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Sweet satiation: acute effects of consumption of sweet drinks on appetite for and intake of sweet and non-sweet foods

Peter J. Rogers^{a,b}, Danielle Ferriday^a, Beyrom Irani^a, Julianne Ka Hei Hoi^a, Clare Y. England^b, Kimran K. Bajwa^a, Thomas Gough^{a,c}

^a Nutrition and Behaviour Unit, School of Psychological Science, University of Bristol, Bristol, BS8 1TU, UK

^b National Institute for Health Research Bristol Biomedical Research Centre, University Hospitals Bristol NHS Foundation Trust and University of Bristol, UK.

^c Current address: School of Psychology, University of Liverpool, Liverpool, L69 7ZA, UK

Corresponding author:

Peter J Rogers

Nutrition and Behaviour Unit

School of Psychological Science

University of Bristol

12a Priory Road

Bristol, BS8 1TU, UK.

peter.rogers@bristol.ac.uk

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Abstract

Sensory-specific satiety (SSS) describes a reduction in the pleasantness of the taste of (momentary liking) and desire to consume a food that occurs with consumption, compared with the relative preservation of liking and desire for uneaten foods. We conducted three studies in healthy female and male participants to test whether SSS generalises from sweet drinks to sweet foods. Studies 1 (n = 40) and 2 (n = 64) used a two-condition cross-over design. Participants consumed non-carbonated, fruit squash drinks sweetened with low-calorie sweeteners (LCS) versus water and evaluated various food and drink samples (stimuli). Generalisation of SSS was evident across all sweet stimuli, without an effect on non-sweet (savoury) stimuli. These SSS effects were present when measured shortly after consumption of the sweet drink, but not 2 hours later. There was no evidence of a 'rebound' increase above baseline in liking or desire to consume sweet foods 2 hours after the sweet drink versus water. In study 3, 51 participants consumed labelled and branded 500 ml cola and water drinks (4 conditions, cross-over design) immediately before and during ad libitum consumption of sweet and non-sweet snack foods. Compared with still water, 'diet' (LCS-sweetened) cola reduced sweet food intake, but not total ad libitum intake. Carbonated water decreased hunger and increased fullness compared with still water, without differentially affecting thirst. Energy compensation from the ad libitum snacks for consumption of sugar-containing cola averaged only 20%. Together, these results demonstrate that consumption of LCS drinks acutely decreases desire for sweet foods, which supports their use in place of sugar-sweetened drinks. Further studies on the effects of carbonation of appetite are warranted.

1. Introduction

Previously, we and others have concluded that consumption of low-calorie sweeteners (LCS) compared with the consumption of sugars reduces energy intake and body weight (Rogers, Hogenkamp, de Graaf, Higgs, Lluch, Ness, Penfold, Perry, Putz, Yeomans & Mela, 2016; Miller & Perez, 2014). Possibly, however, it would be more beneficial to reduce exposure to sweetness in our diet, as articulated in the following quotes. ‘Lastly, artificial sweeteners, precisely because they are sweet, encourage sugar craving and sugar dependence’ (Yang, 2010, p 106), ‘In addition, overstimulation of sugar receptors by frequent consumption of hyper-intense sweeteners may cause taste preferences to remain in, or revert to, an infantile states (i.e., with limited tolerance to more complex tastes)’ (Ludwig, 2009, p 2477), and ‘Thus, repeated exposure to NNS (non-nutritive sweeteners) would be expected to establish and maintain a preference for sweet items in the diet’ (Mattes & Popkin, 2009, p 9). Whilst this ‘sweet tooth’ hypothesis is plausible, especially given the relationship between exposure to salt and preference for saltiness in foods (Mattes & Popkin, 2009), there is no good evidence to support it. A recent systematic review (Appleton, Tuorila, Bertenshaw, de Graaf & Mela, 2018) concluded that currently the evidence on the effects of dietary exposure to sweetness on the subsequent generalised acceptance, preference or choice of sweet foods and drinks is limited. Nonetheless, if anything, controlled studies show that in the short term (<1 month) greater exposure to sweet taste tends to reduce preference for sweetness, with small effects of longer-term exposure (Appleton et al., 2018). Results of a subsequent study (Fantino, Fantino, Matray, & Mistretta, 2018) specifically on the effects of repeated exposure to a LCS drink versus water support these conclusions.

Also against the sweet-tooth hypothesis, our meta-analysis found that body weight was reduced in participants randomised to receive LCS drinks versus those randomised to receive water (Rogers et al., 2016). There were, however, only three eligible trials, and the largest effect was found for a trial that compared the effect of LCS versus water in LCS drink consumers. In other words, participants randomised to water had to discontinue consuming LCS drinks (Peters, Wyatt, Foster, Pan, Wojtanowski, Vander Veur, Herring, Brill & Hill, 2014). Nonetheless, a relevant additional finding from another of these trials was that energy intake from desserts was lower in LCS versus water group participants (Piernas, Tate, Wang, & Popkin, 2013), which suggests that consumption of LCS might satisfy rather than increase desire for sweetness, at least acutely (Rogers, 2018). This would be consistent with the robust phenomenon of sensory-specific satiety (SSS), originally described by Rolls and her colleagues (Rolls, Rolls, Rowe & Sweeny, 1981). SSS describes the reduction in the pleasantness of the taste of a food (momentary liking) that occurs with consumption, compared with the relative preservation of momentary liking for uneaten foods, and particularly so for uneaten foods with dissimilar oro-sensory properties (Hetherington and Havermans, 2013; Guinard & Brun, 1988). Not surprisingly, SSS is also characterised by a decrease in desire to consume and appetite for the eaten food (Rogers & Hardman, 2014; Hetherington and Havermans, 2013; Griffioen-Roose, Finlayson, Mars, Blundell & de Graaf, 2010; Brunstrom & Mitchell, 2006; Guinard & Brun, 1988). Furthermore, SSS persists largely undiminished for the first 5-15 minutes after eating (Rogers & Hardman, 2014, Brunstrom & Mitchell, 2006) and is still present after 1 hour (Hetherington, Rolls & Burley, 1989).

It is possible, therefore, that consumption of LCS drinks will cause intake of sweet, sugar-containing foods to be reduced overall because the effect of SSS outweighs any tendency there might be for LCS consumption to increase long-term preference for sweetness. The plausibility of this proposal depends on the generalisation of SSS from a sweet drink to a sweet food. Testing this possibility was the primary purpose of the three studies described hereafter. Our focus was on the effects of LCS drinks versus water because functionally LCS can replace all of the added sugars and all of the calories in a drink, and because from a public health perspective LCS drinks or water could be the recommended alternative for sugar-containing drinks (Borges, Louzada, de Sá, Lavery, Parra, Fellegger Garzillo, Monteiro & Millett, 2017). Our primary hypothesis for these studies was that desire for and consumption of sweet food would be reduced more by consumption of a sweet drink than by consumption of still water. In previous research we found that desire to consume (eat) is a good predictor of actual food intake (Rogers & Hardman, 2014).

We present three studies in total. Study 3 was conducted during 2012-2013, and studies 1 and 2 were conducted during 2015-2016 and 2016-2017, respectively. We describe the earliest study last as this best reflects the progression of evidence concerning satiation of desire for sweetness (Studies 1 and 2) to the measurement of effects on sweet food intake (Study 3).

2. Study 1

Study 1 compared the effect of consumption of water and blackcurrant squash on desire to consume, pleasantness and sweetness of water, blackcurrant squash, apple juice, fresh apple fruit and apple pie. The blackcurrant squash drink was a 'no-added sugar' drink sweetened with sucralose. Such drinks, either sweetened with sugars or LCS, are popular in the UK. The effect of consuming water versus blackcurrant squash on the evaluation of water and blackcurrant squash is essentially a test of classic SSS – in other words it tests the effect of consuming a stimulus on evaluation of the same stimulus and the evaluation of another stimulus, and vice versa (Rolls et al., 1981). In our study, however, these two stimuli were calorie free or nearly calorie free. Additionally, the study tested whether effects of consuming the sweet drink versus the effects of consuming water might generalise to other sweet, calorie-containing stimuli, namely apple juice, apple and apple pie. Level of dietary exposure to LCS was not a criterion for participation in this or the subsequent studies (nor was this measured). However, the information sheets for all the studies noted that the foods or drinks served might contain LCS.

