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Glycaemic index and glycaemic load of breakfast predict cognitive function and mood in school children: a randomised controlled trial

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Abstract

The macronutrient composition of a breakfast that could facilitate performance after an overnight fast remains unclear. As glucose is the brain's major energy source, the interest is in investigating meals differing in their blood glucose-raising potential. Findings vary due to unaccounted differences in glucoregulation, arousal and cortisol secretion. We investigated the effects of meals differing in glycaemic index (GI) and glycaemic load (GL) on cognition and mood in school children. A total of seventy-four school children were matched and randomly allocated either to the high-GL or low-GL group. Within each GL group, children received high-GI and low-GI breakfasts. Cognitive function (CF) and mood were measured 95–140 min after breakfast. Blood glucose and salivary cortisol were measured at baseline, before and after the CF tests. Repeated-measures ANOVA was used to identify differences in CF, mood, glucose and cortisol levels between the breakfasts. Low-GI meals predicted feeling more alert and happy, and less nervous and thirsty ($P<0·05$ for each); high-GL meals predicted feeling more confident, and less sluggish, hungry and thirsty ($P<0·05$ for each). High-GL ($P<0·001$) and high-GI ($P=0·05$) meals increased glucose levels 90 min after breakfast, and high-GI meals increased cortisol levels ($P<0·01$). When baseline mood, glucose and cortisol levels were considered, low-GI meals predicted better declarative-verbal memory ($P=0·03$), and high-GI meals better vigilance ($P<0·03$); observed GI effects were valid across GL groups. GI effects on cognition appear to be domain specific. On balance, it would appear that the low-GI high-GL breakfast may help to improve learning, and of potential value in informing government education policies relating to dietary recommendations and implementation concerning breakfast.

Key words: Feeding trials: Glycaemic index: Glycaemic load: Cognitive function: Mood: Breakfast: School children: Adolescents

The potential influences of nutritional factors on cognitive function (CF) and mood in children are of major importance, especially during adolescence, which is a crucial period for the development and maturation of both body and mind[1]. Skipping breakfast has been shown to have adverse effects on memory and learning[2–11]. Nonetheless, despite the wealth of studies that have been conducted in this area, the macronutrient composition of a breakfast that could selectively facilitate CF after an overnight fast remains unclear. Since glucose is the major source of energy for the central nervous system, it has been suggested that glucose content may be mediating the memory-enhancing effects of breakfast[12,13]; the effects of glucose on CF have been extensively reviewed[14–18]. Nonetheless, pure glucose will rarely be consumed as part of a balanced diet. Therefore, the interest nowadays is in varying the carbohydrate quality of breakfast meals by means of the glycaemic index (GI), and the subsequent glycaemic responses (the potential mediator), to test whether low-GI meals can facilitate performance by minimising glycaemia fluctuations[7,19–22]. The findings from recent studies differ, in part because of variations in design, and especially in relation to the cognitive domains affected. Furthermore, the underlying mechanism remains unclear; it has been recently suggested that perhaps an interaction between glucoregulatory processes, arousal and cortisol could be mediating any observed effects[23].

To elucidate these issues, we investigated the effects of breakfast meals that differed in their blood glucose-raising potential (i.e. glycaemic potency) on CF and mood in seventy-four adolescent school children. The glycaemic potency of carbohydrate-containing meals can be evaluated not only by GI[24], but also by glycaemic load (GL), which is

Abbreviations: CF, cognitive function; GI, glycaemic index; GL, glycaemic load.

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a stronger predictor of the glycaemic response[25,26]. Although GL is in part a function of GI, they represent two different aspects of dietary impact on blood glucose; GI reflects the rate of absorption of carbohydrate, while GL reflects the rate of the quantity of carbohydrate absorbed. Of course, these measures of carbohydrate quality are not the same physiologically as carbohydrate content *per se*. Therefore, the aim of the present study was to (i) take into account both the GI and the GL as measures of carbohydrate quality; (ii) use breakfast meals that have been tested in relation to their glycaemic and insulinaemic responses[27]; (iii) measure capillary blood glucose and salivary cortisol levels (the latter as a biomarker of stress); (iv) assess mood both as a predictor of CF and as an outcome of the meals; and (v) report findings in adolescents. We hypothesised that 90 min after breakfast, CF test scores would be higher and mood would be improved on a low-GI high-GL breakfast compared with a high-GI low-GL breakfast. The assumptions made were that a low-GI meal would be better compared with a high-GI meal, and that a high-GL meal would potentiate the glycaemic potency of a meal compared with a low-GL meal.

