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Original article

Associations of quantity and quality of carbohydrate sources with subjective appetite sensations during 3-year weight-loss maintenance: Results from the PREVIEW intervention study

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SUMMARY

Background & aims: The association of quantity and quality of carbohydrate sources with appetite during long-term weight-loss maintenance (WLM) after intentional weight loss (WL) is unclear. We aimed to investigate longitudinal associations of quantity and quality of carbohydrate sources with changes in subjective appetite sensations during WLM.
Methods: This secondary analysis evaluated longitudinal data from the 3-year WLM phase of the PREVIEW study, a 2 × 2 factorial (diet–physical activity arms), multi-center, randomized trial. 1279 individuals with overweight or obesity and prediabetes (25–70 years; BMI≥25 kg m^{-2}) were included. Individuals were merged into 1 group to assess longitudinal associations of yearly changes in appetite sensations. Quantity and quality of carbohydrate sources including total carbohydrate, glycemic index (GI), glycemic load (GL), and total dietary fiber were assessed via 4-day food diaries at 4 timepoints (26,

Abbreviations: BW, body weight; GI, glycemic index; GL, glycemic load; HOMA-IR, homeostatic model assessment of insulin resistance; MVPA, moderate to vigorous physical activity; OGTT, oral glucose tolerance test; PA, physical activity; VAS, visual analog scale; RCT, randomized controlled trial; T2D, type 2 diabetes; WL, weight loss; WLM, weight-loss maintenance.

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52, 104, and 156 weeks) during WLM. Visual analog scales were used to assess appetite sensations in the previous week.

Results: During WLM, participants consumed on average 160.6 (25th, 75th percentiles 131.1, 195.8) g·day^{-1} of total carbohydrate, with GI 53.8 (48.7, 58.8) and GL 85.3 (67.2, 108.9) g day^{-1}, and 22.3 (17.6, 27.3) g·day^{-1} of dietary fiber. In the available-case analysis, multivariable-adjusted linear mixed models with repeated measures showed that each 30-g increment in total carbohydrate was associated with increases in hunger (1.36 mm year^{-1}, 95% CI 0.77, 1.95, $P < 0.001$), desire to eat (1.10 mm year^{-1}, 0.59, 1.60, $P < 0.001$), desire to eat something sweet (0.99 mm year^{-1}, 0.30, 1.68, $P = 0.005$), and weight regain (0.20%·year^{-1}, 0.03, 0.36, $P = 0.022$). Increasing GI was associated with weight regain, but not associated with increases in appetite sensations. Each 20-unit increment in GL was associated with increases in hunger (0.92 mm year^{-1}, 0.33, 1.51, $P = 0.002$), desire to eat (1.12 mm year^{-1}, 0.62, 1.62, $P < 0.001$), desire to eat something sweet (1.13 mm year^{-1}, 0.44, 1.81, $P < 0.001$), and weight regain (0.35%·year^{-1}, 0.18, 0.52, $P < 0.001$). Surprisingly, dietary fiber was also associated with increases in desire to eat, after adjustment for carbohydrate or GL.

Conclusions: In participants with moderate carbohydrate and dietary fiber intake, and low to moderate GI, we found that higher total carbohydrate, GL, and total fiber, but not GI, were associated with increases in subjective desire to eat or hunger over 3 years. This study was registered as ClinicalTrials.gov, NCT01777893.

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1. Introduction

Identifying successful interventions to reduce the prevalence of obesity has become an urgent public health priority worldwide. Obesity has multiple health consequences, increasing the risk of metabolic diseases such as type 2 diabetes (T2D) [1]. The adverse outcomes caused by obesity can be improved by weight loss (WL) [2], but weight regain especially after rapid intentional WL is common [3]. Weight regain may be explained by physiological adaptations such as an increase in drive to eat [4,5]. An improvement in appetite control may reduce food and energy intake and aid in weight-loss maintenance (WLM).

Appetite control may be linked to dietary macronutrient composition [6,7]. Diets with higher protein were found to lead to a reduction in appetite [8], whereas the effect of carbohydrate quantity remains highly controversial [9–11]. Quality of carbohydrate sources, which is related to various health outcomes [12], may also play a role in appetite control. Glycemic index (GI) is regarded as an indicator of the glycemic potential of carbohydrate sources in individual foods [13], while glycemic load (GL) is considered an indicator of the combination of quantity and quality of carbohydrate sources [14]. Although data from long-term studies are lacking, short-term investigations indicate that consumption of low-GI carbohydrates may delay the return of hunger relative to consumption of higher-GI carbohydrates [15]. However, a recent review reported conflicting findings and suggested that there was no acute effect of GI on satiety [16]. Regarding longer-term studies on GL, in a randomized WL intervention, there were no differences between high and low GL diets in hunger or satiety [17]. A recent meta-analysis of prospective and clinical studies showed that dietary fiber could be a better indicator than GI and GL [12]. A systematic review suggested that most dietary fibers failed to reduce appetite in clinical trials with acute design [18]. Collectively, to date, the majority of studies on total carbohydrate, GI, GL, fiber, and self-reported appetite are short- or medium-term, and small-scale.

The PREVIEW study was a 3-year lifestyle intervention to examine the effect of 2 diets combined with 2 physical activity (PA) programs on WLM and prevention of T2D in adults with overweight or obesity and pre-diabetes. The trial consisted of a diet-induced WL phase and a WLM phase [19]. PREVIEW data showed that GI and GL were associated with weight regain during the WLM phase [20]. The present study aimed to explore whether total carbohydrate, GI, GL, and total fiber were associated with subjective appetite sensations in the PREVIEW study.

2. Methods

2.1. Study design

The current study is a secondary analysis of longitudinal data derived from the PREVIEW study (ClinicalTrials.gov, NCT01777893). Detailed information about the trial design [21] and the main findings have been published previously [19]. Briefly, PREVIEW was a 3-year, multi-center, 2 × 2 factorial randomized controlled trial (RCT) which aimed to explore the effects of 2 diets and 2 physical activity (PA) treatments on the prevention of T2D in adults with overweight or obesity and pre-diabetes. The primary endpoint was incidence of T2D between the 2 diet groups. PREVIEW consisted of 2 phases: an 8-week WL period (at least 8% loss of initial weight) with a liquid formula-based low-energy diet of 3.4 MJ per day [22] followed by a 148-week WLM period based on 2 diets and 2 PA programs in a 2 × 2 factorial design. The 2 intervention diets were: 1) moderate protein (15 E%) and higher carbohydrate (55 E%), with moderate dietary GI (>56); and 2) higher protein (25 E%) and moderate carbohydrate (45 E%), with lower dietary GI (<50). Both diets contained moderate fat (30 E%). Diets were consumed *ad libitum* during WLM. Eight intervention centers (Denmark, Finland, the UK, the Netherlands, Spain, Bulgaria, Australia, and New Zealand) were involved. The study was approved by the Human Ethics Committees at each site and conducted according to the Declaration of Helsinki (1957) and its later amendments (1983).