3. Methods

3.1 Participants

The participants were recruited via a database of healthy people held by the University of Bristol Nutrition and Behaviour Unit, and via a Facebook page belonging to the University of Bristol Student Psychology Society. Eligibility criteria included age ≥ 18 years, not using medication known to affect food intake or appetite, not following a vegan diet, not currently dieting and not having a history of disordered eating. In total 40 participants (26 women) were recruited and completed the study. On completion of their second test

session each participant was paid £10 in compensation for the time they contributed to the study.

The procedures for this and the other two studies described here were approved by the University of Bristol, Faculty of Science Human Research Ethics Committee. Informed consent was obtained from all participants for their participation in the studies. Eligibility criteria included being familiar with cola and diet cola, to be able to consume 'fizzy' drinks, not using medication known to affect food intake or appetite, not being vegan, not currently dieting and not having a history of disordered eating.

3.2. Design

The participants consumed 330 ml water on one occasion and 330 ml blackcurrant squash on another occasion one week apart, with drink order being balanced across participants. They evaluated the five food and drink stimuli for desire to consume, pleasantness and sweetness shortly before and shortly after consuming the drink. The order in which they evaluated the stimuli was balanced using a design that controlled for first-order carry-over effects (Williams design). Four participants were allocated to each of the 10 orders.

As this was an exploratory study, we did not perform a formal power calculation.

3.3. Drinks and foods

Details of the drinks and foods used in the study and their nutrient composition are shown in Table 1. These products were purchased from a local branch of Sainsbury's Supermarkets Ltd, London, UK. The energy content of the 330 ml blackcurrant squash drink was 7 kcal, and 0 kcal for 330 ml water. The drinks were served at a temperature of approximately 15°C, and the foods were served at room temperature. The taster portions of the drinks and foods were presented in small glasses ('shot' glasses) and small ramekin dishes arranged evenly spaced on a tray. For the desire to consume task each food and drink was photographed in colour in the portion shown in Table 1. The name of the product was presented in the top left-hand corner of the photograph. The drinks were contained in a clear glass and the foods were cut in half and displayed on a white plate. A description of each product (e.g., '250 ml no-sugar, low-calorie blackcurrant squash', or 'Mr Kipling Bramley Apple Pie') was added to the picture for presentation to the participants. The amounts of foods depicted for this task represented a small to medium typical portion of the respective food. The amounts for the taster portions were chosen to be a bite- or sip-size portion of each item.

3.4. Outcome measures

Participants evaluated the food and drink stimuli whilst seated at a table in a private booth within a larger room. The table was furnished with a LCD computer monitor, mouse and QWERTY keyboard, leaving room to serve the tray of food and drink stimuli when appropriate. The name of each taster stimulus was presented on the computer screen in one of the ten pre-determined orders. The on-screen instructions instructed the participants to taste and swallow whichever stimulus was named and press the Enter key when this was done. The picture of the larger portion (Table 1) of that drink or food stimulus was then

presented on the screen along with three clickable 100-point line scales presented singly and in an order determined fully randomly. The rating scales were worded as follows. 'Please rate how strong your desire is to consume a full portion (shown below) of this food/drink RIGHT NOW', 'Please rate how pleasant the drink/food tasted in your mouth', 'Please rate how sweet the drink/food tasted in your mouth'. For each scale the left-hand end of the line was labelled 'NOT AT ALL' and the right-hand end of the line was labelled 'EXTREMELY'. Participants were instructed to click at the appropriate point on the line to make their rating and once they had done this to press the Enter key. This triggered the appearance of the next rating, or the next food if all three ratings for that food had been completed.

197 **Table 1**

198 Composition of the foods and drinks used in Study 1.

Food/drink name	kcal per 100 ml or 100 g	Fat per 100 ml or 100 g	Carbohydrate (of which sugars) per 100 ml or 100 g	Protein per 100 ml or 100 g	Amount for taster portion	Amount depicted for desire to consume task
Water ^a	0	0	0	0	25 ml (0 kcal)	250 ml
Blackcurrant squash ^b	2	0	0.5 (0.5)	0	25 ml (0.5 kcal)	250 ml
Apple juice ^c	68	< 0.5	10.5 (9.2)	< 0.5	25 ml (17 kcal)	250 ml
Apple fruit ^d	47	< 0.5	12.0 (12.0)	< 0.5	12.5 g (6 kcal)	100 g
Apple pie ^e	351	13.2	54.0 (25.6)	3.4	15 g (53 kcal)	59 g

199 ^aTap water.

200 ^bSainsbury's double concentrated no added sugar blackcurrant squash, diluted 1 part with 5 parts tap water.

201 ^cSainsbury's pure apple juice.

202 ^dUnpeeled, fresh Cox apple cut into 12.5 g segments.

203 ^eMr Kipling Bramley apple pie, consisting of sweet shortcrust pastry with a sweet apple filling (an individual pie weighed 59 g).

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3.5. Procedure

The study was advertised and presented as a study requiring rating and tasting non-alcoholic drinks and foods. Testing took place between 9 AM and midday on weekdays, with each test session lasting approximately 25 minutes. Participants were asked to consume their usual breakfast, but not to eat or drink anything during the hour before their test session. After arrival on their first test session participants gave their signed informed consent to participate in the study, and on conclusion of the second test session they were weighed to the nearest 100 g and their height measured using a stadiometer. Finally, they were paid £10 and debriefed as to the full purpose of the study.

On both test session participants began the computer-guided set of tasks by completing rating of their hunger ('How hungry do you feel right now'), fullness ('How full do you feel right now') and thirst ('How thirsty do you feel right now') on clickable 100-point scales. They were then served with the five food and drink stimuli to consume and evaluate individually, and within one minute of completing that task they were served with either 330ml water or 330 ml blackcurrant squash as appropriate. On-screen text instructed them to consume all of the drink gradually over a period of 5 minutes. A digital stopwatch showed the time remaining, and participants were asked to adjust their rate of drinking to finish their drink as the 5 minutes elapsed. Within the next minute they were served with fresh samples of the five food and drink stimuli to consume and evaluate again individually one at a time. The computer-guided tasks ended with the evaluation of the final food or drink stimulus.

3.6. Data analysis

The primary outcome variable was change in desire to consume the evaluated food and drink stimuli from before to after consumption of the drinks (water and blackcurrant squash). Secondary outcomes were changes in pleasantness of taste and sweetness of the evaluated stimuli. Accordingly, we calculated post-drink minus pre-drink scores for these variables. Therefore, a reduction in, for example, desire to consume a food stimulus occurring from before to after consumption of one of the drinks is represented by a negative desire to consume score.

Because pre-drink data for one participant on one test session was corrupted and could not be recovered, the final sample of participants data was reduced to 39 (25 women and 14 men). All results reported hereafter for Study 1 are for those 39 participants.

Data analysis was carried out using IBM SPSS Statistics 24 (IBM Corporation, Armonk, NY, USA). We calculated summary information (mean $\pm$ SD) for participants' age, weight and body mass index (BMI), and for their degree of hunger, fullness and thirst (measured immediately before the pre-drink evaluation of the food and drink stimuli, and averaged across water and blackcurrant drink sessions),

We tested differences in evaluations of the five food and drink stimuli (averaged across water and blackcurrant drink sessions) using single factor repeated measures ANOVA, followed by Bonferroni corrected paired comparisons.

We used two-factor repeated measures ANOVA to test the effects of drink (water and blackcurrant squash) on post-drink minus pre-drink evaluations of the water and blackcurrant squash stimuli. Likewise, we used two-factor repeated measures ANOVA to

test the effects of drink (water and blackcurrant squash) on post-drink minus pre-drink evaluations of the apple juice, apple fruit and apple pie stimuli. As outlined in the Introduction, these analyses test for, respectively, classic SSS and the generalisation of SSS to other sweet stimuli. Exploratory analyses which included gender as a third factor in these analyses showed no clear effects of gender, so gender is not included in the results reported here. No gender differences were hypothesised. For ANOVA the Greenhouse-Geisser correction was applied where appropriate (adjusted p values are reported).

4. Results

Participant characteristics (mean $\pm$ SD) were as follows: age, 23.2 ± 4.5 years, weight 66.3 ± 10.9 kg, BMI 23.0 ± 3.6 kg/m². Mean $\pm$ SD pre-drink hunger, fullness and thirst ratings were respectively, 49.1 ± 16.9 , 40.3 ± 16.2 , 60.9 ± 11.9 .

