The association between sugar at breakfast and energy intake in people with or at high risk of type 2 diabetes: a within-person analysis of STAMP-2 data

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Abstract

Background: The role of nutrient timing in energy intake amongst people with dysglycaemia is understudied but could be a simple method to help regulate appetite. This study analysed within-person associations of sugar intake at breakfast and subsequent energy intake.

Methods: We used 4-day diet diary data from 147 participants (47 % men) encompassing 547 days of diet recording in the Sedentary Time and Metabolic Health in People with Type 2 diabetes project (STAMP-2). Linear two-level models were used to investigate within- (day-level) and between-person (participant-level) variation in total and post-breakfast energy intake according to skipping breakfast, low- (> 0-14.2 g) or high- (> 14.2 g) sugar intake at breakfast, adjusting for potential confounding or mediation.

Results: Post-breakfast energy intakes were observed to be lower after eating low- and high-sugar breakfasts (compared to skipping), but higher total energy intake was associated with eating a high-sugar breakfast. Compared to breakfast skipping, both low- and high-sugar breakfasts were strongly associated with lower post-breakfast energy intake (-178, 95 % confidence interval [CI] -261, -94 kcal/d; -151, 95 % CI -235, -67 kcal/d, respectively). However, compared to skipping breakfast, low-sugar breakfasts were weakly associated with higher total daily energy intake (64, 95 % CI -18, 146 kcal/d), whereas high-sugar breakfasts had a strong association (135, 95 % CI 52, 217 kcal/d). Post-breakfast energy intakes were similar between low- and high-sugar breakfast days (27, 95 % CI -53, 106 kcal/d), whilst total daily energy intake tended to be higher with high- (compared to low-) sugar breakfasts (70, -8, 149 kcal/d). We also observed evidence of energy compensation whereby 86 % of the extra energy consumed in a low-sugar breakfast was compensated for by reductions in post-breakfast energy intakes, compared to only 53 % after a high-sugar breakfast.

Conclusion: Overall, high-, but not low-, sugar breakfasts were associated with higher total daily energy intake when compared to breakfast skipping, despite a similar reduction in post-breakfast energy intake. We found evidence of poorer post-breakfast energy intake compensation with high-sugar breakfasts than low-sugar breakfasts. These findings suggest portion size may be important to consider in future breakfast research, with sugar being a proxy of portion size.

Key words: sugar; breakfast; energy intake; appetite; type 2 diabetes; sweet perception; energy balance; health

Introduction

Cross-sectional studies have suggested an inverse association between breakfast consumption and body mass (Brown *et al*., 2013). Longitudinally, a dose-response relationship has been shown, with higher percentage of energy from breakfast being associated with lower body weight gain over ~4 years (Purslow *et al.*, 2008). In contrast, meta-analyses of randomised trials report that skipping breakfast has null (Bohan Brown *et al*., 2020) or favourable (Bonnet *et al*., 2020; Sievert *et al*., 2020) effects for weight-loss compared to breakfast consumption. Such an effect may be driven by lower total daily energy intake when skipping breakfast (Sievert *et al*., 2020).

Discordance between the observational and experimental literature suggest confounding factors like higher education or SES (Purslow *et al*, 2008) could be influencing associations. Such factors, which are fixed at a person level, can be accounted for by using within-person analyses. For example, Kant and Graubard (2015) found when individuals consumed breakfast (compared to skipping), they also consumed higher total daily energy intake, in accordance with experimental research (e.g. Sievert *et al*., 2020).

The question of whether different nutrients consumed at breakfast influence energy intake has primarily focused on protein and fibre manipulations, particularly in healthy adults. However, public health guidelines specifically target a reduction in breakfast sugar (e.g. NHS, 2018), and the World Health Organization (2015) have recognised the role of sugar in energy intake as an important influence for type 2 diabetes (T2D) management. Considering breakfast is typically a carbohydrate-rich meal that incorporates high-sugar foods (Reeves *et al*., 2013), it is important to understand the appetitive effects of this eating pattern, particularly in populations with impaired metabolic health.

Previous research has shown that in those with obesity, fasting until noon did not result in lower energy intake compared to those consuming 700 kcal before 1100 h (Chowdhury *et al*., 2016). In contrast to the above meta-analyses (Bonnet *et al.*, 2020; Sievert *et al.*, 2020), this suggests in those with obesity, skipping breakfast results in incomplete compensation for energy eaten at breakfast in energy intake consumed later in the day. The effect of sugar at breakfast on later energy intakes has not specifically been investigated specifically in those with obesity or T2D; however, in healthy volunteers, no differences in energy intake have been found according to the sugar content of iso-caloric breakfasts (Carroll *et al*., 2020; Mattes, 1990).

In obesity and T2D, the hormonal response to food can be disrupted, potentially impacting appetitive responses. For example, whilst postprandial gluco-regulation is typically favourable in the morning compared to the evening in healthy adults (Morgan *et al.*, 2003), morning hyperglycaemia and hyperinsulinaemia can occur in those with T2D, known as the dawn effect (Bolli & Gerich, 1984; Carroll & Schade, 2005). This may impact appetite as the satiating properties of insulin (Verdich *et al.,*2001) are blunted in those with insulin resistance (Speechly & Buffenstein, 2000).

Thus, the aim of this study was to investigate whether (total) sugar at breakfast is associated with higher total- or post-breakfast energy intake in those at high risk of T2D (e.g. with obesity), or newly diagnosed with T2D. Due to potential ethical issues of feeding high-sugar loads to those with (suspected) dysglycaemia, we used observational methods to investigate this with a multilevel model to account for both within- and between-participant variation, reducing between-person confounding influences. We hypothesised that high-sugar breakfasts would be associated with higher total- and post-breakfast energy intake from incomplete compensation due to a dulled satiety response from insulin resistance.

Methods

Study design and population

This study is a secondary analysis of the Sedentary Time and Metabolic Health in People with Type 2 diabetes (STAMP-2) study, which was a cross-sectional observational study investigating behavioural and metabolic correlates of sedentary time in people at high risk of, or with newly diagnosed T2D. Participants were recruited from three UK NHS trusts, covering Bristol and Somerset via GP surgeries, adult obesity clinics, diabetes education days, and direct advertising. Two visits to a Clinical Research Unit were made by participants, separated by one week. During the first visit, demographic, anthropometric, and characteristic data were obtained, along with a fasted blood sample. Following this, participants wore an activity monitor (accelerometer) for seven days and completed an estimated (i.e. unweighed) food diary for four days concurrent with wearing the activity monitor. Equipment and data were then collected from the participants on the second clinical visit.

Inclusion criteria for those with newly diagnosed T2D were 5-12 months from clinical T2D diagnosis, body mass index (BMI) > 25 kg/m^2, no ketosis, and aged between 30-65 y. Inclusion criteria for those at risk of T2D were BMI > 35 kg/m^2, and aged between 30-65 y. Exclusion criteria for both groups were unstable angina, myocardial infarction within previous three months, and limited ability to do physical activity (e.g. current diabetic foot ulcer). In total, 178 participants (79 % with a T2D diagnosis) were included in the STAMP-2 study. All participants gave informed consent before participating. The research gained ethical approval from the South West-Central Bristol NHS Research Ethics Committee (ref: 13/SW/0187).

Measure of diet

Participants were instructed to report all food and drink including brand names and portion size estimations (such as household measures, weights from labels, and/or pictures) in a 4-day diet record. At least one of the four days was a weekend day. Food diaries were coded and analysed using Dietplan7 Pro dietary assessment software (Forestfield Software Limited, Horsham, UK). Diaries were coded by one expert coder and checked for accuracy and agreement by a second independent coder. If portion size information was not recorded, weights were assigned using appropriate portion size data from Food Standards Agency calculations (Wreiden and Barton, 2006) or from the manufacturer's data available online. The nutrient databases used were the Composition of Foods Integrated Dataset, 2015 (Public Health England, 2015), food composition data from the 2002 UK National Diet and Nutrition Survey (Henderson *et al.*, 2002) and from Pepsico International.

Within the STAMP-2 dataset, eating occasions were recorded in time slots throughout the day: 0600-0900 h, 0900-1200 h, 1200-1400 h, 1400-1700 h, 1700-2000 h, 2200-0600 h, with corresponding meal numbers. We defined breakfast as: "participant-defined 'meal 1' if it occurred during the timeslots of 0600-1200 h, and contained ≥ 50 kcal", which captures the first meal of the day in the morning a common method for defining breakfast, whilst minimising the inclusion of those who delay their first meal after waking. Other possible definitions of breakfast were considered and some were investigated; a full rationale for the choice of breakfast definition can be found in Supplementary Material S1.

