drink to match the colour and mouthfeel of the sucrose drink. The jelly and candy preloads were prepared with lower volumes of water and larger amounts of thickener as shown in Table 1. The volumes served were lower than for the drink, reflecting the typical energy densities of equivalent commercial products. The jelly had the soft-to-bite consistency of a jelly (e.g., Jell-O) dessert, whilst the candy was chewy, similar to wine gums and Gummy-Bears. The difference in total energy content of each pair of sucrose and sucralose preloads was 162 kcal, due entirely to their different sugar content. The preloads were prepared during the afternoon before or during the early morning of each test day. They were served in a glass (drink), in a bowl with a spoon (jelly), and on a plate (candy), slightly chilled at between 15 °C and 17 °C.

2.4. Test-meal

The test-meal consisted of cheese sandwiches, ham sandwiches and a creamy yogurt dessert served with a glass of water (300 ml). The sandwiches were made from crustless bread (50% white and 50% brown flour) with spread (Sainsbury’s Butterlicious) and medium Cheddar cheese or honey roast ham. These sandwiches were cut into small triangular pieces, each of which could be consumed comfortably in two bites, and served with a small amount of salad garnish (lettuce, without dressing). Each participant was served 28 cheese (861 kcal) and 28 ham sandwich (652 kcal) triangles. They were also served, at the same time, a creamy yogurt dessert (80 g Sainsbury’s double cream and 400 g Onken fat-free strawberry yogurt; total energy content 568 kcal). The total energy content of this test-meal was 2090 kcal.

2.5. Appetite and preload ratings

Participants rated their hunger, desire to eat and fullness on 100 mm line scales anchored on the left with the words ‘not at all’ (= score of 0) and on the right with the word ‘extremely’ (= score of 100) [19]. We do not report results for desire to eat or fullness ratings here, as these are highly correlated with hunger ratings unless participants are directed to rate desire to eat with reference to tasting a specific food.

Table 1

Composition of the preloads.

<table>
<thead>
<tr>
<th>Preload</th>
<th>Juice, ml</th>
<th>Water, ml</th>
<th>Thickening agent*, g</th>
<th>Amount served, ml</th>
<th>Sugar content, g</th>
<th>Energy valueb, kcal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drink</td>
<td>Sucralose</td>
<td>50 (50 g)</td>
<td>250</td>
<td>0.36</td>
<td>300</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>Sucrose</td>
<td>89 (105 g)</td>
<td>211</td>
<td>0</td>
<td>300</td>
<td>41.3</td>
</tr>
<tr>
<td>Jelly</td>
<td>Sucralose</td>
<td>50 (50 g)</td>
<td>200</td>
<td>1.62</td>
<td>250</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>Sucrose</td>
<td>89 (105 g)</td>
<td>161</td>
<td>0.50</td>
<td>250</td>
<td>41.3</td>
</tr>
<tr>
<td>Candy</td>
<td>Sucralose</td>
<td>50 (50 g)</td>
<td>50</td>
<td>3.60</td>
<td>100</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>Sucrose</td>
<td>89 (105 g)</td>
<td>11</td>
<td>3.00</td>
<td>100</td>
<td>41.3</td>
</tr>
</tbody>
</table>

Also, 0.05 g black food dye was added to the sucralose preloads to match the darker colour of the sucrose preloads.

a Carrageenan, FMC Biopolymer, Brussels, Belgium, 1.24 kcal/g (0.1 g sugar and 0.42 g fibre).
b Sugar (4 kcal/g) and thickening agent. Sugar content was confirmed by Dionex ion chromatography analysis.
or rate how full their stomach feels [19]. Participants also rated their liking for (‘How much did you like the taste of the product?’) and familiarity with (‘How familiar was the product to you?’) the preloads, how filling they found them (‘How filling did you find the product?’), as well as various oro-sensory attributes: sweetness, fruitiness, thickness and chewiness. Like hunger, these ratings were made on 100 mm line scales anchored on with the words ‘not at all’ and ‘extremely.’