Results for pre-drink evaluations of desire to consume, pleasantness and sweetness of the food and drink stimuli are shown Table 2. Broadly, desire to consume and pleasantness were lowest for blackcurrant squash and water, and highest for apple fruit and apple pie, with apple juice being intermediate. Sweetness was highest for blackcurrant squash, apple pie and apple juice, lower for apple fruit and much the lowest for water. Water and blackcurrant squash differed significantly only for sweetness.

Table 2

Pre-drink evaluations of the five food and drink stimuli used in Study 1.

Food/drink stimulus	Desire to consume	Pleasantness of taste	Sweetness
Water	$53.6 \pm 2.7^{a,b}$	$56.8 \pm 2.7^{a,b}$	18.9 ± 2.5^a
Blackcurrant squash	41.5 ± 3.8^a	51.5 ± 3.3^a	77.9 ± 2.1^b
Apple juice	55.9 ± 3.1^b	$64.9 \pm 2.4^{b,c}$	71.4 ± 2.5^b
Apple fruit	$61.9 \pm 2.7^{b,c}$	$71.8 \pm 1.7^{c,d}$	60.5 ± 2.0^c
Apple pie	70.6 ± 3.2^c	78.0 ± 2.1^d	77.5 ± 1.6^b
Main effect of drink $F(4,152)$, p , partial η^2	12.34, <.0001, .245	19.37, <.0001, .338	153.40, <.0001, .801

Data are means $\pm$ SEs.

Means within a column not sharing a letter in common differ significantly ($p < .05$, Bonferroni adjustment for multiple comparisons).

Results for post-drink minus pre-drink changes in desire to consume, pleasantness of taste and sweetness are shown in Figure 1. Overall, desire to consume and pleasantness of taste, but not sweetness, decreased from before to after consumption of the drinks ($F(1,38)$, p and partial η^2 values were respectively: desire to consume, 127.06, <.001, .770; pleasantness of taste, 29.41, <.001, .434; sweetness, 1.31, .259, .033).

The relevant statistical results comparing the effect of consumption of the water versus blackcurrant squash (i.e., the factor drink) on evaluations of the five food and drink stimuli (i.e., the factor stimulus) are summarised in Table 3. Together with Figure 1 these results show that there was a classic sensory specific-satiety effect. This is evidenced by the significant drink by stimulus interaction effect for desire to consume. Consumption of blackcurrant squash reduced desire to consume blackcurrant squash more than it reduced

287 desire to consume water, whereas there was a small difference in the reverse direction after
288 consumption of water. There were no significant main or interaction effects for
289 consumption of blackcurrant squash versus consumption of water on pleasantness of taste
290 or sweetness of water and blackcurrant squash.

291 In the test of the generalisation of SSS, desire to consume and pleasantness of taste
292 were reduced more by consumption of blackcurrant squash than by consumption of water
293 (significant main effects of drink). For desire to consume the difference in the effect of
294 blackcurrant squash versus water was almost identical for the three stimuli – apple juice,
295 apple fruit and apple pie (non-significant drink by stimulus interaction); whereas for
296 pleasantness of taste it varied across these stimuli, the difference being largest for apple
297 juice and smallest for apple pie (significant drink by stimulus interaction). Consumption of
298 both drinks reduced desire to consume apple juice more than apple fruit and apple pie
299 (significant main effect of stimulus). Again, stimulus sweetness was unaffected by
300 consumption of blackcurrant squash versus water (no significant main or interaction
301 effects). A further noteworthy result was a main effect of stimulus for desire to consume,
302 due primarily to a greater decline of desire to consume apple juice after the drinks
303 compared with the decline in desire to consume apple fruit and apple pie.
304

Fig. 1. Study 1. Changes in desire to consume, pleasantness of taste and sweetness of five food and drink stimuli after consumption of water and consumption of blackcurrant squash (BC squash). Evaluations were made on line scales, with the minimum and maximum scores being 0 and 100. Effects for water versus BC squash (classic SSS), and apple juice versus apple fruit versus apple pie (generalisation of SSS) were analysed separately.

Table 3

Study 1. Statistical results for post-drink minus pre-drink changes in evaluations of the five food and drink stimuli, separated for evaluations of the same and different sweet stimuli^a.

	Main effect of drink	Main effect of stimulus	Drink by stimulus interaction
<i>Classic SSS: water and blackcurrant squash stimuli</i>			
	$F(1,38), p, \text{partial } \eta^2$	$F(1,38), p, \text{partial } \eta^2$	$F(1,38), p, \text{partial } \eta^2$
Desire to consume	2.38, .131, .059	4.78, .035, .112	13.90, <.001, .268
Pleasantness of taste	2.95, .094, .072	0.69, .410, .018	1.85, .182, .046
Sweetness	0.10, .754, .003	0.96, .333, .025	0.22, .641, .006
<i>Generalisation of SSS: apple juice, apple fruit and apple pie stimuli</i>			
	$F(1,38), p, \text{partial } \eta^2$	$F(2,76), p, \text{partial } \eta^2$	$F(2,76), p, \text{partial } \eta^2$
Desire to consume	9.83, .003, .205	6.68, .004, .150	<.01, .999, <.001
Pleasantness of taste	15.81, <.001, .294	0.53, .552, .014	3.40, .039, .182
Sweetness	0.52, .477, .013	2.87, .077, .070	0.45, .641, .012

^aAnalyses were conducted separately for evaluation of samples of the drinks consumed in the tests (water and blackcurrant squash stimuli) and for samples of different sweet stimuli (apple juice, apple fruit and apple pie). Note that classic SSS effects are demonstrated by significant drink by stimulus interaction effects, and generalisation of SSS by significant main effects of drink.

5. Discussion

The results of this study demonstrate a SSS effect of consuming a near zero-calorie sweet drink and found that this generalised to other sweet stimuli. The effects of the blackcurrant drink versus water were most consistent for evaluations of desire to consume the sweet stimuli, although the pleasantness of the taste of, especially, apple juice was also reduced after the blackcurrant drink versus water. In previous studies we found that desire to consume (eat) was a good predictor of actual food consumption (Rogers & Hardman, 2014), and furthermore that desire to consume is predicted independently by pleasantness of taste (i.e., momentary liking) and hunger.

In this context, it is worth noting that the participants began the test sessions in a moderate state of hunger and thirst, which indicates that they were ready to consume the study drinks and foods. Their initial (i.e., pre-drink) evaluations of these stimuli showed that apple pie followed by apple fruit were more or somewhat more desirable and pleasant to taste (liked) than water and blackcurrant juice, with apple juice receiving intermediate ratings. Mean ratings were above the mid-point of the not-at-all to extremely scale, except for desire to consume blackcurrant squash. However, substantial decreases in desire to consume were observed for all of the drink stimuli, including blackcurrant squash, which indicates that floor effects are not a significant problem in this study.

A further finding from this study was that changes in sweet taste intensity contributed almost nothing to SSS, as there were no significant effects of consumption of blackcurrant juice versus water on perceived sweetness of the evaluated stimuli. Apple fruit was rated the least sweet of the four sweet stimuli, but nonetheless there was ample room

for a change in sweetness to occur for this stimulus. These results accord with observations from a variety of other studies showing that exposure (consumption or merely repeated tasting) results in sensory-specific decreases in pleasantness and/or desire for food and drink stimuli in the absence of substantial changes in rated stimulus intensity (e.g., Fernandez, Bensafi, Rouby & Giboreau, A. 2013; Pepino & Mennella, 2012; Brunstrom & Mitchell, 2006).

Another result was that consumption of the drinks caused a greater decrease in desire to consume apple juice than apple pie, with apple fruit being somewhat intermediate. This is likely due simply to a reduction in thirst being more relevant to desire for fluid than for food stimuli. In other words, an important motive for consuming apple juice, but not apple pie, is thirst, and thirst is substantially reduced by consuming 330 ml of either water or 330 ml of blackcurrant juice. Extending our model of food reward (Rogers & Hardman, 2014) to fluid reward, we would predict that desire to consume, but not liking for (pleasantness of taste of), a fluid would change with thirst. That is supported, at least for the effect of consumption of water. Figure 3 shows that whilst there were substantial decreases in desire to consume water, blackcurrant juice and apple juice after drinking 330 ml of water, the pleasantness of the taste of these stimuli changed very little.