Sugar in this study was defined as total sugar (including milk sugars) as reported in the STAMP-2 dataset (i.e. the sum of all types of sugar). Sugar at breakfast was heavily positively skewed so three sugar at breakfast categories were created: 'breakfast skipper', 'low sugar breakfast', and 'high sugar breakfast'. The breakfast skipper category was defined as consuming ≤ 50 kcal at breakfast, similar to previous breakfast research (e.g. Betts *et al.*, 2011). Low (≤ 14.2 g) and high (> 14.2 g) sugar categories were based on a median split of sugar at breakfast after excluding days in the breakfast skipping category. By these definitions, participants in the skipping, low-, and high-sugar at breakfast groups were consuming a median, interquartile range (IQR) 1 (0, 4) %, 14 (9, 18) %, and 29 (21, 42) % of their daily sugar intake at breakfast, respectively.

Energy intake was investigated in two ways. Firstly, total energy intake was investigated to understand whether sugar at breakfast was associated with total daily energy intake. Secondly, post-breakfast energy intake was calculated by subtracting breakfast energy intake from total energy intake to understand whether sugar was associated with higher energy consumption later in the day (i.e. independent of breakfast intake).

Anthropometry

Height and body mass were measured wearing light clothes with no shoes, using a stadiometer (to the nearest 0.1 cm; Seca 220, Hamburg, Germany) and digital scales (to the nearest 0.1 kg), respectively. Body fat percentage was measured using bioelectrical impedance.

Physical activity

Participants in the STAMP-2 study were asked to wear an accelerometer (ActiGraph GT3X+ or Actigraph GT1M [n = 12 participants]), Actigraph, Florida, USA) around their waist for seven consecutive days, removing devices for sleep, swimming and bathing. All data were processed using Kinesoft software (version 3.3.62; Kinesoft, Saskatoon, SK, Canada) to generate variables representing total physical activity (total daily accelerometer counts divided by total daily wear time in minutes; counts per minute [cpm]) and proportion of time spent in different physical activity intensities defined using standard thresholds (sedentary: < 100 cpm; light: 100-1951 cpm; moderate to vigorous physical activity [MVPA]: ≥ 1,952 cpm; Freedson *et al*., 1998).

Energy intake reporting

To account for energy intake misreporting, a ratio EI:EER was computed of reported energy intake to estimated energy requirements, based on the Institute of Medicine equations (Institute of Medicine, 2005). Upper and lower confidence limits for EI:EER were then calculated assuming energy balance i.e. EI:EER = 1 and under-, plausible-, and over-reporting ranges were set within 1 SD of 1, using equations from Mendez *et al.* (2011) to compute an SD in EI:EER. Accordingly, a EI:EER of 0.86 to 1.14 was deemed 'plausible' and anything below or above this range was deemed 'under-' or 'over-reporting', respectively. Participants were categorised according to their EI:EER into the relevant reporter category and this was included in the regression models as a dummy variable with under-reporter as the reference category (Tooze *et al*., 2016).

Statistical analyses

Descriptive statistics

Descriptive data are divided into person-level and day-level. Normality was checked visually via histograms, PP-plots, and QQ-plots. Due to the skewed distribution of several variables, median and interquartile ranges (IQR) were used to describe all the data for consistency. Overall averages are presented, as well as averages being split by the three sugar at breakfast categories as described above. Mann-Whitney U, *t*-tests, analysis of variance (ANOVA), Kruskal-Wallis, and χ^2 were used to determine differences between the three breakfast groups, as appropriate.

Multilevel model

The primary research questions of these analyses were: (i) is the amount of sugar eaten at breakfast associated with greater total daily energy intake, and (ii) is the amount of sugar eaten at breakfast associated with greater post-breakfast energy intake. To adjust for data clustering and to estimate within- and between-participant associations, multilevel modelling specifying a random intercept was used. There were two levels within the data: day-level (level 1) and person-level (level 2), therefore associations estimate the total or post-breakfast energy intake on days where participants had skipped breakfast or consumed low- or high-sugar breakfasts.

Theoretical associations between the available variables and the primary predictor and outcome variable were mapped to ascertain which variables to include in the regressions and in what order. Models were adjusted at the day level for fibre (g/1000 kcal), physical activity (counts/min), and day of week (weekend/weekday); and at the person level for sex (male/female), age, ethnicity (white/non-white), smoking (yes/no), body fat percentage, glycated haemoglobin (HbA1c), homeostatic model assessment-insulin resistance (HOMA-IR), index of multiple deprivation (IMD), and reporter category (under-, plausible and over-reporter).

The three sugar at breakfast categories (breakfast skipper, low-, and high-sugar breakfast) were entered as dummy variables with breakfast skipper as the reference category (i.e. for the comparisons of breakfast skipping *versus* low sugar breakfasts, and breakfast skipping *versus* high-sugar breakfasts). To gain insight into the possible dose-response a second model was run with low sugar at breakfast as the reference category (i.e. for the remaining comparison of low- *versus* high-sugar breakfasts). A linear trend was tested for both total daily, and post-breakfast energy intake. In order to do this, a pseudo-continuous breakfast variable was created using the average sugar at breakfast intakes from the three breakfast categories, and the unadjusted multilevel model was re-run. A likelihood ratio test was then used to compare the fit (indicated by the -2 log likelihood) of the pseudo-continuous model to the categorical model. The intra-class correlation was calculated by dividing between-participant variance by total variance and multiplying by 100, representing the percent variation of energy intake that is explained by differences between participants.

Post-hoc (unplanned) analyses

We additionally investigated post-breakfast energy compensation based on the equation by Kral *et al.* (2012):

$$\text{Post-breakfast energy intake compensation} = (\text{PostBF-EI}_{diff} / \text{Total-EI}_{diff}) \times 100$$

Where PostBF-EI_{diff} is the difference in post-breakfast energy intake compared to breakfast skipping breakfast, and Total-EI_{diff} is the difference in total daily energy intake compared to breakfast skipping. Data were obtained from the most adjusted multilevel models for both low- and high-sugar breakfasts.

After running the above analyses, further questions arose and were explored. Firstly, we included energy consumed at breakfast as a day-level variable into the models to understand whether the results were due to total energy consumed at breakfast rather than the sugar consumed at breakfast *per se*. Secondly, we aimed to test whether consuming sugar at breakfast was associated with higher consumption of sugar later in the day as some literature has alluded to (e.g. the priming effect; Cornell *et al.*, 1989); accordingly we ran the same models as the planned analyses, but with total and post-breakfast sugar intake as the dependent variables. Additional sensitivity analyses were run to assess the impact of the breakfast definition used on associations observed (details in Supplementary Material S1). All analyses were run using Stata (StataCorp MP, version 13 and version 16).

Results

Descriptive data

A total of 147 participants were included in these analyses, encompassing 547 days of diet recording (Figure 1). The median (interquartile range; IQR) age of the sample was 56 (50, 63) years with an average BMI of 33.3 (29.2, 38.7) kg/m^2 (Table 1), and 47 % of the sample were men (Table 2). One-hundred and fifty-five days were categorised as 'skipping breakfast', 197 days were 'low-sugar breakfasts', and 195 days were 'high-sugar breakfasts' (Table 3). In total, 14 (10 %) participants skipped breakfast on all recording days, 17 (12 %) participants ate breakfast on all days, and the remainder (n = 116, 79 %) varied day to day. Demographic and participant characteristic data did not appear to be substantively different in those included *versus* excluded from the analyses (Supplementary Material Table S1). In this sample, 80 % of respondents were considered under-reporters, 14 % plausible-reporters, and 6 % over-reporters.