The current observational *post hoc* analysis is based on the diet and appetite sensation data collected during WLM (phase 2). Individuals were pooled into 1 group, irrespective of original diet or PA randomization. The outcomes of interest were changes in ratings of the subjective appetite sensations including hunger, satiety, desire to eat, desire to eat something sweet, and desire to eat something savory, collected at 8, 26, 52, 104, and 156 weeks. Self-reported dietary intakes and device-measured PA were collected at 26, 52, 104, and 156 weeks.

2.2. Study population

The enrolment of PREVIEW participants occurred from June 2013 to April 2015, mainly via advertisements in newspapers, newsletters, and on the radio, and television. In order to be included, participants had to be: 1) adults (age 25–70 years); 2) overweight or obese (body mass index (BMI)$\geq$25 kg m^{-2}); 3) pre-diabetic as defined by American Diabetes Association [23]: fasting plasma glucose of 5.6–6.9 mmol L^{-1} and/or plasma glucose at 2 h after oral administration of 75 g glucose of 7.8–11.0 mmol L^{-1} and fasting plasma glucose less than 7.0 mmol L^{-1}. Individuals with pre-existing T2D were excluded from the trial. The complete list of inclusion and exclusion criteria has been published elsewhere [21]. Potentially eligible participants were asked to give written informed consent. They were further screened for body weight (BW), height and resting blood pressure and were given an oral glucose tolerance test (OGTT) at the laboratories to confirm whether they met the inclusion criteria. Once eligibility was confirmed, participants were randomized based on sex and age groups ($\leq$45, 46–54 and > 54 years) to 1 of the 4 intervention groups and started the 8-week WL phase. Participants who failed to lose at least 8% of initial BW were ineligible to enter the WLM phase and excluded from further analysis.

In the current study, we performed both complete-case and available-case analyses. The complete-case analysis involved participants who completed all phases and available-case analysis involved participants who started the WLM phase. We excluded participants where total carbohydrate and GI data were not available at 26 weeks and/or those with implausible energy intake (<600 or >3500 kcal$\cdot$day^{-1} for women and <800 or >4200 kcal$\cdot$day^{-1} for men) [24].

2.3. Assessment of dietary intake

Dietary intake was evaluated by 4-day food diaries on 4 consecutive days including 1 weekend day. Participants used scales to weigh food or estimated food intake using conventional household measurements. The importance of detailed food description such as the type of foods and cooking methods was emphasised by dietary instructors. Participants also estimated the type and amount of the food when eating outside the home. Food diaries, including weight, portion size, and description of food were checked and errors were identified by an investigator. All information from food diaries was entered into nutrient analysis software, specifically Dankost Pro (Denmark), AivoDiet (Finland), Mijn Eetmeter (the Netherlands), Nutritics (the UK), Dial (Spain), Nutrition Calculation (Bulgaria), and Foodworks (Australia and New Zealand), for further calculation. Self-reported consumption of dietary fiber (not including fiber supplements) and other dietary factors including fat, protein, carbohydrate, alcohol was calculated per time point. Percentage of energy from self-reported fat, protein, dietary fiber, and alcohol (E%) were calculated.

Quantity and quality of carbohydrate sources were expressed as total carbohydrate, GI, GL, and dietary fiber. GI databases, including DiOGenes GI Table, PREVIEW generic GI list, The National (Finnish) GI Database produced by National Institute for Health and Welfare, and University of Sydney online GI database, were used to calculate GI and GL. Total dietary GI and GL were calculated based on van Woudenbergh et al. [25]:

$$Dietary\ GI = \frac{\sum_{i=1}^{n}(GI_i \times carbohydrates_i)}{\sum_{i=1}^{n}(carbohydrates_i)}$$

$$Dietary\ GL = \frac{\sum_{i=1}^{n}(GI_i \times carbohydrates_i)}{100}$$

2.4. Assessment of subjective appetite sensations

Subjective appetite sensations were assessed by using previously validated electronic questionnaires with 5 separate visual analogue scales (VAS) [26–28]. Participants were asked to consider their feelings during the week prior to filling out the questionnaires in the morning, whilst they were participating in an OGTT. The questionnaires were digitally presented to the participants with 5 100-mm horizontal lines anchored with extreme appetite sensations on both ends of each line (eg very little (left, 0) to very much (right, 100)). Specifically, questions included: 1) how hungry have you felt?; 2) How satiated have you felt?; 3) Have you felt a desire to eat?; 4) Have you felt like eating something sweet?; and 5) Have you felt like eating something savory? Ratings of hunger, satiety, desire to eat, desire to eat something sweet, and desire to eat something savory were expressed as the overall feeling of the fasting and postprandial state.

2.5. Assessment of physical activity and other covariates

Covariates of interest included age, sex, ethnicity, appetite sensation ratings and BMI at 8 weeks, as well as intervention center, physical activity, dietary factors, and time. Age, sex, and ethnicity were self-reported at 0 weeks via questionnaires and were treated as constant variables. PA was measured using a hip-worn ActiSleep+ (ActiGraph LLC, Pensacola, FL) accelerometer, sampling at 100 Hz, over 7 consecutive days. The detailed PA measurements has been described elsewhere [29]. Briefly, total PA was estimated using mean activity counts, expressed in counts$\cdot$min^{-1} over valid wear time. Troiano cut points were used to assess time (min$\cdot$day^{-1}) spent at different types of PA: sedentary<100, light 100–2020, moderate<2020, and vigorous<5999 counts$\cdot$min^{-1}. Moderate to vigorous PA (MVPA) was the sum of moderate and vigorous activity.

2.6. Statistical analysis

Continuous descriptive characteristics at the start of WLM (8 weeks) with normal distribution and skewed distribution are presented as mean ± standard deviation and median (25th, 75th percentiles) respectively. Categorical characteristics are presented as absolute values (frequencies).