Although this study found evidence consistent with a SSS effect in that consumption of a sweet drink reduced desire to consume sweet food and drink stimuli more than did consumption of water, it remains possible that at least part of the effect of the sweet drink was to more generally decrease appetite, for example because exposure to sweetness is rewarding and/or satiating (Rogers, 2018; Martin, Ferriday, Rogers & Brunstrom, 2016). Therefore, in the next study we sought to extend the present findings by testing the effect of consuming a sweet drink versus consuming water on desire to consume predominantly non-sweet (savory) as well as sweet-tasting stimuli. The SSS hypothesis would be supported if the reduction in desire to consume generalised to sweet but not to non-sweet stimuli. A further aim of the next study was to investigate the time-course of the effects of consuming a sweet drink on desire to consume sweet and non-sweet stimuli, so the stimuli were evaluated shortly after consumption of the drinks and again 2 hours later. Finally, to increase the generalisability of the findings of the studies the sweet drink was an orange- rather than blackcurrant-flavoured LCS squash in Study 2.

6. Study 2

In this study participants evaluated a total of 8 sweet and non-sweet stimuli after consuming water on one occasion and LCS orange squash on another occasion. Apart from orange squash the sweet stimuli were orange fruit, banana, apple pie and milk chocolate, and apart from water the non-sweet stimuli were cheese and potato crisps. Participants evaluated these stimuli starting as soon as feasible (i.e., approximately 1 minute) after consumption of the drink and then again after an interval of 2 hours. Otherwise the methods were very similar to those for Study 1. The primary hypothesis for the study was that the consumption of orange squash compared with water would reduce desire to consume the sweet but not the non-sweet food and drink stimuli.

7. Methods

7.1. Participants

The participants were recruited via a database of healthy people held by the University of Bristol Nutrition and Behaviour Unit, via noticeboards around the University of Bristol and by word of mouth. Eligibility criteria included age ≥ 18 years, not using medication known to affect food intake or appetite, not following a vegan diet, not currently dieting and not having a history of disordered eating. In total 64 participants (35 women) completed the study. On completion of their second test session each participant was paid £20 in compensation for the time they contributed to the study.

Results from G-power (Faul, Erdfelder, Lang & Buchner, 2007) analysis using the average effect size ($d = 0.46$) for pleasantness of the three foods (apple juice, apple fruit and apple pie) rated after water versus blackcurrant squash from Study 1 indicated a sample size of 58 to achieve 80% power for a 1-tail test and $\alpha = 0.05$. So that the order of the foods could be counterbalanced the target number of participants was increased to 64.

7.2. Design

The participants consumed 330 ml water on one occasion and 330 ml orange squash on another occasion one week apart, with drink order being balanced across participants. They evaluated the eight food and drink stimuli for desire to consume, pleasantness and sweetness shortly before, shortly after and 2 hours after consuming the drink. The order in which they evaluated the stimuli was balanced using a design that controlled for first-order carry-over effects (Williams design). Eight participants were allocated to each of the 8 orders.

7.3. Drinks and foods

Details of the drinks and foods used in the study and their nutrient composition are shown in Table 4. The energy content of the 330 ml orange squash drink was 16 kcal. Serving temperatures and presentation of the drinks and foods were the same as for Study 1. The amounts of foods depicted for this task represented a small to medium typical portion of the respective food. The amounts for the taster portions were chosen to be a bite- or sip-size portion of each item.

7.4. Outcome measures

Participants evaluated the food and drink stimuli whilst seated at a table in a private booth within a larger room. Unlike Study 1, participants recorded their evaluations in paper booklets. There was a separate page for each food and drink stimulus. This contained printed step-by-step instructions for tasting and rating each stimulus, together with a colour photograph depicting the full portion of the food or drink for the desire to consume task as in Study 1. There were eight versions of the booklets corresponding to the eight different pre-determined orders of the stimuli. Participants made their ratings by marking 100 mm line scales with a pencil. The scales were labelled as for Study 1. Responses were measured to the nearest mm from left-hand end of the lines (labelled NOT AT ALL). For each food and

drink stimulus participants made their ratings in the following order: sweetness, pleasantness of taste, desire to consume.

7.5. Procedure

The study was advertised and presented as a study testing the pleasantness of different drinks and snacks. The basic procedures for testing were the same as for Study 1, except that participants evaluated each food and drink stimulus twice after each drink, starting after 1 minute (as in Study 1) and again 2 hours later. Participants were allowed to leave the laboratory during the interval. They were instructed not to eat or drink anything during that time.

7.6. Data analysis

Data from all of the 64 participants who completed the study were included in all analyses. Primary and secondary outcome variables and summary information on participants were the same as for Study 1.

We also used the same basic procedures to test for pre-drink differences in desire to consume, pleasantness of taste and sweetness between the eight food and drink stimuli, and for the effects of drink (orange squash versus water) on those evaluations. For the latter, for each outcome variable we conducted six separate two-factor (drink and stimulus) analyses. We compared the effect of drink on (post- minus pre- drink) evaluations of water and orange squash stimuli (classic SSS), on evaluations of orange fruit, banana, apple pie and chocolate (generalisation of SSS to other sweet stimuli), and on evaluations of cheese and potato crisps (generalisation to non-sweet stimuli). We did this separately for the 1-minute and 2-hour evaluations.

To compare the generalisation of SSS to sweet versus non-sweet stimuli over time for desire to consume (the primary outcome variable) we used three-factor repeated measures ANOVA. The three factors were drink (water and orange squash), stimulus (sweet and non-sweet) and time (1-minute and 2-hour intervals). The data comprising sweet in this analysis were the average of desire to consume orange fruit, banana, apple pie and chocolate, and the data comprising non-sweet were the average of desire to consume cheese and potato crisps.

466 **Table 4**

467 Composition of the foods and drinks used in Study 2.

Food/drink name	kcal per 100 ml or 100 g	Fat per 100 ml or 100 g	Carbohydrate (of which sugars) per 100 ml or 100 g	Protein per 100 ml or 100 g	Amount for taster portion	Amount depicted for desire to consume task
Water ^a	0	0	0	0	25 ml (0 kcal)	330 ml
Orange squash ^b	2	0	0.5 (0.5)	0	25 ml (1.0 kcal)	330 ml
Orange fruit ^c	41	< 0.5	8.2 (7.8)	0.8	15 g (6 kcal)	80 g
Banana fruit ^d	103	< 0.5	23.2 (20.9)	1.2	15 g (15 kcal)	100 g
Apple pie ^e	351	13.2	54.0 (25.6)	3.4	15 g (53 kcal)	59 g
Milk chocolate ^f	534	30.0	57.0 (56.0)	7.3	10 g (53 kcal)	45 g
Cheese ^g	416	34.9	<0.5 (<0.5)	25.4	15 g (62 kcal)	60 g
Potato crisps ^h	537	32.2	55.4 (<0.5)	5.3	4 g (22 kcal)	25 g

468 ^aTap water.

469 ^bSainsbury's double concentrated no added sugar orange squash, diluted 1 part with 5 parts tap water.

470 ^cPeeled, fresh orange fruit, cut into 12.5 g segments.

471 ^dPeeled, fresh banana fruit.

472 ^eMr Kipling Bramley apple pie, consisting of sweet shortcrust pastry with a sweet apple filling (each individual pie weighs 59 g).

473 ^fCadbury Dairy Milk chocolate.

474 ^gSainsbury's mature Cheddar cheese.

475 ^hSainsbury's ready salted potato crisps.

476

8. Results

Participant characteristics (mean $\pm$ SD) were as follows: age, 27.2 ± 8.0 years, weight 67.7 ± 13.6 kg, BMI 23.2 ± 3.8 kg/m². Mean $\pm$ SD pre-drink hunger, fullness and thirst ratings were respectively, 56.2 ± 20.1 , 32.7 ± 17.2 , 64.5 ± 16.2 .

The results for pre-drink evaluations of desire to consume, pleasantness and sweetness of the food and drink stimuli are shown Table 5. Broadly, desire to consume and pleasantness were lowest for cheese, orange squash and water, and highest for banana, chocolate and crisps, with orange fruit and apple pie being somewhat intermediate. Sweetness was highest for chocolate, orange squash and apple pie, lower for banana and orange fruit, and much the lowest for cheese, crisps and water. Water and orange squash differed significantly only in respect of sweetness.

Table 5

Pre-drink evaluations of the eight food and drink stimuli used in Study 2.