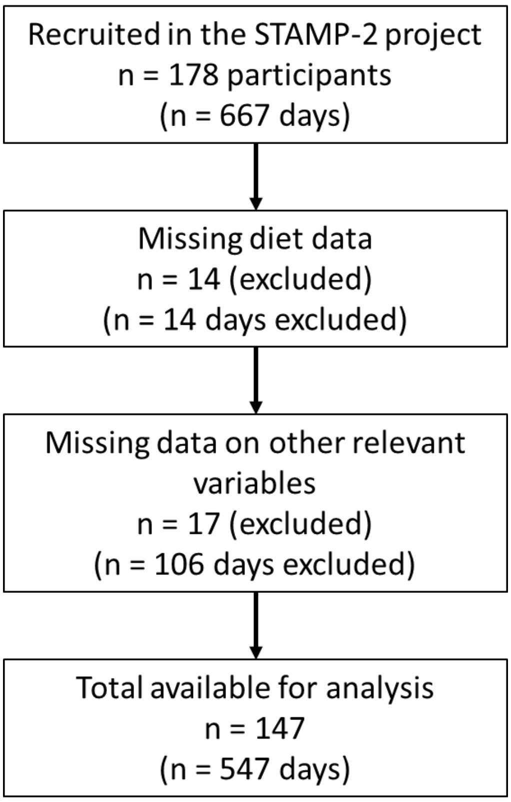

Figure 1. Flow chart of participants and days included in the analyses

Table 1. Average (median, interquartile range) person-level demographic characteristics (continuous variables)

	n	Median (IQR)	Sugar at breakfast category[1] Breakfast skipper n = 28	Low sugar n = 71	High sugar n = 48	*p* for difference
Sugar at breakfast (g/d)[2]	147	11 (3, 17)	1 (1, 2)	9 (4, 12)	21 (17, 31)	< 0.001*†‡
Age (y)[2]	147	56 (50, 63)	59 (48, 64)	56 (52, 62)	56 (50, 63)	0.959
BMI (kg/m^2)[2]	147	33.3 (29.2, 38.7)	36.2 (30.6, 39.6)	33.3 (29.6, 38.1)	31.8 (26.9, 38.0)	0.342
Body fat %[2]	147	39.6 (30.7, 47.3)	44.9 (36.3, 50.7)	40.4 (31.4, 47.4)	35.3 (28.7, 43.8)	0.006†
Fasting glucose concentration (mmol·L^{-1})[2]	147	6.4 (5.6, 7.5)	6.2 (5.4, 7.3)	6.4 (5.7, 7.3)	6.7 (5.7, 7.8)	0.664
HbA1c (%)[2]	147	6.4 (5.9, 7.0)	6.3 (5.9, 7.0)	6.3 (5.9, 6.9)	6.6 (5.9, 7.2)	0.469
HOMA IR[2]	147	2.2 (1.5, 3.1)	2.0 (1.5, 2.9)	2.2 (1.5, 3.2)	2.2 (1.7, 2.9)	0.768
T2D duration (months)[2]	116	7 (5, 10)	8 (6, 10)	7 (5, 11)	7 (5, 10)	0.736
Fibre (g/1000 kcal)[3]	147	12 (10, 15)	12 (8, 15)	12 (10, 15)	12 (10, 14)	0.246
Total energy intake (kcal/d)[3]	147	1698 (1403, 2080)	1510 (1227, 1952)	1643 (1361, 1982)	1854 (1617, 2281)	0.033
Post-breakfast energy intake (kcal/d)[3]	147	1499 (1207, 1839)	1487 (1191, 1898)	1449 (1140, 1778)	1540 (1352, 1874)	0.290
Total daily sugar intake (g/d)[2]	147	72 (47, 98)	58 (37, 94)	69 (44, 85)	96 (63, 111)	< 0.001†‡
Post-breakfast sugar intake (g/d)	147	60 (40, 80)	56 (35, 87)	58 (39, 73)	63 (47, 85)	0.236
PA (counts/min)[2]	147	258 (177, 354)	234 (162, 307)	242 (169, 354)	279 (198, 383)	0.172
Sedentary (%)[3]	147	64 (57, 70)	64 (57, 73)	64 (58, 71)	65 (59, 70)	0.850
Light (%)[3]	147	33 (27, 39)	34 (25, 40)	34 (26, 38)	32 (27, 39)	0.980
MVPA (%)[2]	147	2 (1, 4)	2 (0, 3)	2 (1, 4)	3 (1, 5)	0.022†
IMD score[2]:	147	13.2 (9.4, 23.4)	10.1 (7.9, 17.9)	15.1 (9.3, 23.3)	13.3 (10.2, 27.2)	0.128
Lower deprivation[2]	78	9.7 (6.6, 11.2)	9.2 (7.6, 10.4)	8.8 (6.5, 10.5)	10.4 (5.6, 12.0)	0.276
Higher deprivation[2]	69	23.8 (17.7, 32.6)	28.7 (21.7, 36.4)	22.1 (16.7, 31.0)	28.9 (19.3, 33.5)	0.214
EI:EER[3]	147	0.67 (0.53, 0.81)	0.67 (0.48, 0.80)	0.63 (0.51, 0.81)	0.68 (0.59, 0.81)	0.589

Abbreviations: BMI, body mass index; EI:EER, energy intake:energy expenditure; HbA1c, glycated haemoglobin; HOMA-IR, homeostatic model assessment-insulin resistance; IMD, Indices of Multiple Deprivation; IQR, interquartile range; MVPA, moderate-to-vigorous physical activity; PA, physical activity; T2D, type 2 diabetes

[1]Breakfast categories created based on the median split of sugar at breakfast in the day-level data after excluding when breakfast was skipped, using averaged (median) dietary data across 3-4 days to create person-level data

[2]Comparisons using Kruskall-Wallis with post-hoc Dunn-Bonferroni correction

[3]Comparisons using ANOVA with post-hoc Bonferroni correction

*Difference between breakfast skippers and low sugar at breakfast ($p < 0.001$)

†Difference between breakfast skippers and high sugar at breakfast ($p \leq 0.014$)

‡Difference between low and high sugar at breakfast ($p < 0.001$)

Table 2. Average (median, interquartile range) person-level demographic characteristics (categorical variables)

	n	% sample	Sugar at breakfast category			*p* for difference
			Breakfast skipper n (%) sample	Low sugar n (%) sample	High sugar n (%) sample	
Sex[1]: Women	78	53	20 (15)	35 (38)	23 (26)	
Men	69	47	8 (13)	36 (33)	25 (23)	0.095
Ethnicity: White	140	95	28 (20)	68 (49)	44 (31)	
Non-white	7	5	0 (0)	3 (43)	4 (57)	0.247
Smoking: Current smoker	15	10	5 (33)	7 (47)	3 (20)	
Current non-smoker	132	90	23 (17)	64 (48)	45 (34)	0.270
Diabetes medication use:						
Yes	54	37	7 (13)	28 (52)	19 (35)	
No	93	63	21 (23)	43 (46)	29 (31)	0.359
Under-reporter	87	59	17 (20)	44 (51)	26 (30)	
Plausible-reporter	37	25	7 (19)	17 (46)	13 (35)	
Over-reporter	23	16	4 (17)	10 (43)	9 (39)	0.930

All data analysed using Chi Square

[1]Energy-adjusted

Table 3. Average (median, interquartile range) breakfast and day level characteristics

	n	Days when breakfast was skipped	n	Days with low sugar at breakfast	n	Days with high sugar at breakfast	*p* for difference
Sugar at breakfast (g/d)[1]	155	1 (0, 2)	197	8 (4, 11)	195	24 (19, 34)	< 0.001*†‡
% daily sugar from breakfast[1]	155	1 (0, 4)	197	14 (9, 18)	195	29 (21, 42)	< 0.001*†‡
Breakfast energy intake (kcal)[1]	155	8 (0, 16)	197	207 (166, 316)	195	284 (222, 406)	< 0.001*†‡
Breakfast quantity (g)[1]	155	260 (252, 300)	197	446 (335, 584)	195	543 (413, 700)	< 0.001*†‡
Breakfast energy density (kcal/g)[1]	155	0.04 (0.00, 0.06)	197	0.51 (0.36, 0.84)	195	0.55 (0.43, 0.79)	< 0.001*†
Breakfast water (mL)[1]	155	257 (250, 292)	197	379 (283, 529)	195	432 (340, 609)	< 0.001*†‡
Breakfast carbohydrate (% BFE)[1]	102	42 (40, 57)	197	62 (50, 72)	195	70 (62, 78)	< 0.001*†‡
Breakfast fibre (g/100 kcal)[1]	155	0 (0, 0)	197	1 (1, 2)	195	2 (1, 2)	< 0.001*†
Breakfast fat (% BFE)[1]	102	30 (7, 33)	197	26 (15, 40)	195	17 (11, 27)	< 0.001*†
Breakfast saturated fat (% BFE)[1]	102	18 (0, 24)	197	9 (5, 13)	195	6 (4, 10)	< 0.001†‡
Breakfast protein (% BFE)[1]	102	34 (23, 40)	197	17 (12, 20)	195	15 (12, 19)	< 0.001*†‡
Total daily energy intake (kcal/d)[2]	155	1547 (1218, 2033)	197	1642 (1298, 1980)	195	1826 (1551, 2292)	0.001†‡
Post-breakfast energy intake (kcal/d)[2]	155	1543 (1203, 2021)	197	1368 (1067, 1739)	195	1541 (1233, 1959)	0.007*
Total daily sugar (g/d)[1]	155	64 (38, 95)	197	59 (40, 80)	195	92 (67, 118)	< 0.001†‡
Post-breakfast sugar intake (g/d)[1]	155	62 (38, 92)	197	53 (32, 72)	195	63 (41, 89)	< 0.001*‡
Total daily fibre (g/1000 kcal)[2]	155	11 (8, 15)	197	12 (9, 15)	195	12 (9, 15)	0.219
Physical activity: Counts/min[1]	155	235 (163, 331)	197	253 (160, 357)	195	269 (181, 380)	0.146
% time sedentary[1]	155	64 (55, 71)	197	65 (57, 73)	195	64 (56, 71)	0.751
% time light activity[1]	155	33 (26, 42)	197	32 (25, 40)	195	33 (26, 39)	0.339
% time moderate to vigorous activity[1]	155	2 (0, 3)	197	2 (1, 5)	195	2 (1, 5)	0.057
Day of week:	n	%	n	%	n	%	
Monday[3]	13	8	11	6	10	5	0.410
Tuesday[3]	21	14	20	10	15	8	0.199
Wednesday[3]	29	19	34	17	31	16	0.786
Thursday[3]	29	19	35	18	47	24	0.251
Friday[3]	27	17	45	23	41	21	0.453
Saturday[3]	26	17	35	18	29	15	0.736
Sunday[3]	10	6	17	9	22	11	0.285