Longitudinal associations of total carbohydrate, GI, GL, and fiber with yearly changes in appetite sensations and percentage of BW over time were determined using a linear mixed model with repeated measurements. Yearly changes in appetite were calculated as changes from 8 to 26, 52, 104, and 156 weeks divided by corresponding changes in years. To best capture dietary and PA (including total PA and other types of PA) patterns during long-term WLM, a cumulative average method [24] was used based on all available measurements of self-reported dietary intake and device-measured PA. In the calculation, the 26-week self-reported diet was linked to yearly changes in appetite sensations from 8 to 26 weeks; the average of the 26- and 52-week self-reported diets was linked to yearly changes in appetite sensations from 8 to 52 weeks; the average of the 26-, 52-, and 104-week self-reported diets was linked to yearly changes in appetite sensations from 8 to 104 weeks; the average of the 26-, 52-,104, and 156-week self-reported diets was linked to yearly changes in appetite sensations

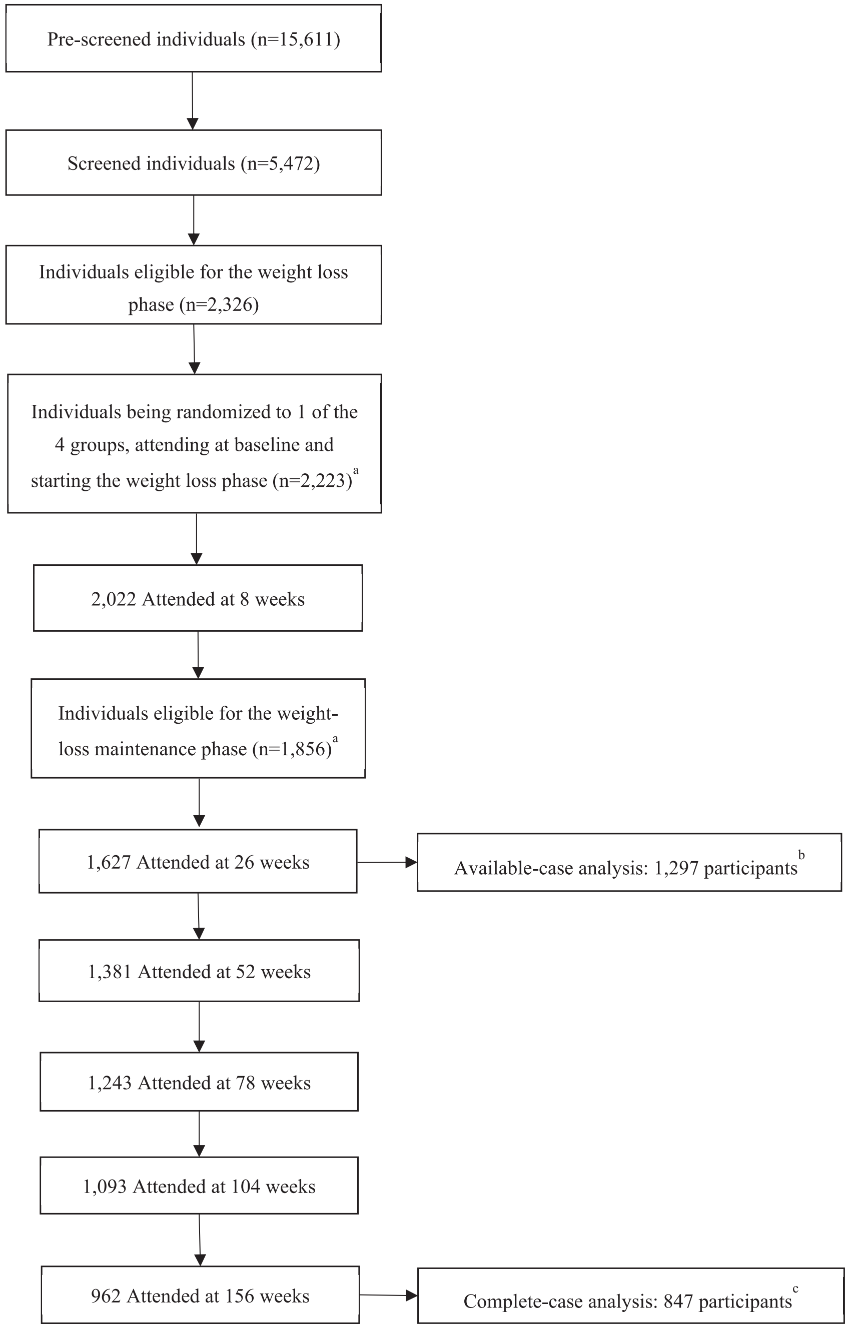


Fig. 1. Participant flow. [a]A total of 2224 individuals entered the weight loss phase and 1857 individuals commenced the weight-loss maintenance phase, but 1 withdrew consent and asked for data deletion. [b]330 individuals were excluded from 1627 individuals who attended at 26 weeks, because their total carbohydrate and GI data were not available and/or with implausible energy intake (<600 or >3500 kcal·day^{-1} for women and <800 or >4200 kcal·day^{-1} for men). [c]115 individuals were excluded from 962 individuals who attended at 156 weeks, because their total carbohydrate and GI data were not available and/or with implausible energy intake (<600 or >3500 kcal·day^{-1} for women and <800 or >4200 kcal·day^{-1} for men) were excluded.

from 8 to 156 weeks. Cumulative device-measured PA were calculated using the same method as diet. The further information is included in Supplementary Materials and Supplementary Table 1.

Three models with confounding factors were used. In model 1, age (continuous), sex (categorical), ethnicity (categorical), appetite sensation ratings or BW at 8 weeks, BMI at 8 weeks (continuous), intervention group, and time (categorical) were included as fixed factors and intervention center (categorical) and participant-ID were included as random factors. In model 2, time-varying total PA (continuous) and percentage of energy from fat, protein, dietary fiber or carbohydrate, and alcohol (all in E%, continuous) were additionally controlled for as fixed factors. To account for within-participants correlation, "diagonal" was used as a covariance structure for models with change in appetite sensations as a dependent variable and "compound symmetry: heterogenous" was used as a covariance structure for models with weight changes as a dependent variable. Sensitivity analyses were conducted by 1) adding MVPA, light activity, sedentary time, and average wear time (all in min·day^{-1}) instead of total PA to the models (because the results were similar, they were not shown); 2) adding carbohydrate

Table 1
Characteristics of participants at the start of weight-loss maintenance (8 weeks) or 26 weeks.