Food/drink stimulus	Desire to consume	Pleasantness of taste	Sweetness
Water	54.6 ± 2.8 ^{a,b,c}	60.2 ± 2.7 ^{a,b,c}	15.3 ± 2.0 ^a
Orange squash	48.9 ± 3.2 ^{a,b}	56.8 ± 2.9 ^{a,b}	75.2 ± 2.2 ^b
Orange fruit	58.7 ± 2.9 ^{b,c}	65.1 ± 2.8 ^{b,c,d}	54.3 ± 2.5 ^c
Banana fruit	63.2 ± 3.0 ^c	74.2 ± 2.2 ^d	59.8 ± 2.1 ^c
Apple pie	56.9 ± 2.9 ^{b,c}	68.6 ± 2.1 ^{c,d}	74.5 ± 1.8 ^b
Milk chocolate	63.7 ± 3.0 ^c	74.9 ± 3.0 ^d	79.8 ± 2.1 ^b
Cheese	41.2 ± 3.5 ^a	51.3 ± 3.2 ^a	22.2 ± 2.4 ^a
Potato crisps	65.9 ± 2.8 ^c	75.0 ± 2.0 ^d	17.7 ± 2.0 ^a
Main effect of drink $F(7,441)$, p , partial η^2	8.83, <.0001, .123	14.58, <.0001, .188	192.43, <.0001, .753

Data are means $\pm$ SEs.

Means within a column not sharing a letter in common differ significantly ($p < .05$, Bonferroni adjustment for multiple comparisons).

The results for post-drink minus pre-drink changes in desire to consume, pleasantness of taste and sweetness are shown in Figure 2. Overall, desire to consume, pleasantness of taste and sweetness decreased from before to 1 minute after consumption of the drinks ($F(1,63)$, p and partial η^2 values were respectively: desire to consume, 167.06, <.001, .726; pleasantness of taste, 98.53, <.001, .610; sweetness, 8.53, .005, .033). These decreases were not sustained 2 hours after consumption: overall, neither desire to consume, pleasantness of taste, nor sweetness differed substantially from before to 2 hours after consumption of the drinks ($F(1,63)$, p and partial η^2 values were respectively: desire to consume, 2.72, .104, .041; pleasantness of taste, 1.64, .204, .025; sweetness, 2.30, .134, .035).

The relevant results comparing the effect of consumption of the water versus orange squash (i.e., the factor drink) on evaluations of the eight food and drink stimuli (i.e., the factor stimulus) are summarised in Table 6 and Figure 2.

At the 1-minute interval there was a significant drink by stimulus interaction effect for desire to consume and for pleasantness of taste which demonstrates a classic SSS.

Consumption of orange squash reduced desire to consume orange squash more than it reduced desire to consume water, and vice versa. The drink by stimulus interaction effect for desire to consume was also significant at the 2-hour interval. There were no significant main or interaction effects for consumption of orange squash versus consumption of water on sweetness of water and orange squash after either interval.

In the test of the generalisation of SSS to other sweet stimuli, at the 1-minute interval desire to consume and pleasantness of taste were reduced more by consumption of orange squash than by consumption of water (significant main effects of drink). These effects did not differ among the four sweet stimuli, namely orange fruit, banana, apple pie and chocolate (non-significant drink by stimulus interaction effects). There was also a significant main effect of drink on sweetness at the 1-minute interval. Consumption of orange squash reduced sweetness more than did consumption of water, in large part due to its effect on the sweetness of orange fruit (drink by interaction effect, $p = .084$). There were no main effects of drink or significant drink by stimulus interaction effects for desire to consume, pleasantness of taste or sweetness at the 2-hour interval.

In the test of the generalisation of SSS to savoury stimuli, there were no significant main or interaction effects for desire to consume, pleasantness of taste or sweetness at either interval.

In the comparison of the generalisation of SSS to sweet versus non-sweet stimuli there was a significant drink by stimulus by time interaction effect ($F(1,63) = 6.56$, $p = .013$, partial $\eta^2 = .094$) for desire to consume. This confirms the different effects for the sweet versus non-sweet food stimuli. As shown in Figure 3, 1 minute after consumption, orange squash reduced desire to consume the sweet food stimuli more than did water, whereas there was no difference in the effects of these two drinks after 2 hours. By contrast, desire to consume the non-sweet food stimuli was not differentially affected by the two drinks over time.

Table 6

Study 2. Statistical results for post-drink minus pre-drink changes in evaluations of the eight food and drink stimuli, as a function of interval after drink consumption and separated for evaluations of the same sweet stimuli, different sweet stimuli and savoury stimuli^a.

	Main effect of drink	Main effect of stimulus	Drink by stimulus interaction
<i>Classic SSS: water and orange squash stimuli</i>			
	<i>F(1,63), p, partial η^2</i>	<i>F(1,63), p, partial η^2</i>	<i>F(1,63), p, partial η^2</i>
<i>1-minute interval</i>			
Desire to consume	0.42, .520, .008	0.01, .944, <.001	20.50, <.001, .245
Pleasantness of taste	4.73, .033, .070	1.21, .294, .017	4.96, .030, .073
Sweetness	0.19, .665, .003	3.60, .062, .054	1.68, .199, .026
<i>2-hour interval</i>			
Desire to consume	0.215, .645, .003	4.05, .049, .060	5.58, .021, .081
Pleasantness of taste	2.45, .123, .037	3.58, .063, .054	2.11, .151, .032
Sweetness	0.37, .547, .006	1.67, .202, .026	0.16, .687, .003
<i>Generalisation of SSS to sweet stimuli: orange fruit, banana, apple pie and chocolate</i>			
	<i>F(1,63), p, partial η^2</i>	<i>F(3,189), p, partial η^2</i>	<i>F(3,189), p, partial η^2</i>
<i>1-minute interval</i>			
Desire to consume	5.79, .019, .084	1.49, .224, .023	0.472, .702, .007
Pleasantness of taste	8.48, .005, .119	1.73, .168, .027	0.26, .862, .003
Sweetness	4.81, .032, .071	1.08, .353, .017	2.37, .084, .036
<i>2-hour interval</i>			
Desire to consume	0.35, .556, .006	2.32, .077, .036	1.93, .126, .030
Pleasantness of taste	0.11, .747, .002	5.14, .003, .075	0.73, .520, .012
Sweetness	2.64, .109, .040	11.57, <.001, .155	1.55, .213, .024
<i>Generalisation of SSS to savoury stimuli: cheese and crisps</i>			
	<i>F(1,63), p, partial η^2</i>	<i>F(1,63), p, partial η^2</i>	<i>F(1,63), p, partial η^2</i>
<i>1-minute interval</i>			
Desire to consume	0.30, .585, .005	0.84, .364, .013	0.48, .492, .008
Pleasantness of taste	1.03, .313, .016	3.03, .087, .046	2.85, .097, .043
Sweetness	2.70, .105, .041	0.46, .830, .001	0.20, .658, .003
<i>2-hour interval</i>			
Desire to consume	0.26, .613, .004	1.32, .255, .021	0.09, .765, .001
Pleasantness of taste	0.38, .541, .006	0.51, .822, .001	0.12, .726, .002
Sweetness	0.19, .665, .003	3.14, .081, .003	0.21, .647, .003

^aAnalyses were conducted separately for evaluation of samples of the drinks consumed in the tests (water and orange squash stimuli) and for samples of different sweet stimuli (orange fruit, banana, apple pie and chocolate) and savoury stimuli (cheese and crisps). Note that classic SSS effects are demonstrated by significant drink by stimulus interaction effects, and generalisation of SSS by significant main effects of drink.

1-minute interval

2-hour interval

Fig. 2. Study 2. Changes in desire to consume, pleasantness of taste and sweetness of eight food and drink stimuli after consumption of water and consumption of orange squash. Evaluations were made on line scales, with the minimum and maximum scores being 0 and 100. Effects for water versus orange squash (classic SSS), orange fruit, banana, apple pie and milk chocolate (generalisation of SSS to sweet stimuli) and cheese and potato crisps (generalisation of SSS to non-sweet stimuli) were analysed separately.

Fig. 3. Interaction diagram showing desire to consume sweet food stimuli (average of orange fruit, banana, apple pie and chocolate) and non-sweet food stimuli (average of cheese and crisps) 1 minute and 2 hours after consuming water and orange squash. The data are mean $\pm$ SE post- minus pre-drink desire to consume ratings made on a 100-point scale. The interaction effect was significant ($p = .013$).

9. Discussion

As in Study 1, the participants began the test sessions in a moderate state of hunger and thirst. Their pre-drink evaluations of the food and drink stimuli showed that water, cheese and potato crisps were rated equally low on sweetness and, as expected, less sweet than orange squash, banana, apple pie and milk chocolate. The two drinks, water and orange squash, did not differ on ratings of either desire to consume or pleasantness of taste.