Experimental methods

Design and participants

We studied girls and boys aged 11–14 years in good health and free from learning disabilities from five schools in London (2324 pupils approached, ninety-four recruited, twenty dropped out and seventy-four completed the study). Recruitment began in November 2006. The present study was conducted according to the guidelines laid down in the Declaration of Helsinki and all procedures involving human subjects/patients were approved by the King's College Research Ethics Committee. Written informed consent was obtained first by the head teachers of participating schools, and then individually from each participant and their parents/guardians. No monetary or other incentive was offered to the pupils or schools to participate in the study. The School Food Trust (Department of Education and Skills, London, UK) was an external collaborator, and offered £500 to each school as a token of appreciation on completion of the study and without previously informing them that any funds would be offered.

We administered four breakfast meals differing in their GI and GL (2 × 2 factorial design) in thirty-two pairs of matched children in a randomised cross-over design. Participants were matched (see Screening section below) and randomly allocated either to a high-GL or a low-GL group: if one participant was allocated to the high-GL group, their match was allocated to the low-GL group. Within each GL group, children were given a high-GI and a low-GI breakfast (see Testing and Breakfast meals sections below).

Screening

A screening questionnaire was filled in by the parents/carers to determine socio-economic class based on occupation (i.e. analytic class)[28], and level of education as adapted from the Low Income Diet and Nutrition (LIDNS) survey[29], and to exclude children for medical or other grounds (i.e. anaemia or other blood disorders, diabetes or glucose intolerance, other acute or chronic illnesses/diseases, colour blindness, learning disabilities and mood disorders). Children who never had breakfast or had allergy or intolerance to any of the components of the breakfast meals were also excluded.

Following receipt of the questionnaire, appointments for in-person screening were made for all initially suitable pupils on a random day of the school week at 08.10 hours. Height and weight were measured to further exclude pupils that were underweight or obese (BMI-for-age z scores, −2 SD or +2 SD, respectively)[30,31]. Eligible participants were matched on same school year, same sex, height (± 3–5 cm), age (± 6 months), BMI (± 1 centile) and same school. A fasting baseline saliva sample was also taken to measure cortisol levels on a 'stress-free' day as a pre-test measure to compare it with cortisol levels on a 'testing' day when stress levels would in theory be higher.

A brief interview followed: participants were asked about food and drink consumed (if any) on the morning of the screening, their usual eating habits and physical activity, their current health status, medication/supplements, sleeping patterns and menstrual status. A photographic atlas of food portion sizes[32] was used to quantify the amounts of food and drink consumed, which has been previously validated[33].

Testing

After recruitment into the study and successful screening, each participant was seen twice more (2 weeks apart). Participants were given instructions to follow the day before and on the morning of their appointment, which was set at 08.00 hours, and on the same day of the week. Instructions were based on the standard GI testing protocol[34], and on the cortisol testing[35]. Specifically, the day before their appointment participants were asked to follow their normal routine, to avoid alcohol consumption, to limit consumption of caffeine-containing products, to restrict their participation in intense physical activity, and to have a good night's sleep (about 8 h). In addition, participants were instructed to record their dinner before each appointment, which had to be the same before each visit and consumed by 21.00 hours. Subjects were studied after a 10–12 h overnight fast. On the morning of the testing, participants were asked not to drink (with the exception of water) or eat anything, and to avoid any form of strenuous physical activity.

The order of procedures was as follows: brief screening to ensure nothing was eaten on the morning; saliva sample (baseline); finger-prick blood sample (baseline); mood scales (baseline); breakfast administration; anthropometric measurements. At 90 min after the start of breakfast the following procedures took place: saliva sample (before); finger-prick blood sample (before); mood scales (before); CF testing; mood scales (after); task demand questions; saliva sample (after); finger-prick blood sample (after). The entire testing procedure lasted on average 56 (SE 7) min.