Characteristics	All participants[c]	Completers	Non-completers	*P*-value
N	1279	847	432	–
Socio-demographics[a]				
Female, n (%)	851 (66.5)	550 (64.9)	301 (69.7)	0.089
Age (years)	56 (45, 63)	57 (48, 63)	53 (43, 61)	<0.001
Height (m)	1.68 ± 0.09	1.68 ± 0.09	1.67 ± 0.09	0.057
Ethnicity, n (%)				0.016
Caucasian	1158 (90.5)	780 (92.1)	378 (87.5)	–
Asian	29 (2.3)	19 (2.2)	10 (2.3)	–
Black	19 (1.5)	13 (1.5)	6 (1.4)	–
Arabic	4 (0.3)	3 (0.4)	1 (0.2)	–
Hispanic	22 (1.7)	12 (1.4)	10 (2.3)	–
Other	47 (3.7)	20 (2.4)	27 (6.3)	–
Anthropometric outcomes[a]				
Body weight (kg)	83.0 (74.1, 94.4)	81.3 (72.8, 90.7)	86.3 (76.5, 99.7)	<0.001
BMI ($kg \cdot m^{-2}$)	29.2 (26.6, 32.8)	28.4 (26.0, 31.7)	30.8 (28.2, 34.6)	<0.001
Subjective appetite sensations[a]				
Hunger (mm)	34 (14, 60)	35 (15, 60)	31 (14, 59)	0.623
Satiety (mm)	56 (42, 76)	54 (40, 75)	60 (49, 77)	0.060
Desire to eat (mm)	58 (41, 74)	58 (41, 74)	57 (40, 73)	0.809
Desire to eat something sweet (mm)	30 (10, 59)	29 (9, 59)	32 (10, 58)	0.990
Desire to eat something savory (mm)	62 (40, 78)	62 (40, 78)	61 (43, 80)	0.491
Diet and lifestyle outcomes[b]				
Energy intake from food diary ($kcal \cdot day^{-1}$)	1648.9 ± 447.6	1674.1 ± 431.9	1599.7 ± 473.4	0.005
Carbohydrate intake from food diary ($g \cdot day^{-1}$)	166.4 ± 55.2	169.1 ± 54.2	161.2 ± 56.6	0.269
Glycemic index from food diary	53.5 ± 8.2	53.9 ± 8.0	52.8 ± 8.5	0.028
Glycemic load from food diary	90.5 ± 35.6	92.5 ± 35.6	86.5 ± 35.5	0.005
Dietary fiber from food diary ($g \cdot day^{-1}$)	22.6 ± 8.2	23.4 ± 8.1	21.2 ± 8.1	<0.001
Dietary fiber from food diary (E%)	2.7 ± 0.8	2.7 ± 0.8	2.6 ± 0.8	0.001
Protein intake from food diary (E%)	21.0 ± 4.6	21.0 ± 4.6	21.1 ± 4.5	0.688
Fat intake from food diary (E%)	32.8 ± 6.9	32.5 ± 7.0	33.4 ± 6.7	0.022
Total physical activity ($counts \cdot min^{-1}$)	311.6 (248.2, 396.9)	315.1 (255.2, 404.1)	305.2 (228.0, 382.0)	0.022
Moderate to vigorous physical activity ($min \cdot day^{-1}$)	30.8 (18.9, 48.2)	33.0 (20.6, 49.7)	28.6 (16.4, 45.2)	0.003
Light activity ($min \cdot day^{-1}$)	319.5 ± 80.8	319.6 ± 79.2	319.2 ± 84.2	0.934
Sedentary time ($min \cdot day^{-1}$)	576.9 ± 83.5	577.2 ± 84.0	576.4 ± 82.5	0.884

Values represent mean ± standard deviation, median (25th, 75th percentiles), and the number of participants (%).
Difference between completers and non-completers in characteristics was examined by independent-samples *t* test, Mann–Whitney *U* non-parametric test, and χ^2 test. Independent-samples *t* test was used for approximately normally-distributed variables, Mann–Whitney *U* non-parametric test was used for non-normally-distributed variables, and χ^2 test was used for categorical variables.
[a] Data were collected at 8 weeks.
[b] Data were collected at 26 weeks.
[c] Participants who entered the weight-loss maintenance phase.

intake in grams or GL instead of carbohydrate intake in E% to the fiber models.

Multiple imputation was not used to account for the missing data because it did not increase precision [30,31]. Data were analysed using IBM SPSS (Statistical Package for the Social Sciences, v26.0, Chicago, IL, USA). *P* values were based on 2-tailed tests, with statistical significance accepted at $P < 0.05$.

3. Results

The participant flow chart is shown in Fig. 1. A total of 1857 participants commenced the WLM phase and 1279 participants (3868–3948 observations of appetite outcomes) had available dietary data and plausible energy intake and were included in the available-case analysis. Of these, 847 participants (3152–3214 observations) were included in the complete-case analysis.

The median age of the 1279 participants (66.5% female) was 56 (range: 25–70) years at the start of WLM (8 weeks) (Table 1). The median (25th, 75th percentiles) values were 83.0 (74.1, 94.4) kg for BW, 29.2 (26.6, 32.8) $kg \cdot m^{-2}$ for BMI at 8 weeks (end of WL). The mean ± standard deviation values were 166.4 ± 49.7 $g \cdot day^{-1}$ for total carbohydrate, 53.4 ± 7.8 for GI, 89.9 ± 32.1 for GL, and 23.0 ± 7.4 $g \cdot day^{-1}$ for dietary fiber during WLM. The median (25th, 75th percentiles) values were 160.6 (131.1, 195.8) $g \cdot day^{-1}$ for total carbohydrate, 53.8 (48.7, 58.8) for GI, 85.3 (67.2, 108.9) for GL, and 22.3 (17.6, 27.3) $g \cdot day^{-1}$ for fiber during WLM. On average, compared with non-completers, completers had lower BW, BMI, and MVPA at the start of WLM, but higher GI, GL, fiber, energy intake, and total PA at 26 weeks.

Figure 2 shows the longitudinal associations between total carbohydrate and yearly changes in appetite sensations and percentage of BW over time. In models 1 and 2, total carbohydrate was positively associated with increases in ratings of hunger, desire to eat, and desire to eat something sweet in both the complete-case and available-case analyses. In the available-case analysis, higher total carbohydrate was associated with greater weight regain in models 1 and 2.

Figure 3 shows the longitudinal associations between GI and yearly changes in appetite sensation ratings and percentage of BW over time. In model 1, GI was positively associated with increases in ratings of desire to eat something sweet in the complete-case and available-case analyses. In model 2, however, the significant associations in model 1 no longer remained significant after additionally adjusting for dietary factors and PA. In the available-case and complete-case analyses, higher GI was associated with greater weight regain in models 1 and 2.

Figure 4 shows the longitudinal associations between GL and yearly changes in appetite sensation ratings and percentage of BW over time. In models 1 and 2, GL was positively associated with increases in ratings of hunger, desire to eat, and desire to eat something sweet in the complete-case and available-case analyses. In the available-case and complete-case analyses, higher GL was associated with greater weight regain in models 1 and 2.