The results of the study replicated and extended the results of Study 1. Confirming the primary hypothesis of the study, they showed that, compared with the consumption of water, consumption of the LCS-sweetened orange squash drink reduced desire to consume and the pleasantness of taste of sweet foods but not non-sweet foods. This result demonstrates generalisation of SSS rather than a more general effect on appetite resulting from the consumption of the sweet, low-calorie drink. As such, it is consistent with observations of the generalisation (or 'transfer') of SSS from the consumption of savoury food to other savoury foods, whilst having no effect on, or even slightly increasing, liking for sweet food stimuli (Griffioen-Roose et al., 2010; Rolls et al., 1981).

In the present study, the magnitude of the generalisation of SSS did not differ among the four sweet stimuli (orange fruit, banana, apple pie and milk chocolate), as shown by the non-significant drink by stimulus interaction effects for desire to consume and pleasantness of taste (Table 6). A classic SSS effect was also evident. That is, consumption of orange squash reduced desire to consume orange squash more than it reduced desire to consume

water, and vice versa. A further result was that the classic SSS effect, albeit much reduced in size, persisted for at least 2 hours. By contrast there was no evidence that generalisation of SSS persisted for 2 hours. This is demonstrated by the similar mean scores for desire to consume the sweet stimuli 2 hours after consumption of orange squash and water, illustrated in Figure 3. Importantly, these same data also show no evidence of a rebound increase in desire for sweet foods 2 hours after consumption of a sweet drink compared with consumption of water.

Apple pie was included in both Study 1 and Study 2, and it noteworthy that the effect of consuming the sweet drink (blackcurrant squash and orange squash, respectively) compared with water was similar for both studies. That is, in terms of effects on desire to consume and the pleasantness of taste of apple pie the magnitude of the generalisation of SSSs did not differ appreciably between the studies (Figures 1 and 2).

A result that differed between the two studies was that the generalisation of SSS was accompanied by significantly decreased sweetness after the sweet drink versus water in Study 2 but not in Study 1 (as shown in Tables 6 and 3, the effect sizes were partial $\eta^2 = .071$ and partial $\eta^2 = .013$, respectively). On the other hand, if anything, the corresponding effects for desire to consume and pleasantness of taste were greater in Study 1 than in Study 2. As noted in the discussion to Study 1, a variety of studies have shown, at most, relatively small changes in taste intensity of foods and drinks following consumption of those foods and drinks (Fernandez et al., 2013; Pepino & Mennella, 2012; Brunstrom & Mitchell, 2006). In Brunstrom and Mitchell's (2006) study, for example, the rated taste intensity of Jaffa Cakes declined by 10 mm after eating five Jaffa Cakes, compared with a decline of 36 mm in desire to eat (results for non-distracted participants). Together these results indicate that decreased taste intensity is at least not a major mechanism for SSS. It is unclear to us why changes in taste intensity vary somewhat between SSS studies.

Finally, it is worth noting that the procedures used in the both Study 1 and Study 2 involved tasting multiple sweet stimuli. It is possible that tasting one sweet stimulus reduces the pleasantness of the taste of the next sweet stimulus. We avoided this causing systematic bias by varying the order in which the stimuli were tasted across participants. However, it is conceivable that multiple tasting of sweet stimuli had a greater effect when it was preceded by consumption of water (no very recent exposure to sweetness) than when it was preceded by consumption of a sweet drink. If that is so, it will have caused these studies to underestimate the magnitude of the SSS effects.

Together, Studies 1 and 2 provide good evidence for the generalisation of SSS from very low-calorie sweet drinks to sweet foods. This predicts that intake of sweet food, but not non-sweet food, would be reduced when a low-calorie sweet drink is consumed compared with when water is consumed. This hypothesis was tested in Study 3.

10. Study 3

This study used a preload test-meal procedure to investigate the effect of consuming sweet drinks on sweet and non-sweet food intake. Participants consumed a fixed preload, comprising a cheese sandwich and a drink. Chocolate chip cookies (sweet) and corn chips (non-sweet) comprised the ad libitum test-meal. Participants were given access to these test-meal foods shortly after consuming all of the cheese sandwich and half of the drink,

and they consumed the remainder of the drink during the test-meal phase (so actually the drink ‘preload’ was consumed partly contemporaneously with the test meal). We reasoned that this should help maximise the generalisation of any SSS effect from the sweet drink to the sweet food, because the drink would be consumed close in time to the test-meal. Furthermore, consumption of fluid throughout a meal is typical of many eating occasions. We tested the effects of four drinks, namely still water, carbonated water, LCS-sweetened cola (‘diet cola’) and sugar-sweetened cola (‘sugar cola’). Our primary hypothesis was that consumption of diet cola would reduce sweet but not non-sweet food intake compared with consumption of still water. This tests for generalisation of SSS, and the comparison with still water follows on Studies 1 and 2 and is the most relevant comparison from the perspective of public health recommendations (Borges et al., 2017); however, because the cola drinks were carbonated, we also included a carbonated water condition. We tested branded cola drinks (Coca-Cola products), because these are highly familiar drinks in the UK, and indeed worldwide, and the ‘diet’ version is clearly labelled as containing no calories. We included sugar-sweetened cola because of the interest in the effects of consumption of LCS versus consumption of sugar on energy intake (Rogers et al. 2016). The study was conducted according to a within-subjects (cross-over) design.

11. Methods

11.1. Participants

The participants were recruited via a database of healthy people held by the University of Bristol Nutrition and Behaviour Unit, via noticeboards around the University of Bristol and by word of mouth. Eligibility criteria included age ≥ 18 years, being familiar with cola and diet cola, to be able to consume ‘fizzy’ drinks, not using medication known to affect food intake or appetite, not following a vegan diet, not currently dieting and not having a history of disordered eating. In total 51 participants (31 women) completed the study. On completion of their fourth test session each participant was paid £30 in compensation for the time they contributed to the study.

11.2. Design

Participants attended for four lunchtime test sessions. They consumed a different drink on each occasion (within subjects design). Drink order was balanced across participants. Two participants were allocated to each of the 24 possible drink orders, with the remaining three being allocated randomly. Participants consumed a fixed preload (cheese sandwich) followed immediately by ad libitum access to chocolate chip cookies and corn chips. They consumed half of their allocated drink with the preload and the other half with the test-meal.

We did not perform a formal effect size calculation, as we were unable to identify a directly relevant similar published study. However, based on data from previous related studies in our laboratory comparing the effects of sweet drinks on primarily savoury food intake (Gadah, Brunstrom & Rogers, 2016a) we aimed to recruit 48 participants. We slightly exceeded this target.

11.3. Drinks and foods

Details of the drinks and foods are summarised in Table 7. The drinks were served in their labelled and branded plastic bottles, so for example it was apparent to participants in the diet cola condition that they had been served a low-calorie drink.

11.4. Outcome measures

The primary outcome measures were the amounts (kcal) of the test-meal foods consumed. Secondary outcomes were post-meal hunger, fullness and thirst ratings.

11.5. Procedure

Eligibility to take part in the study was determined from responses to an online questionnaire completed by individuals expressing an interest in participating. The study was advertised and presented as a study 'investigating how different drinks affect alertness and cognitive performance'. In order to support this cover story, a simple reaction time task and measures of mood and alertness (Rogers, Hohoff, Heatherley, Mullings, Maxfield, Evershed, Deckert & Nutt, 2010) were included, but not analysed. The hunger, fullness and thirst questions were embedded in the mood and alertness questionnaire. The format and method for these questions were the same as that for Study 1.

Participants attended four test sessions scheduled for one-hour slots between 11 AM and 2 PM on weekdays. Individual participants attended the same time slot for all four sessions and, as far as possible, on the same day of the week, and one week apart. They were asked to consume their usual breakfast, but not to eat or drink anything except water 3 hours before the test session. After arrival on their first test session participants gave their signed informed consent to participate in the study. On conclusion of the fourth test session they completed the Three-Factor Eating Behavior Questionnaire (TFEQ) (Stunkard & Messick, 1985), and then they were weighed to the nearest 100 g and their height measured using a stadiometer. Finally, they were debriefed as to the full purpose of the study and paid £30.