2.6. Blood glucose

Fingertip capillary blood glucose was measured using the FreeStyle Lite® blood glucose monitoring system (Abbott Laboratories, Chicago, Illinois, USA). The accuracy of the FreeStyle Lite system has been established by Schwartz et al. [21] who compared the results from 142 diabetic patients with the Yellow Springs Instrument 2300 Stat Plus Glucose Analysers (YSI Inc., Yellow Springs, Ohio, USA) plasma equivalent glucose values (r = .99, mean absolute bias = 4.7%). They also report that 99.3% of values fell within ISO accuracy limits (± 0.83 mmol/ L).

2.7. Procedures

On the baseline day participants arrived at the laboratory at 12.15 h. After giving their informed consent they completed appetite ratings at 12.30 h and were served the test-meal at 12.35 h. On the test day participants arrived at midday, and completed appetite ratings at 12.05 h before being served the preload at 12.10 h. They were instructed to consume the preload within 5 min (i.e., by 12.15 h). Having done that, they completed the various oro-sensory and other evaluations of the preload. They then rated their appetite again at 12.20 h, 12.25 h, and 12.35 h. The test-meal was served immediately after they completed the 12.35 h ratings. After finishing the test-meal participants were weighed and their height measured, and then paid for their participation in the study.

For the blood glucose study, participants arrived at midday and had a (baseline) blood sample taken. They next consumed the preload within 5 min starting at 12.10 h. Further blood samples were taken at 5, 10, 20, 40, 60, 80, 100 and 120 min after consumption of the preload. Results reported here are for the samples taken up to and including 40 min, as this covers the period encompassing the consumption of the preload and end of the test-meal in the main study. No test-meal was consumed in the blood glucose study. Appetite ratings were taken to match the timing of viscosity measurement (baseline) blood sample taken. They next consumed the preload within 5 min starting at 12.10 h. Further blood samples were taken at 5, 10, 20, 40, 60, 80, 100 and 120 min after consumption of the preload. Results reported here are for the samples taken up to and including 40 min, as this covers the period encompassing the consumption of the preload and end of the test-meal in the main study. No test-meal was consumed in the blood glucose study. Appetite ratings were taken to match the procedure in the main study, but these data were not analysed.

For both studies participants were instructed to keep to their usual routine of physical activity, eating and drinking the evening before and on the morning of testing up to 9.00 h. They were told that thereafter they should not consume any food or drink, except water, before the start of their test session. They were told that they could consume water up to 11.00 h. In the main study participants were tested in groups of up to six, with each participant seated in a private booth within a larger room. Participants were tested individually in the blood glucose study.

2.8. Data analysis

Data on energy intake (total and for savoury and sweet foods separately) in the test-meal on the test (preload) day were analysed using ANCOVA with sweetener (sucralose and sucrose), viscosity (drink, jelly and candy) and gender as between subjects factors. Energy intake on the baseline day was included as a covariate, to adjust for individual differences in food intake. Hunger on the test day was analysed using a similar model, except that the covariate was hunger recorded 5 min before consumption of the preload (baseline), and the addition of a repeated measures factor of time (hunger rated 5, 10 and 20 min after consumption of the preload). We also conducted relevant analyses within each level of viscosity. To test for moderating effects of preload attributes which unintentionally varied with preload viscosity, we ran the main analyses with these variables (preload sweetness, fruitiness, liking and familiarity) as covariates. Where appropriate, the Greenhouse-Geisser correction was applied for effects involving time, with corrected $p$ values reported.

For total energy intake a compensation score (COMXP) [22], which adjusted for baseline test meal energy intake, was calculated for each level of viscosity separately for men and women. The equation we used was:

$$\text{COMXP} = \left( \frac{x_{\text{sucrose}} - x_{\text{sucralose}}}{y_{\text{sucrose}} - y_{\text{sucralose}}} \right) \times 100,$$

where $x$ = test day test-meal energy intake, $y$ = baseline day test-meal energy intake, and 162 is the difference between the energy content of the sucrose and sucralose preloads. COMXP describes the extent to which adjustment in test-meal intake ‘compensates’ for the difference in energy content of the sucralose versus sucrose preload. If COMXP is <0 there is under-compensation for the greater energy content of the sucrose preload (higher cumulative energy intake).