Outcomes	Yearly mean change (95%CI)[a]	Yearly mean change (95%CI)[a]	*P*-value
ΔHunger (mm·year^{-1})			
Complete-case analysis			
Model 1		**0.42 (0.11, 0.72)**	**0.007**
Model 2		**0.98 (0.49, 1.48)**	**<0.001**
Available-case analysis			
Model 1		**0.70 (0.34, 1.05)**	**<0.001**
Model 2		**1.36 (0.77, 1.95)**	**<0.001**
ΔSatiety (mm·year^{-1})			
Complete-case analysis			
Model 1		0.11 (-0.22, 0.43)	0.520
Model 2		-0.03 (-0.55, 0.50)	0.914
Available-case analysis			
Model 1		0.02 (-0.30, 0.33)	0.921
Model 2		-0.08 (-0.60, 0.44)	0.770
ΔDesire to eat (mm·year^{-1})			
Complete-case analysis			
Model 1		**0.42 (0.11, 0.72)**	**0.007**
Model 2		**0.98 (0.49, 1.48)**	**<0.001**
Available-case analysis			
Model 1		**0.48 (0.17, 0.78)**	**0.002**
Model 2		**1.10 (0.59, 1.60)**	**<0.001**
ΔDesire to eat something sweet (mm·year^{-1})			
Complete-case analysis			
Model 1		**0.68 (0.25, 1.12)**	**0.002**
Model 2		**0.97 (0.28, 1.67)**	**0.006**
Available-case analysis			
Model 1		**0.75 (0.33, 1.18)**	**0.001**
Model 2		**0.99 (0.30, 1.68)**	**0.005**
ΔDesire to eat something savory (mm·year^{-1})			
Complete-case analysis			
Model 1		-0.14 (-0.49, 0.22)	0.447
Model 2		0.33 (-0.26, 0.93)	0.272
Available-case analysis			
Model 1		-0.11 (-0.44, 0.21)	0.492
Model 2		0.24 (-0.35, 0.82)	0.432
ΔBody weight (%·year^{-1})			
Complete-case analysis			
Model 1		0.03 (-0.09, 0.14)	0.665
Model 2		0.11 (-0.06, 0.29)	0.199
Available-case analysis			
Model 1		**0.12 (0.01, 0.23)**	**0.039**
Model 2		**0.20 (0.03, 0.36)**	**0.022**

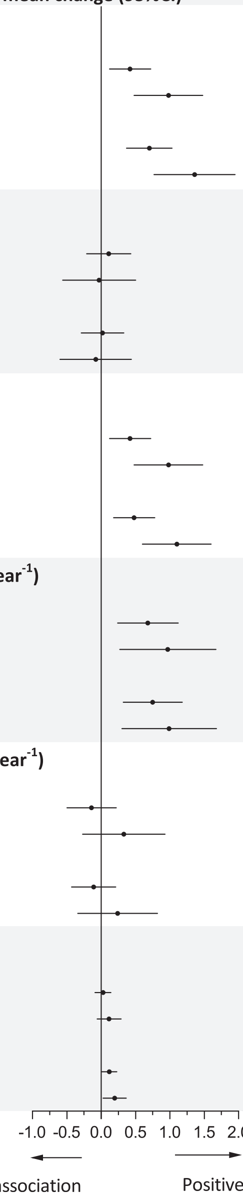
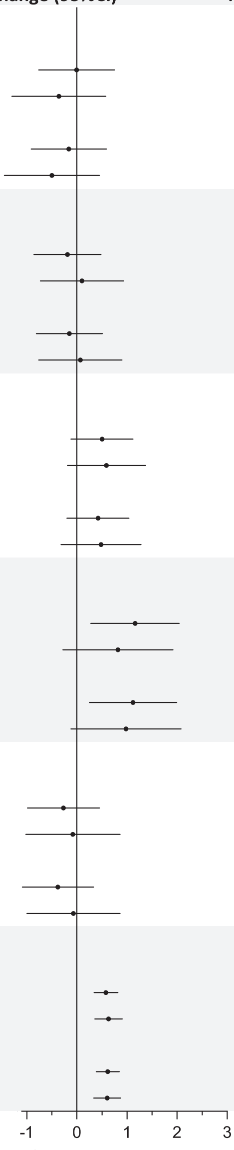


Fig. 2. Longitudinal associations of total carbohydrate (each 30 g·day^{-1}) with yearly changes in subjective appetite sensation ratings and percentage of body weight during weight-loss maintenance. Analyses were performed using a linear mixed model with repeated measures. Model 1 was adjusted for age, sex, ethnicity, intervention group, appetite sensation ratings or body weight at 8 weeks, BMI at the start of weight-loss maintenance (8 weeks), and time as fixed factors and intervention center and participant-ID as random factors. Model 2 was additionally adjusted for time-varying device-measured total physical activity and time-varying self-reported dietary components including percentage of energy from fat, protein, fiber, and alcohol as fixed factors. [a]Yearly mean change and 95% CI of main effects indicating the amount of increase in appetite sensation ratings or percentage of body weight increased per year by 30-unit increment in carbohydrate (g·day^{-1}).

Figure 5 shows the longitudinal associations between total dietary fiber and yearly changes in appetite sensation ratings and percentage of BW over time. In model 1, fiber was positively associated with increases in ratings of hunger and desire to eat in the complete-case and available-case analyses. In model 2, additional associations between fiber and desire to eat something sweet and savory were observed in the complete-case and available-case analyses. In the complete-case and available-case analyses, fiber was not associated with weight regain in model 1 or 2. In model 2, after adjustment for carbohydrate intake in grams or GL instead of carbohydrate intake in E%, fiber was still positively associated with desire to eat, but not with hunger and desire to eat something sweet and savory.

4. Discussion

To our knowledge, the present study is the first large-scale, long-term study to investigate the relationship between quality and quantity of carbohydrate sources and subjective appetite sensations during WLM. We found that in participants with moderate total carbohydrate and dietary fiber intake, with low to moderate GI, total carbohydrate and GL were positively associated with increases in hunger, desire to eat, desire to eat something sweet, and weight regain. Higher GI was associated with greater weight regain, but not increased subjective appetite sensations. Surprisingly, we also found that total dietary fiber was positively associated with increases in desire to eat, after adjustment for carbohydrate or GL.