Participants were seated at a table in a private booth within a larger room. Each test session started with (baseline) mood, alertness, hunger, fullness and thirst ratings, and the reaction time task. Next, participants were presented with the first course of their lunch (the preload), comprising a cheese sandwich served on a plate, and their allocated drink. Half of the drink had been poured into a drinking glass with half left in the bottle. The label on the bottle was clearly visible to the participant. The drink was served at a temperature of approximately 15°C. Participants were told that they would be given 10 minutes to consume the sandwich and exactly half of the drink (i.e. all of what was in the glass). After this first course, the plate was taken away and participants were then presented with the second course (the test-meal), comprising two 'snacks bowls', one containing corn chips and the other containing chocolate chip cookies broken into bite-sized pieces. Participants were told that they would be given access to the snacks for 10 minutes and that they should consume the snacks until they felt 'fully satisfied' and finish the remainder of the drink. When the 10 minutes had elapsed the bowls, drink bottle and drinking glass were taken away. The test session ended with completion of a second set of (post test-meal) mood, alertness, hunger, fullness and thirst ratings, and the reaction time task. The amounts of corn chips and cookies served (approximately 200 g of each to the nearest whole, bite-sized piece) and the

722 **Table 7**

723 Composition of the foods and drinks used in Study 3.

	Weight/volume	Energy, kcal	Fat, g	Carbohydrates (of which sugars), g	Protein, g	Salt, g
Cheese sandwich ^a	69 g	223	12.2	18.9 (2.0)	9.3	0.9
Corn chips ^b	200 g	1012	46.8	117.6 (1.8)	12.8	1.42
Chocolate chip cookies ^c	200 g	982	45.2	127.6 (67)	10.8	1.10
Still water ^d	500 ml	0	0	0	0	0
Carbonated water ^d	500 ml	0	0	0	0	0
Diet cola ^d	500 ml	1	0	0	trace	0
Sugar cola ^d	500 ml	210	0	54 (54)	0	0

724 The data are for the amounts (g, ml and kcal) served.

725 ^aComprising one slice of medium-sliced Kingsmill soft white bread (40 g), Sainsbury's British mild Cheddar cheese slices (24 g) and Lurpak
726 spreadable butter (5 g), purchased from Sainsbury's Supermarkets Ltd, UK).727 ^bDoritos Lightly Salted, Walkers Snack Foods Ltd, UK.728 ^cMaryland Chocolate Chip Cookies, Burton's Biscuits, UK.729 ^dThese were Sainsbury's Caledonian still Scottish water and Sainsbury's Caledonian carbonated Scottish water (Sainsbury's Supermarkets Ltd,
730 UK.), and Diet Coke and Classic Coca-Cola (The Coca-Cola Company), respectively, served in their labelled and branded, plastic bottles.

amounts remaining after the test-meal were weighed to the nearest 0.1 g in order to calculate the amounts consumed.

11.6. Data analysis

Data from all 51 participants who completed the study were included in all analyses. We calculated summary information (mean $\pm$ SD) on participants, including body weight, TEFQ scores, and hunger and thirst at baseline averaged across the four test sessions. We used one-factor repeated measures ANOVA to analyse the effect of drink on the primary outcome measures of sweet (chocolate chip cookies), savoury (corn chips) and total food intake (kcal). To test our primary (pre-specified) hypotheses we conducted paired-samples *t*-tests to compare the effects of still water versus diet cola on sweet and on savoury food intake. We also conducted a two-factor repeated measures ANOVA to test the interaction of the effect of Drink (still water versus diet cola) and Food (chocolate chip cookies versus corn chips) on energy intake. We conducted exploratory analyses on the effects of Drink on hunger, fullness and thirst (post-meal ratings minus pre-meal ratings, one-factor repeated measures ANOVAs). For ANOVA the Greenhouse-Geisser correction was applied where appropriate (adjusted *p* values are reported). Finally, we calculated Energy compensation (COMPX score (Gadah et al. 2016a)), for the energy-containing preload (sugar cola) versus the other preloads.

12. Results

Participant characteristics (mean $\pm$ SD) were as follows: age, 29.9 $\pm$ 11.8 years, weight 68.2 $\pm$ 11.2 kg, BMI 23.4 $\pm$ 3.6 kg/m². Mean $\pm$ SD baseline (pre-drink and meal) hunger, fullness and thirst ratings were respectively, 66.7 $\pm$ 17.6, 17.5 $\pm$ 14.0, 61.0 $\pm$ 16.6. Mean $\pm$ SD TFEQ scores were: Cognitive Restraint of Eating = 7.8 $\pm$ 4.8, Disinhibition = 6.6 $\pm$ 3.3, Hunger = 5.1 $\pm$ 3.1. Maximum possible scores on these factors are 21, 16 and 14, respectively.

Results for test-meal energy intake are shown in Table 8. There was a significant effect of Drink for chocolate chip cookie intake and total intake. In relation to our pre specified hypotheses, cookie (sweet food) intake was lower when diet cola was consumed compared with when still water was consumed ($t(50) = 2.33$, $p = .024$), whereas corn chip (savory food) intake did not differ ($t(50) = 0.06$, $p = .953$). The Drink (still water versus diet cola) by Food (cookies versus corn chips) interaction, however, was not significant ($F(1,50) = 2.14$, $p = .150$, partial $\eta^2 = .041$). Moreover, when compared with carbonated water, diet cola had a negligible effect on cookie intake (Table 8). Sugar cola had the largest effect on test-meal energy intake, predominantly due to lower cookie intake. Two-factor repeated measures ANOVA (Drink 4 levels and Food 2 levels) showed a significant main effect of drink ($F(1,50) = 5.55$, $p = .001$, partial $\eta^2 = .100$), but again not a significant drink by food interaction ($F(3,150) = 1.66$, $p = .179$, partial $\eta^2 = .032$).

There were significant Drink by Time interactions for hunger ($F(3,150) = 3.22$, $p = .024$, partial $\eta^2 = .061$) and fullness ($F(3,150) = 8.23$, $p < .0001$, partial $\eta^2 = .141$), but not thirst ($F < 1$). Mean ($\pm$ SE) changes (post test-meal minus baseline) in hunger for still water, carbonated water, diet cola and sugar cola were -55 $\pm$ 3, -64 $\pm$ 3, -63 $\pm$ 3 and -60 $\pm$ 3

respectively, for fullness they were 48 ± 4 , 65 ± 3 , 64 ± 4 and 66 ± 3 respectively, and for thirst they were -48 ± 4 , -50 ± 4 , -48 ± 4 and -49 ± 4 respectively. Energy compensation (COMPX score) in the test-meal for the energy consumed in the sugar cola preload versus the still water, carbonated water and diet cola preloads was 25%, 21% and 15%, respectively.

Table 8.

Study 3. Test-meal sweet (cookies) and savoury food (corn chips) intakes as a function of drink.

Drink	Cookies (kcal)	Corn chips (kcal)	Total (kcal)
Still water	162 ± 17	130 ± 14	292 ± 25
Carbonated water	150 ± 17	135 ± 14	285 ± 25
Diet cola	140 ± 14	131 ± 13	271 ± 24
Sugar cola	119 ± 18	121 ± 11	240 ± 24
Main effect of drink $F(3,150)$, p , partial η^2	5.07, .004, .092	0.87, .434, .017	5.55, .001, .100

Data are means $\pm$ SEs.

13. Discussion

The healthy weight, non-dieting participants were moderately hungry and thirsty (i.e., they were ready to eat and drink) when they were served the preload in this study. Furthermore, they consumed similar amounts of the two test-meal foods, namely the chocolate chip cookies and corn chips. There was partial support for our primary hypothesis that, consistent with generalisation of SSS, consumption of (sweet) diet cola compared with still water would reduce intake of the sweet food (cookies) significantly, but not affect the intake of the savoury food (corn chips). However, the drink by food interaction was not statistically significant. We conclude, therefore, that there is only weak evidence in favour of our primary hypothesis. Nonetheless, it is clear that consumption of the diet cola did not increase either sweet or savoury food intake.