To investigate the proportion of sweet food consumed we calculated the following ratio: kcal sweet food consumed / kcal total food consumed. The sweet food was the creamy yogurt dessert, and the savoury food was the sandwiches and salad garnish.

For blood glucose, change from baseline values (value minus baseline value) were analysed using ANOVA with sucrose preload (drink, jelly and candy) and time after preload (5, 10 and 20 min) as within and repeated measures factors. The change from baseline values for the 40-min post-preload samples were also plotted.

3. Results

3.1. Preload, test-meal study

3.1.1. Participant characteristics

Participants’ mean ± SD age was 26.2 ± 9.5 years (men = 27.1 ± 10.9, women = 25.3 ± 7.8), their weight was 69.2 ± 12.5 kg (men =

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Participant evaluations of the preloads.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Preload</strong></td>
<td><strong>Thickness</strong></td>
</tr>
<tr>
<td>Drink Sucralose</td>
<td>19 ± 23</td>
</tr>
<tr>
<td>Drink Sucrose</td>
<td>22 ± 25</td>
</tr>
<tr>
<td>Jelly Sucralose</td>
<td>43 ± 19</td>
</tr>
<tr>
<td>Jelly Sucrose</td>
<td>41 ± 21</td>
</tr>
<tr>
<td>Candy Sucralose</td>
<td>58 ± 22</td>
</tr>
<tr>
<td>Candy Sucrose</td>
<td>68 ± 20</td>
</tr>
<tr>
<td>Sweetener $p$ value</td>
<td>.298</td>
</tr>
<tr>
<td>Viscosity $p$ value</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>S x V $p$ value</td>
<td>.424</td>
</tr>
</tbody>
</table>

Data are means ± SDs.
75.0 ± 10.1, women = 63.5 ± 12.1), their BMI was 22.9 ± 3.3 kg/m² (men = 23.1 ± 2.7, women = 22.7 ± 3.9), and their DEBQ restraint score (minimum and maximum possible scores are 1 and 5) was 2.03 ± 0.53 (men = 1.86 ± 0.49, women = 2.20 ± 0.52).

3.1.2. Participant evaluations of the preloads

Table 2 summarises the results for participants’ oro-sensory, liking, familiarity and fillingness ratings for the different preloads. None of the evaluations differed as a function of type of sweetener. Thickness and chewiness increased with increasing viscosity, whilst sweetness, fruitiness, liking and familiarity varied inversely with increasing viscosity.

3.1.3. Hunger

Fig. 2 shows self-rated hunger as a function of preload type and time after consumption of the preload. There were missing data for four (three male and one female) participants for hunger. In the full ANCOVA model (sweetener × viscosity × gender × time, with baseline hunger as covariate), there was a significant effect of time ($F(2,254) = 5.44, p = .008$) and a marginally insignificant effect of sweetener ($F(1,127) = 3.34, p = .070$). Hunger increased overall during the preload to test-meal interval and tended to be lower after the sucrose compared with sucralose sweetened preloads. No other main or interaction effect approached statistical significance ($p > .3$). Analyses conducted separately on the drink, jelly and candy preloads revealed a significant effect of sweetener ($F(1,43) = 5.50, p = .024$) and a significant sweetener by time interaction ($F(2,86) = 3.49, p = .035$) for the drink preload. No other main or interaction effects approached significance ($p > .3$), including effects involving gender (though numerically the time by sweetener effect on hunger was greater in women than men — data not shown). There was a main effect of time on hunger ($p < .05$), but no other significant main or interaction effects for the jelly and candy preloads ($p > .3$). In all of the analyses baseline hunger was a significant predictor of post-preload hunger ($p < .0001$).