Abbreviations: BFE, breakfast energy intake

Energy density includes fluids as a potential proxy for breakfast skippers perhaps consuming fluids < 50 kcal in the defined breakfast period

*Difference between breakfast skipping and low sugar at breakfast ($p \leq 0.004$)

†Difference between breakfast skipping and high sugar at breakfast ($p \leq 0.001$)

‡Difference between low and high sugar at breakfast ($p \leq 0.026$)

[1]Comparisons using Kruskal-Wallis with post-hoc Dunn-Bonferroni correction
[2]Comparisons using ANOVA with post-hoc Bonferroni correction
[3]Comparisons using Chi square

Across sugar at breakfast categories, there were few person-level differences: age, IMD score, ethnicity, smoking status, fibre intake, physical activity, BMI, fasting glucose concentration, HbA1c, HOMA-IR, T2D duration, and T2D medication use were all similar between breakfast categories (Tables 1 and 2). Body fat percentage was highest in breakfast skippers (45 % skippers *versus* 40 % low sugar *versus* 35 % high sugar; p = 0.006). Unadjusted total daily energy intake was highest in those consuming a high sugar breakfast, but post-breakfast energy intake was comparable across the three categories (Table 1 and Figure 2). Similarly, total daily sugar intake was lowest in the breakfast skipping group, with no clear differences in post-breakfast sugar intake (Table 1). Breakfast composition varied between days when breakfast was skipped, and days when it had low- and high-sugar (Table 3). Percentage of energy from carbohydrates was highest in the high sugar breakfast days (70 % compared to 42 % on days when breakfast was skipped and 62 % on the low-sugar days; $p < 0.001$), whilst percentage of energy from fat, saturated fat, and protein were lowest on the high sugar breakfast days and highest in the skipped breakfast days (Table 3).

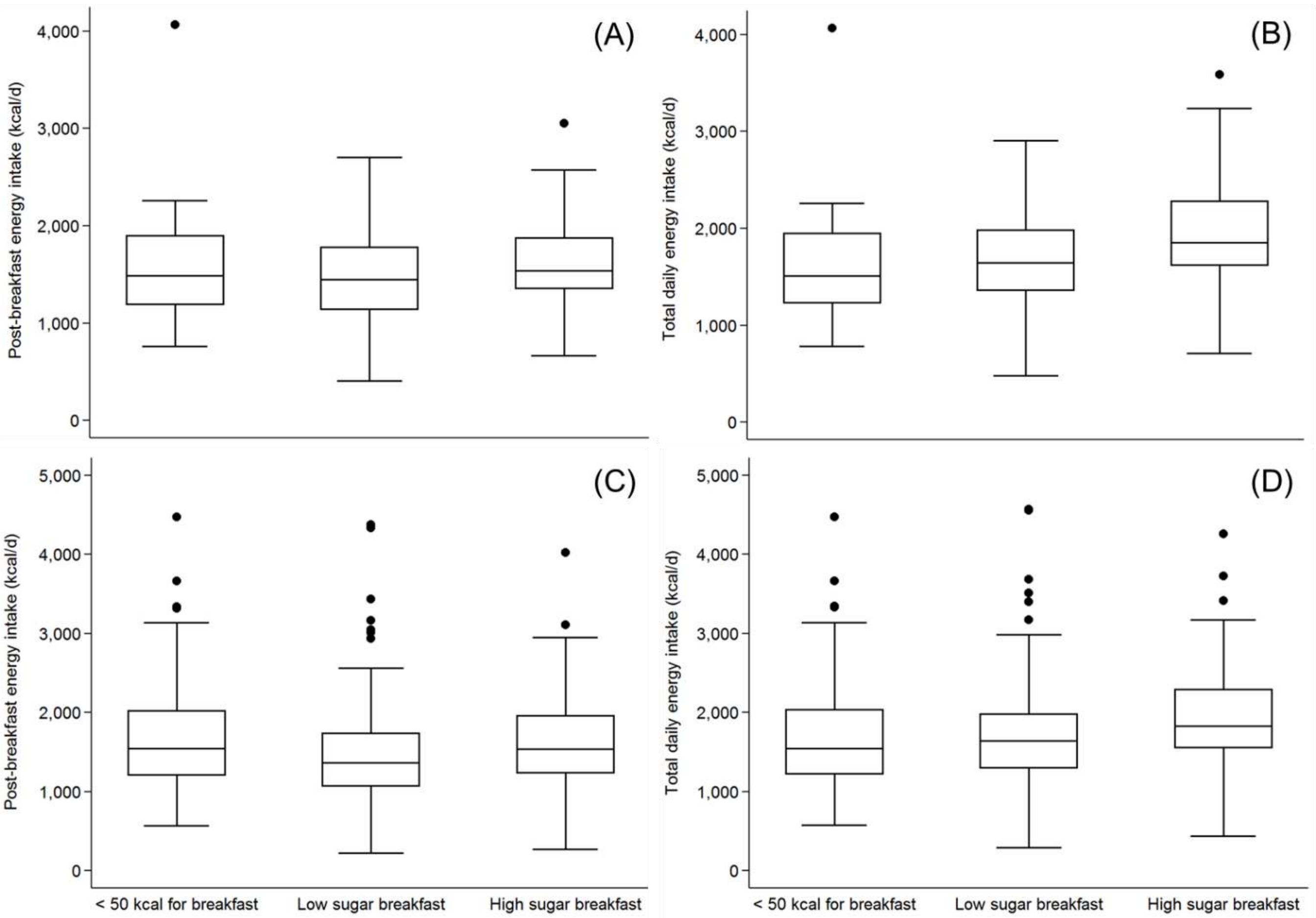

Figure 2. Unadjusted box plots of the relationship between categories of sugar intake at breakfast and post-breakfast and total daily energy intake at the person-level (Fig 3A, 3B) and day-level (Fig 3C, 3D)

Multilevel model

The intra-class correlation showed 42.6 % of variation in total daily energy intake was between-participants i.e. some people eat more than others on average, whereas 57.4 % was within participants i.e. explained by differences in energy intake day to day (Supplementary Material Table S2). Post-breakfast energy intake between person variation was 35.2 %, with 64.8 % of the variation within people (Supplementary Material Table S2).

In the unadjusted model (Table 4, model 1.1), compared with breakfast skipping, on days when low- or high-sugar breakfasts were consumed, total daily energy intake was 70, (95 % CI -53, 194) kcal/d and 151, (95 % CI 27, 275) kcal/day higher. Similarly after adjustment, compared with breakfast skipping, on days when low- or high-sugar breakfasts were consumed, total daily energy intake was 64 (95 % CI -18, 146) kcal/day and 135 (95 % CI 52, 217) kcal/day higher (Figure 3). Therefore, evidence of association for high-, but not low-sugar breakfasts with higher total energy intake was consistent before and after adjustment (Table 4, model 3.0). Test for departure from a linear trend suggested a linear trend for total daily energy intake (p = 0.996). Dose-response analysis comparing consuming a low- to a high-sugar breakfast, found an extra 70, (95 % CI -8, 149) kcal/d were consumed in total, which is similar in magnitude to low-sugar breakfast vs. skipping but the confidence intervals suggest lack of evidence of association for these less extreme comparisons.