Of course, the diet cola not only differed from still water in its sweetness (and flavour), it was also carbonated. The results for carbonated water showed that it was intermediate between still water and diet cola in its effects on both sweet food intake and total food intake (Table 7). Few studies appear to have investigated effects of carbonation on appetite (Pelchat, Bryant, Cuomo, Di Salle, Fass & Wise, 2014). One study found that carbonation reduced appetite and energy intake (Moorhead, Livingstone, Dunne & Welch, 2008). It found a dose-related effect of level of carbonation in an added sugar, orange-juice drink on hunger, fullness and test-meal energy intake, without an effect on thirst. The drink preload was served 10 minutes before the start of the ad libitum test meal. Other studies have found effects on appetite but not on food intake (Pelchat et al., 2014). The present results support an effect of carbonation on hunger and fullness, and an absence of an effect on thirst, in that hunger was lower, fullness higher and thirst the same after a meal (sandwich, cookies and corn chips) accompanied by consumption of 500 ml carbonated water compared with the same meal accompanied by consumption of 500 ml still water. Energy intake in this partly ad libitum meal, however, differed between these conditions by

only a negligible amount (7 kcal), showing a disconnection between the perception and/or reporting of hunger and fullness and energy intake. This disconnection is also evident from the effects of consuming the sugar-containing cola. As discussed below, total energy intake (sandwich, drink, cookies and corn chips) was highest in this condition, but hunger and fullness were not affected differently from the other carbonated drink conditions.

There is ample evidence from preload, test-meal studies that sugar consumed in a drink versus consumption of the equivalent (zero-calorie) drink sweetened with LCS reduces energy intake (Rogers et al., 2016). As participants were, in almost all these studies, blinded to the sweetener and energy content of the drink, this result implicates a post-oral mechanism for the effect on intake. Across studies, this effect averages 50% compensation for the energy content of the sugar-containing drink. In the present study, compensation was only 15% versus the LCS drink (diet cola), and 21% and 25% when compared, respectively, with the carbonated water and still water preloads. This lower compensation may have occurred, at least in part, because the drinks were consumed with the test-meal rather than 20 to 90 minutes before the test-meal which was the case in a large majority of previous studies. This delay likely maximises the detection of post-oral effects of sugar, on satiety (Gadah, Kyle, Smith Brunstrom & Rogers, 2016b).

Arguably, the procedure we used in the current study, whereby the drink was consumed with and throughout the meal is more naturalistic than consuming an entire drink 20 minutes or more before a meal, and also more naturalistic in that the identity of the drinks was fully apparent to participants. It is particularly noteworthy, therefore, that in this context energy compensation versus the LCS cola drink was minimal. That is, total energy intake comprising the sandwich, drink and ad lib cookies and corn chips was considerably greater (157 kcal) with the sugar cola drink than with the LCS cola drink. The 15% partial compensation may have been due to post-oral effects of the sugar, and/or conscious compensation based on the knowledge of having consumed some sugar or calories. Importantly, however, in this naturalistic context, the compensation fell a long way short of full or greater than full compensation. In other words, there was no 'conscious overcompensation' (Rogers, 2018), so consumption of LCS cola, carbonated water and still water all resulted in a net 'saving' of calories.

Whilst consumption of the drink was extended over a longer period in Study 3 than in Studies 1 and 2, it is likely that total oral exposure time was similar for these fluid stimuli (although we did not measure this), as this is determined primarily by the time required for preparation of an oral stimulus for swallowing. Oral exposure time influences satiation (e.g., de Graaf, 2012; Zijlstra, Mars, de Wijk, Westterp-Plantenga & de Graaf, 2008). Per ml or g this can be brief for fluid stimuli, which may limit the extent to which drinks compared with foods contribute to SSS. However, the difference between liquids and solids in oral exposure time per kcal may be less significant. Compare, for example, the energy density of drinking chocolate (<100 kcal/100g) with solid milk chocolate (>500 kcal/100g). Consequently, the satiating effect per kcal may not differ greatly between liquids and solids, at least for some stimuli. Consistent with this, we found similar satiating effects and similar compensation for 41 g sugar used to sweeten a drink (300 ml) versus jelly (250 ml) versus candy (100 ml) (Gadah et al., 2016b). In any case, for a drink sweetened with LCS, oral exposure time per kcal is very high, if not infinite (for a zero-kcal drink).

14. General discussion and conclusions

Taken together, the three studies reported here show that, compared with still water, consumption of a sweet drink reduced the pleasantness, desire for and intake of sweet food. The extent to which sweetness alone is responsible for these effects cannot be determined from our results, because the drinks differed on more dimensions than just sweetness. That is, the squash drinks were flavoured (blackcurrant in Study 1 and orange in Study 2), and in Study 3 the diet cola drink was (cola) flavoured and carbonated. The results of Study 2, nonetheless, indicate that sweetness was more important than flavour in bringing about a reduction in sweet food liking and desire to consume sweet food than was orange flavour, as the magnitude of the SSS effect did not differ between orange fruit and the other sweet foods. Furthermore, there was no generalisation of SSS to non-sweet foods.

On the other hand, in Study 3, compared with the effect of carbonated water, consumption of diet cola had only a small effect on sweet food intake. The potential importance of carbonation is underlined by the effect of carbonated water, which reduced hunger and increased fullness compared with still water. However, in this study this was not accompanied by a difference in food intake (cookies plus corn chips) between still and carbonated water. As far as we are aware, only one previous study has found an effect of varying carbonation on food intake (Moorhead et al., 2008). As such, this would seem to be worthy of further study. Not least because there is also a report that carbonation affects the neural processing of taste in a way that may make the experience of consuming LCS more similar to the experience of consuming sugar (Di Salle, Cantone, Savarese, Aragri, Prinster, Nicolai, Sarnelli, Iengo, Buyckx & Cuomo, 2013).

We did not compare water with just sweet water (i.e., LCS dissolved in water), because that is not how LCS are typically consumed. Similarly, our primary comparator for diet cola was still water, because still bottled water is consumed in much larger quantities than carbonated bottled water (The Business Research Company, 2018), and the alternative, more sustainable source of water, namely tap water, is also still.

From a public health perspective, national food-based dietary guidelines vary in respect as to whether LCS drinks are recommended as suitable alternatives to sugar-sweetened drinks, or whether water is the preferred alternative, including in relation to healthy weight-management (Borges et al., 2017). Relevant to this difference, our results demonstrate that consumption of LCS drinks compared with an equal volume of still water reduces desire for sweet food and, if anything, also reduces sweet food intake. This may help explain the finding reported by Piernas et al. (2013) that participants in the 6-month CHOICE intervention trial randomised to consume LCS drinks versus water reduced their energy intake from desserts and discretionary caloric sweeteners. However, relative to the water group the LCS group in that study also decreased their intake of fruits and vegetables, which is an undesirable outcome if a goal is to improve diet quality. Consistent with this, the present Study 1 showed a SSS effect (indexed by decreased desire to consume) for fresh apple fruit equal in magnitude to the SSS effect for apple juice and apple pie. In terms of potential effects on energy intake, however, it is worth noting that apple pie is considerably more energy dense than apple fruit.

A caveat to the possible benefit of LCS drinks versus water is that a weight loss study comparing LCS drinks and water found greater weight loss in participants randomised to water (Madjd, Taylor, Delavari, Malekzadeh, Macdonald & Farshchi, 2018; Madjd, Taylor, Delavari, Malekzadeh, Macdonald & Farshchi, 2015). This is different from results of three other studies (Peters, Beck, Cardel, Wyatt, Foster, Pan, Z., Wojtanowski, Vander Veur, Herring, Brill, & Hill, 2016; Maersk, Belza, Stodkilde-Jorgensen, Ringgaard, Chabanova, Thomsen, Pedersen, Astrup, & Richelsen, 2012; Tate, Turner-McGrievy, Lyons, Stevens, Erickson, Polzien, Diamond, Wang, & Popkin, 2012) making this comparison. Madjd et al. (2015; 2018), however, restricted their participants to consuming one daily LCS drink after lunch. This will have likely largely prevented the LCS drink from reducing consumption of sweet food in the diet via a SSS effect. Why consuming a rather small volume of LCS drink (250 ml, 5 times per week) should reduce weight loss is unclear, but the results suggest that this specific pattern of LCS intake might be best avoided.

Relatedly, the present Study 2 found no SSS effect extending to sweet foods 2 hours after consumption of a sweet drink (versus water). At the same time there was no evidence that the sweet drink led to a relative increase in desire to consume sweet foods after 2 hours. Other studies also find that longer-term, repeated exposure to sweet taste does not increase sweet taste preference (Appleton et al., 2018; Fantino et al., 2018). Together, these results clearly fail to support claims that exposure to sweetness causes a 'sweet tooth' or increased desire for sweetness (Ludwig, 2009; Mattes & Popkin, 2009; Yang, 2010;), rather, in the short term, at least, it reduces desire for sweet drinks and sweet foods.

Disclosure of potential competing interests

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