3.1.4. Energy intakes

Energy intakes on the baseline and test days are shown in Table 3 separately for men and women for the six different preloads. There was a large difference between men and women in energy intake on the baseline day (mean ± SD, 1086 ± 329 kcal and 765 ± 254 kcal, respectively, $F(1,143) = 42.75, p < .0001$) and on the test day (mean ± SD, 1056 ± 346 kcal and 740 ± 286 kcal, respectively, $F(1,143) = 35.68, p < .0001$). ANCOVA (sweetener × viscosity × gender, with baseline energy intake as covariate) revealed a significant effect of preload sweetener ($F(1,131) = 4.21, p = .042$), no effect of viscosity ($F < 1$), and no sweetener × viscosity interaction ($F < 1$). There were no significant interactions involving gender and sweetener and/or viscosity (largest $F(1,131) = 1.75, p = .188$, sweetener × gender). These results can be best understood with reference to Fig. 3. Overall, sucrose reduced test-meal energy intake compared with sucralose. Analyses conducted separately for the drink, jelly and candy preloads revealed a significant effect of sweetener ($F(1,43) = 5.20, p = .028$) and a marginally insignificant effect of sweetener × gender for the drink preload ($F(1,43) = 2.88, p = .097$), but no significant effects involving sweetener for the jelly or candy preloads ($F < 1$). Men showed a reduction in energy intake after the sucrose compared with the sucralose drink preload which fully compensated for the higher energy content of the sucrose drink, whilst the women showed minimal compensation (Fig. 3).

Including neither preload sweetness, fruitiness, liking nor familiarity in the ANCOVA model altered the effects observed. Only liking was a significant covariate ($F(1,129) = 8.74, p = .004$), and with its inclusion the effect of preload sweetener remained significant ($F(1,129) = 4.13, p = .044$).

In the full ANCOVA model neither the effect of sweetener on test-meal savoury food intake ($F(1,131) = 3.53, p = .069$) nor sweet food intake ($F(1,131) = 1.12, p = .291$) alone was significant.

In all of these analyses relevant baseline test-meal energy intake was a significant predictor of test day test-meal energy ($p < .0001$).

3.1.5. Proportional intake of sweet food

The ratio (mean ± SD) of sweet to total food consumed was lower on the test day (0.38 ± 0.16) compared with the baseline day.
(0.42 ± 0.14) \( F(1,132) = 6.86, p = .010 \), irrespective of sweetener type or viscosity (sweetener \( \times \) viscosity interaction, \( F < 1 \)).

### 3.2. Blood glucose study

The effects on blood glucose concentration of consumption of the three sucrose-sweetened preloads are summarised in Fig. 4. Analysis of the data up to 20 min, which was the time just before the start of the test-meal in the main study, showed a non-significant effect of viscosity \( F(2,16) = 3.86, p = .050 \), a significant effect of time \( F(2,16) = 108.33, p < .0001 \) and a significant viscosity \( \times \) time interaction \( F(4,16) = 6.00, p = .036 \). No other effects, including effects involving gender, were significant \( p > .1 \). It is evident that that viscosity \( \times \) time interaction is due mainly to the slower rise in blood glucose concentration after the candy preload compared with the drink and jelly preloads. At 20 min blood glucose concentration was almost identical after the drink and jelly preloads. At 40 min, the time by which almost all participants \( (96\%) \) had finished their test-meal in the main study, mean blood glucose concentration was relatively more variable and did not differ between the three preloads (Fig. 4).

### 4. Discussion

This study found that consumption of sucrose compared with low-energy sweetener sucralose reduced subsequent energy intake, however that reduction did not fully compensate for the energy value of the sucrose and cumulative energy intake (preload plus test-meal) was increased. Further compensation might have occurred at subsequent eating occasions, but it is likely that this would have been relatively insignificant given that the post-prandial state of satiety and its eventual dissipation would have been dominated by signals arising from the more recent and much larger test-meal. This is consistent, for example, with Levitsky’s [23] finding that although eating versus missing breakfast was partially compensated for \( (21\%) \) by decreased energy intake at lunch (the next meal), there was no further decrease in energy intake after lunch, either at snacking occasions in the afternoon and evening or at the evening meal (see also [24]). The lack of full compensation for sucrose consumption in the present study is consistent with the findings of many previous studies (reviewed by [1,5]) but, as we suggested in the Introduction, this appears not to differ from the consequences of the additional consumption of other carbohydrates or fat (e.g., [8,9,16]).