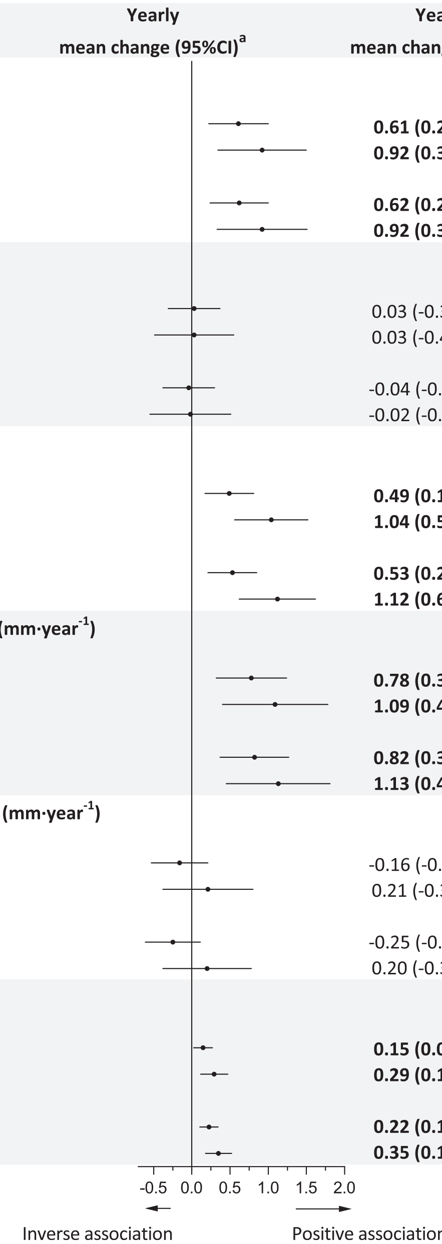


Outcomes	Yearly mean change (95%CI)[a]	P-value
ΔHunger (mm·year^{-1})		
Complete-case analysis		
Model 1	-0.007 (-0.76, 0.75)	0.986
Model 2	-0.36 (-1.31, 0.58)	0.452
Available-case analysis		
Model 1	-0.16 (-0.90, 0.59)	0.681
Model 2	-0.50 (-1.46, 0.45)	0.299
ΔSatiety (mm·year^{-1})		
Complete-case analysis		
Model 1	-0.19 (-0.85, 0.48)	0.583
Model 2	0.10 (-0.73, 0.93)	0.813
Available-case analysis		
Model 1	-0.15 (-0.81, 0.51)	0.656
Model 2	0.07 (-0.75, 0.90)	0.860
ΔDesire to eat (mm·year^{-1})		
Complete-case analysis		
Model 1	0.50 (-0.11, 1.12)	0.108
Model 2	0.59 (-0.18, 1.37)	0.134
Available-case analysis		
Model 1	0.42 (-0.20, 1.04)	0.184
Model 2	0.48 (-0.31, 1.28)	0.235
ΔDesire to eat something sweet (mm·year^{-1})		
Complete-case analysis		
Model 1	**1.16 (0.27, 2.04)**	**0.010**
Model 2	0.82 (-0.27, 1.92)	0.140
Available-case analysis		
Model 1	**1.12 (0.25, 1.99)**	**0.012**
Model 2	0.98 (-0.11, 2.08)	0.079
ΔDesire to eat something savory (mm·year^{-1})		
Complete-case analysis		
Model 1	-0.27 (-1.00, 0.45)	0.462
Model 2	-0.08 (-1.02, 0.86)	0.870
Available-case analysis		
Model 1	-0.38 (-1.09, 0.33)	0.297
Model 2	-0.07 (-1.00, 0.86)	0.884
ΔBody weight (%·year^{-1})		
Complete-case analysis		
Model 1	**0.58 (0.34, 0.82)**	**<0.001**
Model 2	**0.63 (0.36, 0.91)**	**<0.001**
Available-case analysis		
Model 1	**0.62 (0.39, 0.85)**	**<0.001**
Model 2	**0.60 (0.34, 0.87)**	**<0.001**

Fig. 3. Longitudinal associations of glycemic index (GI) (each 10 unit) with yearly changes in subjective appetite sensation ratings and percentage of body weight during weight-loss maintenance. Analyses were performed using a linear mixed model with repeated measures. Model 1 was adjusted for age, sex, ethnicity, intervention group, appetite sensation ratings or body weight at 8 weeks, BMI at the start of weight-loss maintenance (8 weeks), and time as fixed factors and intervention center and participant-ID as random factors. Model 2 was additionally adjusted for time-varying device-measured total physical activity and time-varying self-reported dietary components including percentage of energy from fat, protein, fiber, and alcohol as fixed factors. [a]Yearly mean change and 95% CI of main effects indicating the amount of increase in appetite sensation ratings or percentage of body weight increased per year by 10-unit increment in GI.

In the present study, we found positive associations of appetite sensations, especially desire to eat something sweet, with GL only, but not with GI, which provides support for the carbohydrate-insulin model of obesity [32]. Compared with GI or carbohydrate content, GL is a better predictor of postprandial glycemia [33]. Consumption of high GL diets induce hyperinsulinemia and promote deposition of metabolic fuels to fat tissue. Decreased circulating fuels increase hunger, preference for fasting-digestible carbohydrate, and energy intake [32]. In line with our findings, Chang et al. [34] reported that low GL diets were more satiating than high GL diets in 80 individuals with normal weight and overweight or obesity in a 4-week randomized study. However, it is difficult to separate the effect of GL from fiber, as fiber was not controlled for in that trial and low GL diets had 2-fold higher fiber compared with high GL diets (55 vs 28 g·day^{-1} of fiber) [34]. It is worth noting that although we did not find associations between GI and appetite sensations, we observed positive associations of GI with weight regain. This implies low GI may not affect BW by improving appetite regulation, but via metabolic effects [35].

In the present study, we found positive associations of total carbohydrate intake with subjective appetite sensations. Building on previous research studies investigating the relationship between carbohydrate and subjective appetite, the majority of which



Outcomes	Yearly mean change (95%CI)[a]	*P*-value
ΔHunger (mm·year^{-1})		
Complete-case analysis		
Model 1	**0.61 (0.23, 1.00)**	**0.002**
Model 2	**0.92 (0.33, 1.50)**	**0.002**
Available-case analysis		
Model 1	**0.62 (0.24, 1.00)**	**0.001**
Model 2	**0.92 (0.33, 1.51)**	**0.002**
ΔSatiety (mm·year^{-1})		
Complete-case analysis		
Model 1	0.03 (-0.32, 0.37)	0.886
Model 2	0.03 (-0.49, 0.55)	0.916
Available-case analysis		
Model 1	-0.04 (-0.38, 0.30)	0.824
Model 2	-0.02 (-0.54, 0.51)	0.951
ΔDesire to eat (mm·year^{-1})		
Complete-case analysis		
Model 1	**0.49 (0.18, 0.81)**	**0.002**
Model 2	**1.04 (0.55, 1.52)**	**<0.001**
Available-case analysis		
Model 1	**0.53 (0.21, 0.85)**	**0.001**
Model 2	**1.12 (0.62, 1.62)**	**<0.001**
ΔDesire to eat something sweet (mm·year^{-1})		
Complete-case analysis		
Model 1	**0.78 (0.33, 1.24)**	**<0.001**
Model 2	**1.09 (0.41, 1.78)**	**0.002**
Available-case analysis		
Model 1	**0.82 (0.37, 1.27)**	**<0.001**
Model 2	**1.13 (0.44, 1.81)**	**<0.001**
ΔDesire to eat something savory (mm·year^{-1})		
Complete-case analysis		
Model 1	-0.16 (-0.53, 0.21)	0.394
Model 2	0.21 (-0.38, 0.80)	0.485
Available-case analysis		
Model 1	-0.25 (-0.62, 0.11)	0.170
Model 2	0.20 (-0.39, 0.78)	0.508
ΔBody weight (%·year^{-1})		
Complete-case analysis		
Model 1	**0.15 (0.02, 0.27)**	**0.020**
Model 2	**0.29 (0.12, 0.47)**	**0.001**
Available-case analysis		
Model 1	**0.22 (0.10, 0.34)**	**<0.001**
Model 2	**0.35 (0.18, 0.52)**	**<0.001**