Blood measurements

Hb was measured using 'HemoCue' (CV = 1·3 %) (HemoCue Ltd, Lake Forest, CA, USA). Blood glucose was measured using the Accu-Chek Aviva BG meter[36] (Roche Diagnostics Ltd, Burgess Hill, West Sussex, UK), which is a whole blood calibrated meter, clinically acceptable for extra-laboratory use[37], as it meets the acceptable criterion for imprecision at all concentration levels (CV < 5 %)[38].

Salivary cortisol

Saliva samples were collected at the same time interval for all participants across all visits (i.e. baseline samples were collected between 08.15 and 08.45 hours). We used the tasteless 'Salivette' with a cotton swab without preparation (Starstedt Ltd, Leicester, Leics, UK). 'Salivettes' were frozen within 4–6 h after collection at −20°C in batches. All samples were analysed on completion of the study by King's College's Biochemistry Laboratory for analysis, to minimise variation by using the same lot number of reagents. A specifically adapted ELISA was used to measure salivary cortisol (DRG ELISA kit; DRG International, Mountainside, NJ, USA); intra-assay variability was < 3 % CV, and inter-assay variability < 7 % CV.

Anthropometric measurements

Pupils were weighed in their shirt and trousers or skirt (school uniform), after being instructed to remove their blazer, jumper and shoes, on a portable weighing scale (Salter scale), and measured for height using a portable stadiometer (Leicester height measure; Chasmores Ltd, London, UK).

Assessment of cognitive function

The CF tests selected have been previously used in studies to detect differences in CF induced by glucose administration[13,39,40]. We used the same tests in a pilot cross-sectional study to test the validity of their use in sixty children of same age range, when detecting differences in CF associated with meals differing in their GI and GL[22]. The tests were administered in the same order for each participant for both visits, as follows: word generation task (1); immediate word recall (2); Stroop task (3); matrices (4); number search task (5); serial sevens (6); delayed word recall (7). We created two versions of the same tests for the two visits (for a detailed description of the tests, see the Supplementary Appendix, available online at http://www.journals.cambridge.org/bjn).

Assessment of mood

A self-rating mood questionnaire was developed from the Profile of Mood States bipolar form (POMS-BI)[41] and the short form of the Activation-Deactivation Adjective Checklist. It was modified from previous research[42]; twenty-two words were used to assess mood, energy levels, hunger and thirst, as previously used and described[22]. Responses were made on integer scales from zero ('not at all') to four ('extremely') (for the list of the twenty-two moods states assessed, see the Supplementary Appendix; http://www.journals.cambridge.org/bjn).

In a self-reported task demand questionnaire, participants rated how difficult, effortful and tiring they found the tests to be, using the same rating scale.

Breakfast meals

The breakfast meals were designed to differ in their GI and GL: a low-GI high-GL, a high-GI high-GL, a low-GI low-GL, and a high-GI low-GL. These meals had been previously tested with regard to their glycaemic, insulinaemic and cortisol responses in young adults 0–3 h following breakfast administration[27]. There was a 2-fold difference in GL between the high- and the low-GL meals, and a 1·3-fold difference between the low- and the high-GI meals. The foods that comprised the four test meals and their macronutrient composition are presented in Table 1.

The macronutrient and micronutrient composition of the individual foods that comprised the test meals was obtained from the Nutrient Databank[29,43–46]. The GI of the individual foods was obtained either from the International Table of GI and GL values[47] or from more recently published values

Table 1. Foods and macronutrient composition of the breakfast meals administered in seventy-four adolescent school children*

	Breakfast meals			
	High GL		Low GL	
	Low GI	High GI	Low GI	High GI
Foods				
Alpen muesli, no added sugar (g)	66	0	40	0
Cornflakes (g)	0	55	0	30
Semi-skimmed milk (ml)	200	300	250	300
Apple juice (ml)	245	200	0	0
Sugar, white (g)	7	7	5	5
Volume of liquid food (ml)	445	500	250	300
Water (ml)	55	0	250	200
Macronutrient composition				
GI	48	61	48	61
GL	41	55	21	28
Energy (kJ)	1965·2	1960·6	1176·5	1153·1
Energy (kcal)	469·7	468·6	281·2	275·6
Protein (g)	13·9	14·0	12·5	12·0
Fat (g)	7·1	5·3	6·4	5·1
Of which saturated fats (g)	2·7	3·4	3·0	3·4
Carbohydrate (g)	86·6	90·4	43·2	45·2
Of which sugar (g)	54·7	48·6	23·9	22·4
Of which starch (g)	31·9	41·8	19·4	22·8

GL, glycaemic load; GI, glycaemic index.