Few studies have compared directly the effects of nutrients added to drinks versus food. The present results, contrary to our hypothesis, showed that viscosity did not affect the magnitude of compensation for sucrose (the sweetener \( \times \) viscosity interaction for test meal energy intake was not significant). Indeed, if anything, the evidence was that compensation was more reliable for the drink preload. Our results add to many previous studies [1,5] demonstrating decreased energy intake after consumption of a sugar-sweetened versus equi-sweet, low-energy control drink. It is certainly not the case that case that nutrients in a drink are ‘unrecognised.’ But why did we not observe even greater compensation for sugar in the food preloads, as predicted by the findings of Yeomans and colleagues [12,13,14]?

At least part of the answer might lie in differences in the preload stimuli. The energy difference \( (201 \text{ kcal}) \) in Yeomans and colleagues’ studies was achieved by the addition of protein and carbohydrate (maltodextrin) [12] compared with sucrose in our study, but it is hard to see how that itself could explain why they observed an energy content \( \times \) viscosity interaction for compensation, whilst we did not. More important perhaps is the nature of the oro-sensory differences between the preloads in Yeomans and colleagues’ studies. As well varying in viscosity, these also varied in parallel in creaminess, and compensation was observed for the ‘high-sensory’ \( (\text{thicker and creamier-tasting}) \) preload. Possibly, creaminess or creaminess in combination with thickness acts as a potent signal for energy content and that somehow triggers a decrease in subsequent energy intake when combined with higher but not lower energy content. Having said that, the differences in creaminess and thickness between ‘high sensory’ and ‘low sensory’ preloads, both of which were presented as drinks to the participants, were relatively subtle [12] compared with the differences in thickness \( (\text{and chewiness}) \) in the present study. Additionally, it is unclear why there was no compensation for the energy difference in the ‘low sensory’ condition [12,14]. This result is inconsistent with the large body of evidence, including the present study, showing that nutrients consumed in drinks do decrease short-term energy intake (see above).

Our aim for the present study was to create reasonably naturalistic preload stimuli. Hence they were modelled on a fruit squash drink, a jelly and a candy and presented to participants as such. This meant that the preloads differed in more than in viscosity. While the range in viscosities (assessed by thickness and chewiness) between the three preloads was large (Table 2), there were also differences in sweetness and flavour intensity (fruitiness), which is to be expected as release of flavours and tastants from the preload matrix is reduced with increased viscosity. However, liking and familiarity also varied \( (\text{inversely}) \) with viscosity. It seems, though, that these differences in preload sweetness, fruitiness, liking and familiarity cannot account for the lack of an effect of viscosity on compensation, because of these variables only preload liking predicted test-meal energy intake, and its inclusion in the analysis of the effects of sweetener and viscosity on test-meal energy intake did not change the effects observed \( (\text{i.e., the significant effect of sweetener and non-significant sweetener \( \times \) viscosity interaction}) \). It is worth

### Table 3

Summary statistics for baseline day and test day food intakes shown separately for men and women.