Fig. 4. Longitudinal associations of glycemic index (GL) (each 20 unit) with yearly changes in subjective appetite sensation ratings and percentage of body weight during weight-loss maintenance. Analyses were performed using a linear mixed model with repeated measures. Model 1 was adjusted for age, sex, ethnicity, intervention group, appetite sensation ratings or body weight at 8 weeks, BMI at the start of weight-loss maintenance (8 weeks), and time as fixed factors and intervention center and participant-ID as random factors. Model 2 was additionally adjusted for time-varying device-measured total physical activity and time-varying self-reported dietary components including percentage of energy from fat, protein, fiber, and alcohol as fixed factors. [a]Yearly mean change and 95% CI of main effects indicating the amount of increase in appetite sensation ratings or percentage of body weight increased per year by 20-unit increment in GL.

were conducted over a period of less than 2 years, our findings provide new insights into longer-term associations. In a separate analysis based on the two PREVIEW RCT diet groups, we also found that compared with a moderate carbohydrate, moderate protein diet (carbohydrate~42 E%, protein~19 E%, and fat~33 E%), a lower carbohydrate, higher protein diet (carbohydrate~38 E%, protein~22 E%, and fat~35 E%) was superior in preventing an increase in hunger during WLM [36]. Cheng et al. [37], however, found no significant changes in appetite sensation ratings between higher carbohydrate (carbohydrate~58 E%, protein~20 E%, and fat~21 E%) and higher protein diets (carbohydrate~41 E%, protein~32 E%, and fat~25 E%) in a 1-year weight management trial in women. The conflicting findings may be explained by the variation in macronutrient content and complicated interplay between dietary factors especially dietary fiber [16] and energy density. Dietary protein has been reported to play an important role in appetite regulation [8] and body weight regulation [38]. In the PREVIEW RCT analysis, we did not find differences in weight change between participants in the lower carbohydrate, higher protein and moderate carbohydrate, moderate protein diet groups [36]. In the present study, however, we adjusted for several dietary components especially protein intake, that may affect the results and found a positive association between total carbohydrate and weight regain.

Outcomes	Yearly mean change (95%CI)[a]	P-value
ΔHunger (mm·year^{-1})		
Complete-case analysis		
Model 1	**0.92 (0.14, 1.70)**	**0.021**
Model 2	**2.19 (1.09, 3.30)**	**<0.001**
Available-case analysis		
Model 1	**0.95 (0.18, 1.73)**	**0.016**
Model 2	**2.20 (1.10, 3.30)**	**<0.001**
ΔSatiety (mm·year^{-1})		
Complete-case analysis		
Model 1	-0.0005 (-0.69, 0.69)	0.999
Model 2	-0.34 (-1.33, 0.64)	0.492
Available-case analysis		
Model 1	0.08 (-0.61, 0.77)	0.822
Model 2	-0.38 (-1.35, 0.59)	0.445
ΔDesire to eat (mm·year^{-1})		
Complete-case analysis		
Model 1	**1.32 (0.68, 1.97)**	**<0.001**
Model 2	**2.16 (1.22, 3.09)**	**<0.001**
Available-case analysis		
Model 1	**1.56 (0.91, 2.21)**	**<0.001**
Model 2	**2.51 (1.57, 3.46)**	**<0.001**
ΔDesire to eat something sweet (mm·year^{-1})		
Complete-case analysis		
Model 1	0.85 (-0.08, 1.78)	0.072
Model 2	**1.31 (-0.002, 2.63)**	**0.050**
Available-case analysis		
Model 1	0.86 (-0.06, 1.77)	0.067
Model 2	**1.41 (0.11, 2.70)**	**0.034**
ΔDesire to eat something savory (mm·year^{-1})		
Complete-case analysis		
Model 1	0.24 (-0.52, 0.99)	0.539
Model 2	**1.34 (0.23, 2.46)**	**0.018**
Available-case analysis		
Model 1	0.19 (-0.56, 0.93)	0.618
Model 2	**1.33 (0.24, 2.41)**	**0.016**
ΔBody weight (%·year^{-1})		
Complete-case analysis		
Model 1	-0.14 (-0.39, 0.11)	0.266
Model 2	-0.05 (-0.38, 0.28)	0.764
Available-case analysis		
Model 1	-0.02 (-0.27, 0.22)	0.841
Model 2	0.10 (-0.22, 0.42)	0.530

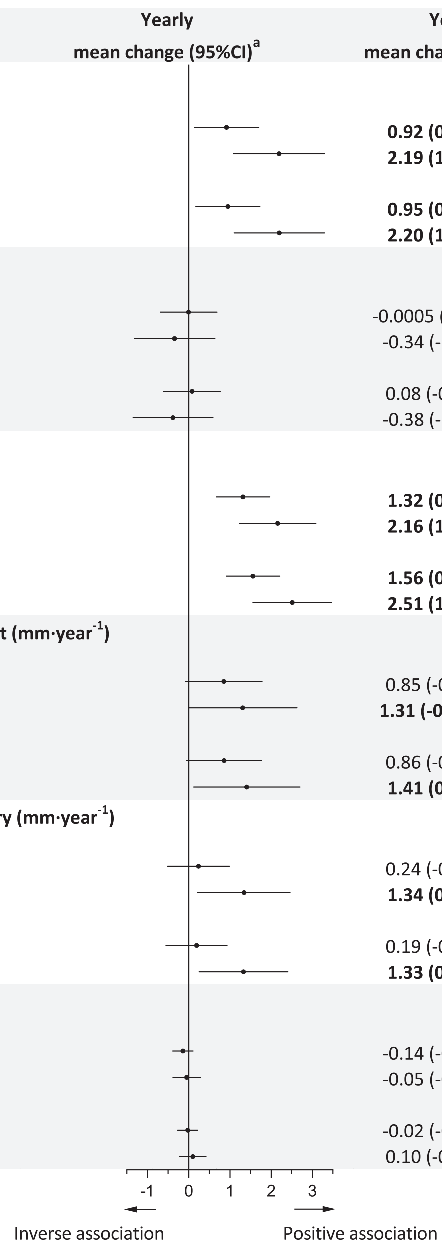


Fig. 5. Longitudinal associations of total dietary fiber (each 10 g·day^{-1}) with yearly changes in subjective appetite sensation ratings and percentage of body weight during weight-loss maintenance. Analyses were performed using a linear mixed model with repeated measures. Model 1 was adjusted for age, sex, ethnicity, intervention group, appetite sensation ratings or body weight at 8 weeks, BMI at the start of weight-loss maintenance (8 weeks), and time as fixed factors and intervention center and participant-ID as random factors. Model 2 was additionally adjusted for time-varying device-measured total physical activity and time-varying self-reported dietary components including percentage of energy from carbohydrate, fat, protein, and alcohol as fixed factors. [a]Yearly mean change and 95% CI of main effects indicating the amount of increase in appetite sensation ratings or percentage of body weight increased per year by 10 g·day^{-1} increment in fiber.