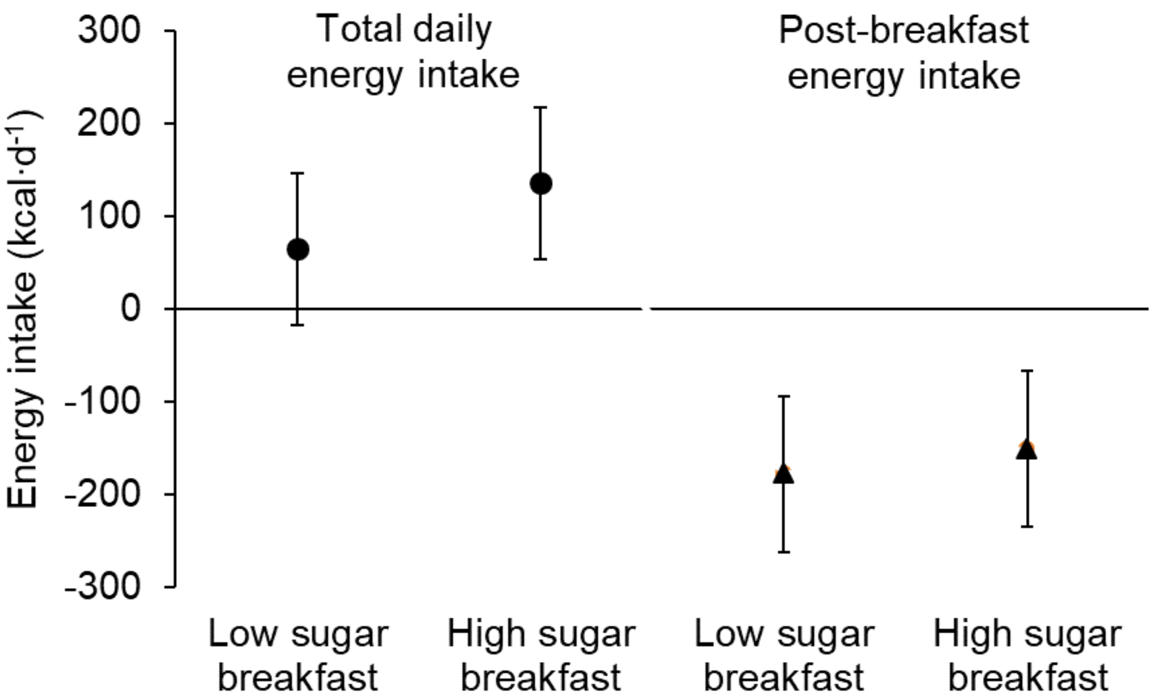

Figure 3. Difference in total and post-breakfast energy intake in low and high sugar breakfast days compared to skipping breakfast. Error bars are 95 % confidence intervals of the beta coefficients

Table 4. Multilevel modelling of sugar at breakfast categories and total/post-breakfast daily energy intake

Model	Intercept	β	95 % CI	*p*	Intercept	β	95 % CI	*p*
	Total daily energy intake (kcal)				Post-breakfast energy intake (kcal)			
	Low sugar at breakfast compared to skipping breakfast				Low sugar at breakfast compared to skipping breakfast			
1.0	1768	-	-	-	1557	-	-	-
1.1	1689	70	-53, 194	0.263	1670	-177	-300, -54	0.005
2.0	1200	46	-41, 132	0.303	1032	-197	-285, -109	< 0.001
3.0	1450	64	-18, 146	0.125	1300	-178	-261, -94	< 0.001
	High sugar at breakfast compared to skipping breakfast				High sugar at breakfast compared to skipping breakfast			
1.1	1689	151	27, 275	0.017	1670	-139	-262, -15	0.028
2.0	1200	117	30, 204	0.008	1032	-169	-257, -81	< 0.001
3.0	1450	135	52, 217	0.001	1300	-151	-235, -67	< 0.001
	High compared to low sugar at breakfast				High versus low sugar at breakfast			
1.1	1759	81	-39, 201	0.187	1493	38	-81, 157	0.533
2.0	1246	72	-12, 155	0.092	835	28	-56, 112	0.519
3.0	1515	70	-8, 149	0.080	1123	27	-53, 106	0.514

Breakfast skipping n = 155 days; low sugar breakfast n = 197 days; high sugar breakfast n = 195 days. Abbreviations: CI, confidence interval

Model 1.0: null intercept model with no predictors, to explore the extent to which differences in energy intake (total or post-breakfast) were bigger between *versus* within people

Model 1.1: unadjusted random intercept model

Model 2.0 (person-level): model 1.1 + sex, age, ethnicity (white or non-white), smoking status (current smoker or non-smoker), body fat (%), HbA1c (%), HOMA-IR, reporter category (under-, plausible-, or over-reporter) + IMD score

Model 3.0 (day-level): model 2.0 + physical activity (counts/min), day of week (weekday or weekend) + fibre (g/1000 kcal)

Post-breakfast energy intake decreased non-linearly when more sugar was consumed at breakfast (Table 4). In unadjusted models (model 1.1), compared with breakfast skipping, eating a low-sugar breakfast was associated with eating fewer post breakfast kcal (-177 (95 % CI -300, -54 kcal/day). The association was similar after adjustment (-178, 95 % CI -261, -94 kcal/day) (Table 4). Similarly, but to a lesser extent, eating a high-sugar breakfast was associated with eating fewer post breakfast kcal (-139 (95 % CI -262, -15) kcal/day) compared with days when breakfast was skipped (model 1.1). Again, the association remained after adjustment (-151, 95 % CI -235, -67 kcal/day). Unlike total daily energy intake, post-breakfast energy intake was similar after high- compared to low-sugar breakfasts (27, 95 % CI -53, 106 kcal/d) (Table 4), which has important implications for evidence of compensatory adjustments for ‘extra’ energy consumed at breakfast. Test for departure from a linear trend showed that post-breakfast energy intake did not change in proportion to an increasing amount of sugar consumed at breakfast (p = 0.037).

<u>Post-hoc (unplanned) analyses</u>

When calculating energy compensation, we found 85 % of the extra energy consumed in a low sugar breakfast was compensated for by reductions in post-breakfast energy intakes. Comparatively, when consuming a high-sugar breakfast, only 53 % of the extra energy at breakfast was compensated for by reductions in post-breakfast energy intake.

We investigated the relationship between sugar at breakfast and total sugar intake, and found eating a low-sugar breakfast was associated with a small reduction of -8 (95 % CI -16, -0) g/d in total daily sugar intake *versus* breakfast skipping (Supplementary Material Table S3). Further, a high-sugar breakfast was associated with higher total daily sugar intake when compared to skipping breakfast (14, 95 % CI 7, 22 g/d) or a low-sugar breakfast (22, 95 % CI 15, 30 g/d) (Supplementary Material Table S3). Compared to breakfast skipping, consumption of a low- (-15, 95 % CI -23, -8 g/d) or high- (-10, 95 % CI -18, -3 g/d) sugar breakfast was associated with lower post-breakfast sugar intake (Supplementary Material Table S3). Post-breakfast sugar intake was similar on days when low- vs. a high-sugar breakfast was consumed (5, 95 % CI -2, 12 g/d), supporting a non-linear trend (i.e. post-breakfast sugar intake does not reduce in proportion to the amount of sugar consumed at breakfast. This challenges the idea of compensation for eating sugar at breakfast by reducing intake later in the day.

Adjusting for total breakfast energy intake resulted in the same coefficients for both total- and post-breakfast energy intake, with all breakfast comparisons resulting in null associations (Supplementary Material Table S6). Descriptive information regarding the sensitivity analyses exploring different breakfast definitions can be found in Supplementary Material Table S4, and breakfast energy and sugar composition can be found in Supplementary Material Table S5. Results from the sensitivity analyses exploring different definitions of breakfast are summarised in the Supplementary Material (Table S6). Overall, definitions did not meaningfully change the associations described above.

Discussion

Our within-person analysis of people at high risk of, or with newly diagnosed T2D, found that that eating a low-sugar breakfast displaced some energy intake after breakfast but total daily energy intake was similar to a day when breakfast was skipped. Similar to eating a low-sugar breakfast, eating a high-sugar breakfast displaced some energy after breakfast, but the reduction in post-breakfast intake was smaller than the extra energy eaten at breakfast itself. Thus, overall, energy consumed after a high-sugar breakfast was associated with less adequate energy intake compensation compared to low-sugar breakfasts, resulting in higher total energy intake *versus* breakfast skipping, in line with our hypothesis. The higher total daily energy intake after a high-sugar breakfast appears to be driven by the higher energy content of high-sugar breakfast meals. Accordingly, breakfast size, rather than simply skipping or consuming may be an important factor to consider in breakfast research, with sugar content of breakfast being a marker of breakfast energy content.