<table>
<thead>
<tr>
<th>Preload</th>
<th>Savoury food intake, kcal</th>
<th>Sweet food intake, kcal</th>
<th>Total food intake, kcal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Baseline day</td>
<td>Test day</td>
<td>Baseline day</td>
</tr>
<tr>
<td><strong>Men</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drink</td>
<td>Sucralose</td>
<td>612 ± 261</td>
<td>684 ± 282</td>
</tr>
<tr>
<td></td>
<td>Sucrose</td>
<td>561 ± 211</td>
<td>483 ± 190</td>
</tr>
<tr>
<td>Jelly</td>
<td>Sucralose</td>
<td>703 ± 157</td>
<td>752 ± 140</td>
</tr>
<tr>
<td></td>
<td>Sucrose</td>
<td>743 ± 425</td>
<td>705 ± 419</td>
</tr>
<tr>
<td>Candy</td>
<td>Sucralose</td>
<td>655 ± 182</td>
<td>652 ± 158</td>
</tr>
<tr>
<td></td>
<td>Sucrose</td>
<td>657 ± 169</td>
<td>639 ± 246</td>
</tr>
<tr>
<td><strong>Women</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drink</td>
<td>Sucralose</td>
<td>393 ± 140</td>
<td>455 ± 209</td>
</tr>
<tr>
<td></td>
<td>Sucrose</td>
<td>422 ± 176</td>
<td>416 ± 241</td>
</tr>
<tr>
<td>Jelly</td>
<td>Sucralose</td>
<td>452 ± 196</td>
<td>435 ± 232</td>
</tr>
<tr>
<td></td>
<td>Sucrose</td>
<td>335 ± 136</td>
<td>377 ± 127</td>
</tr>
<tr>
<td>Candy</td>
<td>Sucralose</td>
<td>548 ± 160</td>
<td>548 ± 250</td>
</tr>
<tr>
<td></td>
<td>Sucrose</td>
<td>423 ± 132</td>
<td>443 ± 148</td>
</tr>
</tbody>
</table>

Data are means ± SD.
noting that within each level of viscosity the sucrose and sucralose preloads were matched well for these various oro-sensory and other attributes.

Our preloads, unlike those used by Yeomans and colleagues [12,13,14], increased in energy density with viscosity. This was a deliberate decision based on our aim to model real drinks and foods — sugar-sweetened candy is typically more energy dense than are sugar-sweetened drinks. It would have been odd to serve a large volume of energy-dilute candy or small volume of energy-dense drink (which would then have a higher than typical viscosity). Informal observation indicated that consumption rate appeared not to differ much between the preloads, with participants finishing them comfortably within the 5 min stipulated. Drinks might be consumed faster than solids g-for-g, but their larger volume (lower energy density) means that kcal-for-kcal consumption rates will differ rather less. Furthermore, in real life drinks are often sipped rather than gulped, in which case consumption rate (kcal/min) is slow. It is revealing that fillingness rated immediately after consumption of the preloads did not differ with preload viscosity, and that, likewise, overall test-meal intake did not differ as a function of viscosity (Table 3 and Fig. 3). In other words, within the large range of these realistic stimuli, merely being more food-like did not increase fillingness. This is consistent with our finding that the expected satiation of sugar-containing drinks (orange juice and Coca-Cola) did not differ from the expected satiation of equi-caloric portions of ‘snack’ foods (peanuts and candy) [25]. Nevertheless, it needs to be considered whether the higher energy densities (lower volume) of the jelly and candy might have offset a tendency towards greater compensation for sugar added to these foods compared with the drink. Similarly, the higher energy densities of peanuts and candy may explain why they are expected to be equally satiating kcal-for-kcal to orange juice and Coca-Cola. We do not have the data to answer this from the present study, but the explanation is consistent with the observation that energy dense foods are in general less satiating kcal-for-kcal than energy dilute foods [26,27]. On the other hand, Akhavan and colleagues [10] kept the energy density of their solid and liquid sucrose-sweetened foods the same and, like us, found that viscosity affected neither overall energy intake nor the magnitude of compensation for added sugar (no energy density × viscosity interaction for compensation).

A notable finding in the present study is that men tended to show greater compensation for the energy difference in the preloads than did the women, and this was particularly evident for the drink preload. While we found no clear gender differences in compensation in our review of preload, test-meal studies comparing sugar with low-energy, sweet control drinks [1], many studies did not separate results by

![Fig. 3](image)

**Fig. 3.** Total (savoury plus sweet food) energy intake in the test-meal after the preload minus total energy intake in the test-meal on the baseline (no preload) day for the six different preloads shown separately for men and women. The figure below each pair of bars is the compensation score (COMPX) for that group. A COMPX score of 100% represents full compensation for the additional energy content of sucrose versus sucralose preload (see Section 2.8 for further details). Mean difference rather than adjusted mean difference in energy intake values are plotted here because this is the basis of the calculation of energy compensation. Averaged across preload viscosity and gender, the sucrose preloads reduced energy intake by 58 kcal compared with the sucralose preloads (COMPX = 36%). Cumulative (preload plus test-meal) intake was correspondingly increased after the sucrose compared with the sucralose preload (by 105 kcal). For the drink preload there was a significant effect of sweetener (sucrose versus sucrose) (\(p = .028\)) and a marginally insignificant sweetener × gender interaction (\(p = .097\)) for test-meal energy intake; see results for further details.