Surprisingly, in the current study, dietary fiber was positively associated with desire to eat, which was inconsistent with previous studies with null findings [39]. The inconsistency of the results may be explained by study design, fiber dose, and differences in subtypes/sources (eg soluble and insoluble fiber; fiber from grains and vegetables) and properties/characteristics (eg particle size, viscosity, gel formation, fermentability, and molecular weight) of fiber [40], which were not considered in the present analysis. We only investigated total dietary fiber, but we excluded fiber supplements. A systematic review suggested that β-glucan (from oats and barley), whole-grain rye, rye bran, and a mixed diet with fiber-rich foods (eg legumes, vegetables, and fruits) might enhance subjective satiety ratings and reduce food intake, whereas psyllium, resistant starch, and wheat bran were not beneficial and in some cases increased appetite ratings [18]. For fiber dose, a systematic review suggested that low total fiber or unavailable carbohydrate intake (5.0–7.4 and 10.0–14.9 g) showed some benefits in subjective satiety ratings, whereas higher fiber intake (30.0–49.9 g) had little effect and 26.2 g of fiber had smallest effect on satiety ratings [18]. In the current study, participants had moderate fiber intake [22.3 (17.6, 27.3) g·day^{-1}] during WLM, but few long-term studies have explored the effect of this range of fiber dose on satiety and the result remains unclear.

Notably, the conflicting results on subjective appetite sensations in the literature may also be explained by differences in the baseline characteristics and interplay of dietary factors, but other reasons may be the assessment of dietary intake and appetite sensations. Short-term studies tend to provide fixed meals and the information of dietary intake is easy to obtain [9,41]. In longer-term studies with *ad libitum* diets, however, dietary intake is estimated via food records, 24-h food recalls or frequency questionnaires [42,43]. Different dietary assessment procedures may introduce bias [43]. Considering assessment of subjective appetite sensation, VAS is commonly used. In short-term studies with fixed meals [41,44–46], acute postprandial appetite is determined at different time points, whereas in longer-term studies the procedures are variable. Some longer-term and weight management interventions evaluate overall daily or weekly appetite [11,27,37], as we did in the present study. For instance, in a 2-year WL intervention, the participants were asked to recall overall appetite during the course of a week at each visit [37].

This secondary analysis of the PREVIEW study dataset has some strengths. First, compared with small-scale studies, this international, multi-center study has a larger population and larger statistical power, which allowed us to adjust for many important confounding factors, especially dietary factors and physical activity. Moreover, we analyzed long-term, repeatedly measured total carbohydrate, GI, GL, and dietary fiber with concurrent changes in appetite sensations, which may show deeper insights into causally relevant associations. Finally, In the PREVIEW study, participants were not only given dietary recommendation, but also encouraged to have high-intensity or moderate PA. In an updated perspective, Beaulieu et al. [47] suggested that habitual physical activity may affect appetite by increasing both drive to eat and satiety. In the current analysis we adjusted for total PA or different types of PA and demonstrated that the association of total carbohydrate and GI with appetite was independent of total and different types of PA.

The weaknesses should also be considered. First, the attrition rate, especially in the third year of the study, was larger than expected and we found significant differences between completers and non-completers in BW, BMI and dietary intake at the beginning of WLM. In order to reduce bias, we conducted both available-case and complete-case analyses. Second, in this study the 4-day food record, a self-report dietary assessment tool to determine total carbohydrate, GI, GL, and fiber, may cause random errors (mainly driven by day-to-day variations in dietary intake) and reactivity bias [48]. Moreover, we did not explore the associations of different fiber subtypes or fiber from different sources, as these sub-categories were not included in our dietary dataset. In addition, because of the dietary interventions, PREVIEW participants did not have a wide range of carbohydrate, GI, GL, and fiber intake, which may make the findings less generalizable. Our findings may not apply to those with high GI with low fiber intake or to low GI with high fiber intake. Finally, as this study is an observational analysis, residual and unmeasured confounders may exist and cause bias. Taken together, our findings, especially those regarding fiber, should be interpreted with caution.

5. Conclusion

The current secondary analysis showed that in participants with moderate carbohydrate and fiber intake with low to moderate GI, higher total carbohydrate, GL, and total dietary fiber, but not GI, were associated with increases in subjective desire to eat or hunger over 3 years. As this study is observational and exploratory, the findings should considered as hypotheses. Further studies, especially RCTs with high evidence hierarchy, should examine and compare longer-term effects of different fiber dose, types and sources.

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Authors' contributions

The PREVIEW project was designed by AR, JB-M, MW-P, MF, Wolfgang Schlicht (WS), and Edith Feskens. The protocol for the PREVIEW adult intervention study was written by MF, TML, and AR. MWP, JAM, SP, WS, SH, Ian Macdonald, and Gareth Stratton were involved in developing the study design. All authors contributed to the implementation of the experimental trial and contributed to analysis and interpretation of the data. RZ drafted the manuscript. All authors contributed to critical revision of the manuscript for important intellectual content. All authors agreed that the accuracy and integrity of the work has been appropriately investigated and resolved, and all approved the final version of the manuscript. The corresponding author had full access to the data and had final responsibility for the decision to submit for publication. The corresponding author attests that all listed authors meet authorship criteria, and that no others meeting the criteria have been omitted. AR and RZ are the guarantors of this work and, as such, had full access to all of the data in the study and take responsibility for the integrity of the data. RZ takes responsibility for the accuracy of the data analysis.

Data availability statement

The datasets generated for this study are available on request to the corresponding author.

Conflicts of interest

AR has received honorariums from the International Sweeteners Association and Unilever. JB-M is President and Director of the Glycemic Index Foundation, oversees of a glycemic index testing service at the University of Sydney and is a co-author of books about diet and diabetes. She is also a member of the Scientific Advisory Board of the Novo Foundation and of ZOE Global. SDP was the Fonterra Chair in Human Nutrition during the PREVIEW intervention. TML is advisor for "Sense" diet programme. TL is employed by NetUnion sarl, who contributed to the data collection process in the absence of commercial or financial conflict of interest with the study analysis. The rest of the authors declare that they have no potential conflicts of interests.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.clnu.2021.11.038.

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