In our exploratory (post-hoc) analyses, when comparing the amount of extra energy eaten in total on a high-sugar breakfast day to the amount of extra energy consumed in breakfast itself (151 kcal vs. 276 kcal), the increase in total energy intake is less than expected under the assumption of no compensation (i.e. breakfast energy added to total energy intake and does not displace energy consumed later in the day). Similarly, total energy intake only increased by 70 kcal on a low-sugar breakfast day when an extra 199 kcal was eaten at breakfast. Thus, our results offer some evidence of incomplete compensation; i.e. that post-breakfast energy intakes are displaced somewhat, but not entirely, by eating energy in the morning, such that total energy intake is not as high as expected after a high-sugar breakfast under the assumption of no compensation. However, the evidence of a non-linear trend in the association of increasing sugar at breakfast with similar reductions in post-breakfast intakes suggests that compensatory changes may get worse as breakfast size (or sugar content) increases.

Our exploratory analyses further examined whether the association between sugar at breakfast and energy intake was due to the energy consumed at breakfast. Across all three comparisons, the amount of sugar consumed at breakfast was not associated with differing total daily energy intake once energy intake at breakfast was held constant in the model. These results suggest that our main findings are explained by energy consumed at breakfast rather than the sugar *per se*; in other words, higher sugar at breakfast was a proxy of greater energy consumed at breakfast. Taken together these findings suggest that high energy breakfasts are associated with slightly higher total daily energy intake compared to skipping breakfast or having a small (low-sugar) breakfast. In other words, the energy consumed at a large breakfast is compensated for less adequately by a reduction in energy eaten post-breakfast. Whilst not directly assessed, our within person models may suggest that erratic patterns (where some days breakfast is eaten and other days not) may result in net overconsumption over longer time periods (assuming that energy needs are being met on days when breakfast is skipped).

Breakfast is often viewed as the 'most important' meal of the day, with seemingly widely accepted wisdom that breakfast can reduce subsequent energy intake by increasing satiety at subsequent meals (Brown *et al*., 2013; Gwin and Leidy, 2018). Our findings suggest larger (higher sugar) breakfasts may actually be associated with higher total daily energy intake, which may not have the benefits for energy balance and weight gain that are generally expected from cross-sectional observational evidence. Many recent breakfast randomised controlled trials used a large breakfast compared to breakfast skipping (e.g. Betts *et al*., 2014; Carroll *et al*., 2020; Chowdhury *et al*., 2016) to study the appetite, energy balance, and health effects of breakfast, and found breakfast eating did not lead to notably different weight change than breakfast skipping. However, these trials may be missing appetitive effects that occur with a smaller portion breakfast. As such, future trials could explore a possible causal explanation of our findings by including a lower energy breakfast arm in light of our findings.

Whilst our findings are likely related to the increase in energy from the high-sugar breakfast, it is noteworthy that the average total daily energy difference between the low- and high-sugar breakfasts was 70 kcal. However, the average difference in sugar content was 64 kcal (~16 g). In other words, the increase in energy at breakfast almost matches energy from sugar. As both quantity (g) of the breakfast, and water content of the breakfast also increased, it may be that the extra breakfast energy is from high sugar fluids, though this was not investigated directly. Thus future research should investigate whether liquid breakfast energy may be a contributory factor to higher total daily energy intake.

We additionally explored whether sugar at breakfast had any relation to post-breakfast and total-daily sugar intake. Compared to skipping breakfast, low-sugar breakfasts were associated with lower post-breakfast (-15 g/d) and total-daily (-8 g/d) sugar intake; whereas high-sugar breakfasts were associated with lower post-breakfast sugar intake (-10 g), but higher (14 g/d) total daily sugar intake. Total daily sugar was also higher (22 g/d) with high- (*versus* low-) sugar breakfasts, whilst post-breakfast sugar was similar (5 g/d) adding credence to the hypothesis that larger portion sizes at breakfast are inadequately compensated for later in the day. As such, our findings suggest that eating some, but not too much, sugar at breakfast may aid in lowering total daily sugar intake, in agreement with public health guidelines recommending low-sugar breakfasts (NHS, 2018), though our results suggest that a low energy breakfast may be a more pertinent focus. This hypothesis needs further testing.

Our present analyses are in some disagreement with previous epidemiological work with regard to daily energy intake. Kant and Graubard (2015) showed slightly higher energy intake on breakfast-eating *versus* breakfast-skipping days (+247 and +187 kcal for men and women, respectively). This study did not differentiate breakfast size however. Thus, in contrast, our analyses show similar daily energy intakes between breaking-eating and breakfast-skipping when the breakfast was classified as low-sugar, but higher energy intakes when the breakfast was classified as high-sugar. Our findings are however concordant with previous randomised controlled trials investigating the appetitive and/or health effects of sugar at breakfast, whereby no consistent differences in energy intake have been found according to the sugar content of isocaloric breakfasts (Carroll *et al.*, 2020; Mattes, 1990).

As these studies used isocaloric breakfast comparisons, the confounding influence of breakfast energy consumed was removed and the role of sugar was isolated. Those previous results accord with our current findings in that post-breakfast energy intake was similar between those consuming low and high sugar breakfasts, despite breakfast energy intake differing in our analyses. Neither of the existing trials (Carroll *et al.*, 2020; Mattes, 1990) found a difference in sweet/sugar intake according to sugar consumed at breakfast. This is again in agreement with our present findings, showing similar post-breakfast sugar intake between low- and high-sugar breakfasts (though there was a difference in total-daily sugar intake in line with the randomised trials). These studies were both done in healthy participants, in contrast to our STAMP-2 cohort (with or high risk of T2D), potentially suggesting the appetitive effects of sugar at breakfast are similar between those with and without gluco-regulatory impairment.

However, our present results contradict an acute study manipulating carbohydrate type and amount in those with T2D as postprandial satiety ratings were lower after the oligosaccharide-based (‘quick release’ carbohydrate) breakfasts (Lenner, 1976). However, the study by Lenner did not measure energy intake. Taken together with our findings and those of Carroll *et al.* (2020) and Mattes (1990), this potentially highlights that acute postprandial satiety following breakfast is not necessarily associated with total energy intake. Another trial in those with obesity found the inclusion of sweet foods in the breakfast meal increased weight loss over 32 weeks compared to a low carbohydrate breakfast (Jakubowicz *et al.*, 2012). These findings are not directly comparable to our analyses though because the breakfasts in both arms of the trial were protein-enriched (i.e. a potent satiating nutrient).

The research investigating sugar and appetite (not specific to breakfast) shows mixed findings, with differing theoretical explanations. For example, some work demonstrates sugar intake increases the subsequent consumption of sweet foods (Brala and Hagen, 1983; Cornell *et al.*, 1989; de Castro *et al.*, 2000a; de Castro *et al.*, 2000b; De Graaf *et al.*, 1999;Melanson *et al.*, 1999; Monneuse *et al.*, 1991; Perez *et al.*, 1994), which we did not find evidence for in our analyses. The discordance between our findings and those of previous studies are likely related to differences in study design. Specifically, many of the cited studies tested sweet preloads on subsequent energy intake at a test meal or other related acute appetite measure. Comparatively, our study investigated free-living participants over multiple days. Thus, it is likely that we captured more ecologically valid habitual intakes rather than the effect of consuming an atypical food in an unfamiliar but well-controlled laboratory setting. Nonetheless, it is unclear if the magnitude of difference in sugar intake that we observed on days when breakfast was eaten (compared to skipping breakfast, low sugar breakfasts were associated with -15 g/d) is meaningful to health.

Our finding of sugary breakfasts being associated with lower post-breakfast sugar intake may be explained by sensory-specific satiety, whereby the ingestion of sweet transiently reduces sweet desires and intake, in line with previous research specifically targeting breakfast (Carroll *et al.*, 2020). Considering we found sugary breakfasts to be associated with lower post-breakfast sugar intake, and lower or similar total-daily sugar intake compared to skipping breakfast (i.e. basically no sugar), there may be compensation for lack of sweet satiety when people skip breakfast. Alternatively, this could be an artefact of consuming the missed energy from breakfast, some of which will inevitably contain sugar.