![Fig. 4](image)

**Fig. 4.** Change in blood glucose concentration after preload consumption shown separately for the drink, jelly and candy sucrose preloads. The data are post-consumption minus baseline values. The baseline values were for blood samples taken 5 min before the preload was served (represented as time 0 on the graph). The baseline values (mean ± SD mmol/L) were as follows: drink: 4.7 ± 0.6, jelly: 5.2 ± 0.5, candy: 4.7 ± 0.7. The times after consumption (points at 5, 10, 20 and 40 min) are times after the 5 min allowed for consumption of the whole preload. There was a significant preload type × time interaction effect (\(p = .026\)).
gender or did not test both men and women. In at least one study that did contrast effects in men and women [28], the result was very similar to the gender difference for the drink preload evident in Fig. 3. That study also compared the effects of sugar- and low-energy sweetener, blackcurrant drinks (Ribena products, currently manufactured by Suntory, UK), and found no compensation in women and full compensation in men. They discussed this finding in relation to possible sex differences in appetite regulation, however in the present study the suppressive effect of sugar on hunger did not differ between men and women, indicating that the sugar was sensed post-ingestively similarly in both men and women. Therefore, we favour an explanation based on possible gender differences in the cognitive control of eating. We suggest that the women in our sample may have had a greater tendency to restrict their intake to within their personal norm for lunch than did the men, irrespective of (small) differences in physiological state, produced by consuming the sucrose- versus sucralose-sweetened drink. In support of this the women ate 30% less than the men in the baseline meal and test-day meals (Table 3), and despite our exclusion of current dieters and highly restrained eaters, the women were more restrained than the men, as measured by the DEBQ.

Lastly, this study also found evidence consistent with our hypothesis that consumption of a sweet drink will decrease appetite for sweetness, rather than increase it as has been suggested by some authors [29,30,31]. Specifically, the ratio of sweet to total food consumed in the test-meal was lower on the test day, when a sweet drink was consumed before the meal than on the baseline day when no sweet drink was consumed. This occurred irrespective of the energy content of the sweet drink, which is what would be expected if this was due to oro-sensory exposure to sweetness. The effect was small, but consistent with the observation that sensory-specific satiety persists for some considerable time after eating [17,19] — here the interval between the end of the consumption of the sweet drink and the beginning of the consumption of the sweet food in the test-meal is likely to have been at least 25 min, assuming that the sweet food was eaten after the savoury sandwiches. It seems likely that the reduction in appetite for a sweet dessert would be even greater if the sweet drink was consumed during the meal, as often happens in real life. We are currently testing this in a further study, which also removes the possible confound in the present study that the no drink condition always preceded the drink condition by balancing the order of treatments. Furthermore, the treatments also include water.

In summary, we found that consumption of sucrose- compared with sucralose-sweetened preloads reduced subsequent test-meal energy intake. Compensation for the energy difference (162 kcal) between the preloads was only partial (35% across drink, jelly and candy preloads), so cumulative intake (preload plus test-meal intake) was greater in the sucrose condition. Compensation was not, as predicted, affected by preload viscosity — if anything, it was greater when the preload was a drink (60%) than when in was food. This unexpected result could not be explained by differences in blood glucose concentration at the start of the test-meal, nor by the lower sweetness and flavour intensity of the food preloads, or because they were less familiar and less liked; however, the higher energy density (smaller volume) of the food preloads may have played a role. Two further notable findings were that men tended to show greater compensation than women, and that consumption of the sweet drinks, irrespective of energy content, reduced the relative intake of sweet food. Most importantly, this study demonstrated that sugar consumed in a drink was not less satiating than the same amount of sugar consumed in realistic semi-solid and solid foods.

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