Our analyses were in those at high risk of or newly diagnosed with T2D. Sugar intake therefore poses additional health concerns beyond appetite dysregulation, specifically relating to glycaemic control. Thus, if these findings are replicated in controlled trials, breakfast would need to avoid gluco-regulatory harm. The impact of sugar at breakfast is particularly important to understand in this group because of the morning hyperglycaemia and hyperinsulinaemia often experienced by those with T2D (Bolli and Gerich, 1984; Carroll & Schade, 2005). Whilst health markers were only explored descriptively, similar fasting glucose concentrations, HbA1c, HOMA-IR scores, medication use rates, and duration of diabetes were found across all three breakfast categories. Thus it does not appear that breakfast consumption patterns or the sugar content of breakfast in this sample was associated with differences in gluco-regulatory health.

Strengths and limitations

A key strength of our analyses is the use of detailed multi-day four-day food diaries, which enable energy intake to compartmentalised during the day and for habitual patterns of eating day to day to be modelled. Whilst there is inherent error in collecting dietary data, food diaries are more accurate than food frequency questionnaires (Park *et al.*, 2018). We assessed and observed under-reporting of energy intake in our sample compared with expected energy requirements. We aimed to address error from under-reporting by including an indicator of plausible reporting status in our models. In addition, under the assumption that under-reporters do not alter their accuracy of reporting from day to day, the within-person approach to estimating associations would have limited the influence of between person differences in reporting bias.

A key limitation of these analyses is that breakfast was not identified by participants and wake time was sometimes incomplete, thus an objective definition had to be applied, which may have misclassified some days as breakfast eating or skipping. In order to ensure our results were robust across different breakfast definitions, we ran extensive sensitivity analyses using a further three definitions of breakfast. Whilst the proportion of observations in each breakfast category altered slightly, sugar intake at breakfast remained fairly stable. Importantly, the results obtained using these definitions were concordant with our main analysis. This is despite a reduction in power from missing wake-time data in some definitions. As such, we feel confident that we captured the eating occasion that most would recognise as breakfast (first morning meal within ~2 h waking; O'Neil *et al.*, 2014).

The use of a multilevel model adds to the robustness of the conclusions made as both between- and within-participant variability was accounted for. Therefore associations reported can be considered independent of person-level confounders. Nonetheless, considering the complexity of running a multilevel model, the relatively small sample size may limit the inferences made. Further, this was a unique sample of people with newly diagnosed or at high risk of T2D in the South West of England, reducing the generalisability of our findings to those with long-term T2D diagnoses or healthy adults, and particularly those outwith the UK. Additionally, as with any cross-sectional analyses, long-term time trends cannot be inferred. However, the use of the multilevel model allowed acute time trends (i.e. within a day) to be prospectively investigated.

Finally, our analyses carry the same limitations as other observational research, namely a lack of ability to strictly infer causality, particularly in isolation of other research. The robustness of our findings may however be demonstrated in their concordance with the limited experimental evidence available; thus our analyses add credence to the use of multilevel modelling as a tool to explore the causal appetite effects in free-living settings, mimicking crossover intervention designs and strengthening our causal inference. Nonetheless, both longitudinal and research with alternative causally informative designs are needed in order to triangulate our findings with, and to confirm how well multilevel modelling mimics randomised crossover trials.

Conclusion

Overall, our analysis in those at risk of, or newly diagnosed with T2D, found evidence of incomplete compensation for the extra energy consumed at breakfast when sugar-consumed at breakfast was high. The greater energy content of higher-sugar breakfasts, rather than the sugar content *per se*, may explain these findings. Low-sugar breakfast eaters also consumed less sugar per day compared to when they skipped breakfast or ate high-sugar breakfasts. Health markers were similar regardless of how much sugar participants consumed at breakfast. Whilst not conclusive, these results challenge the notion that sugary breakfasts *per se* are have a meaningful role in overeating or poor blood sugar regulation in this population. As our results were similar to controlled trials, multilevel modelling may be a useful epidemiological method mimicking crossover trials when analysing data. Future work should investigate the role of breakfast portion size on appetite and explore the implications for long-term weight management.

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STAMP-2: Supplementary material

S1. Rational for breakfast definitions

The 50 kcal cut-off used to define 'breakfast skippers' was included so as not to incorrectly define breakfast skippers as breakfast eaters. For example, those who consume tea with milk and sugar would not culturally be defined as breakfast eaters, and the small amount of energy consumed is unlikely to meaningfully change physiological processes in the same way as eating a meal.

The independent variable of primary interest to this study was total sugar at breakfast. Breakfast can be defined as the first meal within 2 hours of waking after the longest period of sleep (O'Neil *et al.*, 2014). Due to heterogeneity in data collection methods, such specificity is not also feasible. Thus a commonly used time-based definition of breakfast is food consumed between 0500-1100 h (or an interval within that time frame) (Albertson *et al.*, 2008; Aranceta *et al.*, 2001; Barton *et al.*, 2005; Betts *et al.*, 2014; Chowdhury *et al.*, 2016; Dhurandhar *et al.*, 2014; Leidy *et al.*, 2016; Timlin and Pereira, 2007).

Considering the heterogeneity between breakfast definitions, we conducted several sensitivity analyses to ensure we had captured the breakfast meal as accurately as possible within the constraints of the available data:

1. "Meal 1 between 0600-0900 h" (i.e. early morning ingestion of energy)
2. "Meal 1 within 2 hours of waking" (i.e. incorporating natural diurnal rhythms dictating energy ingestion as per O'Neil *et al.*, 2014)
3. "Meal 1 within 2 hours of waking, between 0600-0900 h" (i.e. incorporating diurnal rhythms whilst still appreciating that breakfast is culturally consumed in the morning)

We did also investigate a fourth definition: "Meal 1 within 2 hours of waking, between 0600-1200 h" but this resulted in only two fewer observations than "Meal 1 within 2 hours of waking between 0600-0900 h". Definitions incorporating wake time led to a drop in sample size (~41 % reduction in observations and ~29 % reduction in participants owing to missing data on wake time) hence why these definitions were not our preferred choice. Breakfast categories for these analyses were created as above (i.e. 'breakfast skipper' [≤ 50 kcal for breakfast], 'low sugar breakfast' and 'high sugar breakfast'; the latter two groups created by a median split of sugar at breakfast after excluding breakfast skipping days).

Table S1. Person-level demographic characteristics of those excluded from the main analyses (n = 29)

	n	Median (IQR)
Sugar at breakfast (g/d)	16	11 (4, 16)
Age (y)	29	56 (47, 61)
BMI (kg/m^2)	29	33.6 (27.3, 39.9)
Body fat %	26	37.4 (25.9, 44.9)
Fasting glucose concentration (mmol·L^{-1})	28	6.5 (5.6, 7.9)
HbA1c (%)	29	6.4 (6.0, 7.3)
HOMA-IR	28	2.3 (1.3, 4.1)
T2D duration (months)	22	7 (6, 10)
Fibre (g/1000 kcal)	16	10 (9, 12)
Daily energy intake (kcal/d)	16	1696 (1504, 1914)
Post-breakfast energy intake (kcal/d)	16	1524 (1285, 1665)
Total daily sugar intake (g/d)	16	82 (67, 93)
Post-breakfast sugar intake (g/d)	16	64 (53, 75)
PA (counts/min)	15	224 (174, 442)
Sedentary (%)	15	65 (59, 75)
Light (%)		29 (24, 36)
MVPA (%)		2 (1, 6)
IMD score:	29	16.5 (10.5, 25.5)
Lower deprivation	10	8.9 (5.0, 10.5)
Higher deprivation	19	21.9 (16.5, 39.0)
	n	**% sample**
Sex: Women	11	38
Men	18	62
Ethnicity: White	27	96
Non-white	1	4
Smoking: Current smoker	5	19
Current non-smoker	21	81
Diabetes medication use:		
Yes	10	34
No	19	66

Abbreviations: BMI, body mass index; HbA1c, glycated haemoglobin; HOMA-IR, homeostatic model assessment-insulin resistance; IMD, Indices of Multiple Deprivation; IQR, interquartile range; MVPA, moderate-to-vigorous physical activity; PA, physical activity; T2D, type 2 diabetes

Table S2. Multilevel modelling of sugar at breakfast categories and total/post-breakfast daily energy intake: within- and between-participant variance explained across different models

Model	Δ between- participant variation explained (%)†	Δ within- participant variation explained (%)†	Δ total variance explained (%)†	Intra-class correlation (%)‡	Likelihood ratio test	Likelihood ratio test *p*	Model *p* (Wald chi^2)
			Total energy intake (kcal)				
1.1	0.2	4.1	2.2	50.1	5.69	0.058	0.056
2.0	48.9	65.1	57.1	41.1	409.62	< 0.001	< 0.001
3.0	11.6	5.7	9.2	42.6	60.41	< 0.001	< 0.001
			Post-breakfast energy intake (kcal)				
1.1	1.7	1.1	1.4	45.6	8.6	0.014	0.014
2.0	46.9	64.9	55.1	35.6	390.0	< 0.001	< 0.001
3.0	10.0	11.7	10.6	35.2	59.3	< 0.001	< 0.001

†calculated by: ((*variance in current model* - *variance in previous model*) / *variance in previous model*) * 100 (e.g. ((m2.0 - m1.1) / m1.1 * 100))

‡calculated by: between-participant variance (*var(cons)* / total variance) * 100. Represents % variation of post-breakfast energy intake between participants

Model 1.1: unadjusted random intercept model (compared to null intercept model with no predictors)

Model 2.0 (person-level): model 1.1 + sex, age, ethnicity (white or non-white), smoking status (current smoker or non-smoker), body fat (%), HbA1c (%), HOMA-IR, reporter category (under-, plausible-, or over-reporter) + IMD score

Model 3.0 (day-level): model 2.0 + physical activity (counts/min), day of week (weekday or weekend) + fibre (g/1000 kcal)

Table S3. Multilevel modelling of sugar at breakfast categories and total/post-breakfast daily sugar intake

Model	Intercept	β	95 % CI	*p*	Intercept	β	95 % CI	*p*
	Total daily energy intake (kcal)				Post-breakfast energy intake (kcal)			
	Low sugar at breakfast compared to skipping breakfast				Low sugar at breakfast compared to skipping breakfast			
1.0	78	-	-	-	65	-	-	-
1.1	76	-6	-14, 2	0.132	74	-14	-22, -6	< 0.001
2.0	75	-8	-16, -1	0.036	70	-16	-23, -8	< 0.001
3.0	73	-8	-16, 0	0.042	68	-15	-23, -8	< 0.001
	High sugar at breakfast compared to skipping breakfast				High sugar at breakfast compared to skipping breakfast			
1.1	76	15	7, 23	< 0.001	74	-10	-18, -2	0.015
2.0	75	14	6, 22	< 0.001	70	-11	-18, -3	0.005
3.0	73	14	7, 22	< 0.001	68	-10	-18, -3	0.007
	High compared to low sugar at breakfast				High versus low sugar at breakfast			
1.1	70	21	13, 29	< 0.001	60	4	-3, 12	0.285
2.0	67	22	15, 30	< 0.001	55	5	-2, 12	0.170
3.0	65	22	15, 30	< 0.001	53	5	-2, 12	0.160

Breakfast skipping n = 155 days; low sugar breakfast n = 197 days; high sugar breakfast n = 195 days. Abbreviations: CI, confidence interval

Model 1.0: null intercept model with no predictors, to explore the extent to which differences in energy intake (total or post-breakfast) were bigger between *versus* within people

Model 1.1: unadjusted random intercept model

Model 2.0 (person-level): model 1.1 + sex, age, ethnicity (white or non-white), smoking status (current smoker or non-smoker), body fat (%), HbA1c (%), HOMA-IR, reporter category (under-, plausible-, or over-reporter) + IMD score

Model 3.0 (day-level): model 2.0 + physical activity (counts/min), day of week (weekday or weekend) + fibre (g/1000 kcal)

Table S4. Descriptive information regarding the different breakfast definitions used

	Meal 1 between 0600-1200 h (used in main analysis)	Meal 1 between 0600-0900 h	Meal 1 within 2 h waking	Meal 1 within 2 h waking between 0600-0900 h
Observations (n)	547	547	324	324
Participants (n)	147	147	104	104
Definition of low sugar breakfast (g of sugar at breakfast)	≤ 14.2	≤ 13.9	≤ 15.7	≤ 15.9
Breakfast skipping days (n)	155	265	122	172
Low sugar breakfast days (n)	197	141	101	77
High sugar breakfast days (n)	195	141	101	75
Intraclass correlation for total daily energy intake model (%)	42.5	42.8	43.0	43.7
Intraclass correlation for post-breakfast energy intake model (%)	36.0	40.2	36.6	41.3

Table S5. Descriptive information regarding the energy and sugar content of breakfasts according to different definitions

Definition	Average	Days skipping breakfast	Days with low sugar at breakfast	Days with high sugar breakfast	*P* for difference between high and low sugar days
	Breakfast energy intake (kcal)				
Meal 1 between 0600-1200 h	194 (28, 308)	8 (0, 16)	207 (166, 316)	284 (222, 406)	< 0.001*†‡
Meal 1 between 0600-0900 h	70 (0, 257)	0 (0, 8)	207 (152, 308)	283 (218, 393)	< 0.001*†‡
Meal 1 within 2 h waking	172 (0, 301)	0 (0, 0)	251 (174, 317)	283 (219, 441)	< 0.001*†
Meal 1 within 2 h waking between 0600-0900 h	0 (0, 244)	0 (0, 0)	211 (166, 305)	283 (219, 441)	< 0.001*†‡
	Breakfast sugar intake (g)				
Meal 1 between 0600-1200 h	10 (2, 19)	1 (0, 2)	8 (4, 11)	24 (19, 34)	< 0.001*†‡
Meal 1 between 0600-0900 h	3 (0, 15)	0 (0, 1)	8 (4, 10)	26 (19, 35)	< 0.001*†‡
Meal 1 within 2 h waking	7 (0, 19)	0 (0, 0)	8 (6, 11)	24 (19, 35)	< 0.001*†‡
Meal 1 within 2 h waking between 0600-0900 h	0 (0, 14)	0 (0,0)	8 (6, 11)	26 (20, 36)	< 0.001*†‡

*Difference between breakfast skipping and low sugar at breakfast (*P* ≤ 0.001)
†Difference between breakfast skipping and high sugar at breakfast (*P* ≤ 0.001)
‡Difference between low and high sugar at breakfast (*P* ≤ 0.031)

Table S6. Comparison of fully adjusted multilevel model results according to different definitions

Definition	Intercept	β	95 % CI	*p*	Intercept	β	95 % CI	*p*
	Total daily energy intake (kcal)				Post-breakfast energy intake (kcal)			
	Low sugar at breakfast compared to skipping breakfast				Low sugar at breakfast compared to skipping breakfast			
Meal 1 between 0600-1200 h	1450	64	-18, 146	0.125	1300	-178	-261, -94	< 0.001
Meal 1 between 0600-1200 h*	1364	29	-74, 131	0.582	1364	29	-74, 131	0.582
Meal 1 between 0600-0900 h	1477	56	-25, 136	0.174	1308	-182	-262, -103	< 0.001
Meal 1 within 2 h waking	1184	100	-5, 206	0.062	1016	-143	-252, -34	0.010
Meal 1 within 2 h waking between 0600-0900 h	1190	104	-5, 212	0.060	980	-111	-220, -2	0.047
	High sugar at breakfast compared to skipping breakfast				High sugar at breakfast compared to skipping breakfast			
Meal 1 between 0600-1200 h	1450	135	52, 217	0.001	1300	-151	-235, -67	< 0.001
Meal 1 between 0600-1200 h*	1364	54	-25, 133	0.182	1364	54	-25, 133	0.182
Meal 1 between 0600-0900 h	1477	127	45, 208	0.002	1308	-161	-242, -80	< 0.001
Meal 1 within 2 h waking	1184	120	15, 224	0.024	1016	-186	-294, -78	0.001
Meal 1 within 2 h waking between 0600-0900 h	1190	147	36, 258	0.010	980	-159	-271, -46	0.006
	High compared to low sugar at breakfast				High versus low sugar at breakfast			
Meal 1 between 0600-1200 h	1515	70	-8,149	0.080	1123	27	-53, 106	0.514
Meal 1 between 0600-1200 h*	1393	25	-86, 136	0.657	1393	25	-86, 136	0.657
Meal 1 between 0600-0900 h	1532	71	-22, 165	0.136	1126	22	-71, 115	0.646
Meal 1 within 2 h waking	1284	20	-93, 133	0.732	873	-43	-159, 73	0.464
Meal 1 within 2 h waking between 0600-0900 h	1294	43	-87, 174	0.516	869	-48	-179, 84	0.478

*Includes breakfast kcal as a variate

Adjusted for sex, age, ethnicity (white or non-white), smoking status (current smoker or non-smoker), body fat (%), HbA1c (%), HOMA-IR, reporter category (under-, plausible-, or over-reporter) + IMD score, physical activity (counts/min), day of week (weekday or weekend) + fibre (g/1000 kcal)

Supplementary Material References

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