* The GI values are expressed relative to glucose[34]. The mean GI values for each of the foods are: Alpen muesli, no added sugar (Weetabix), 55 (SE 10) (food entry: 198(46)); cornflakes (Kellogg's), 81 (SE 3) (food entry: 168(46)); semi-skimmed milk (Tesco), 25 (SE 6) (food entry: 66(47)); apple juice, fresh (Tesco), 40 (SE 1) (food entry: 32(46)); sugar, white (Tate and Lyle), 68 (SE 5) (589(46)). The GI of the composite meals was calculated as the sum of weighted GI values of the foods comprising the meal[49], and the glycaemic load (GL) of the composite meal as the sum of the GL values of all the foods comprising the meal[50]. The total volume of the meals was made the same (500 ml) with the addition of water.

based on UK products[48]. The GI values were expressed relative to glucose[34]. The total volume of the meals was made the same (500 ml) with the addition of water. The GI of the composite meals was calculated as the sum of weighted GI values of the foods comprising the meal[49], and the GL of the composite meal as the sum of the GL values of all the foods comprising the meal[50].

Participants and researchers were blinded to the meal administered. Each individual food was weighed with food scales (Precisa XB 3200D; Precisa Instruments Ltd, Dietikon, Switzerland) to the nearest 0·1 g on the morning of the testing. Participants were instructed to consume the meal at a comfortable pace within 15 min, and to consume all food and drink provided; otherwise, they would have to be excluded from the study (this was never the case for any of the participants). Time zero was regarded as the time when eating commenced. Participants were also instructed to remain seated and as calm and relaxed as possible throughout the testing period.

Statistical analysis

Repeated-measures ANOVA was used to identify differences in blood glucose and cortisol responses, mood and CF scores between the four breakfast meals, using initially only GI as the within-subject factor (low, high), and GL as the between-subject factor (low, high), and then adding potential confounders. For all repeated measures (glucose, cortisol and mood) the 'minus baseline' values consisted our prespecified primary analysis, as they take into account any baseline variations. The analysis for glucose and cortisol levels included as potential confounders the order of administration of the breakfast meals, and sex. The analysis for each of the mood states included as confounders the order of administration of the breakfast meals, sex, age, height, weight, BMI, and glucose and cortisol levels at baseline. The repeated-measures analysis for each of the main CF tests included the same confounders that were used for mood, plus mood at baseline. Glucose levels, cortisol levels and mood immediately before the CF tests were regarded as potential intermediates (i.e. explanatory variables in the pathway between breakfast consumption and CF), and were thus not included as covariates in the analysis for cognitive performance. All P values were two-tailed ($\alpha = 0{\cdot}05$). Analyses were performed using SPSS 15.0 (SPSS, Inc., Chicago, IL, USA).

Results

Descriptive characteristics

Table 2 presents the descriptive characteristics of the sample, by GL group. Of the seventy-four participating children, sixty-four were exact matches (i.e. thirty-two matched pairs). Due to some pupils dropping out, of the remaining ten children, seven were in the low- and three were in the high-GL group, respectively. The two GL groups were well matched based on our prespecified matching criteria, with no statistically significant differences observed in mean age, height, weight, BMI and school year.

Table 2. Descriptive characteristics in seventy-four children participating in the study, in the two glycaemic load (GL) groups*

(Number of subjects and percentages or mean values with their standard errors)

	GL groups			
	High		Low	
	n	%	*n*	%
Children (*n*)	35		39	
Females	17		20	
Males	18		19	
Age (years)				
Mean	12·6		12·6	
SE	0·1		0·1	
Height (cm)				
Mean	156·1		157·3	
SE	1·1		1·3	
Weight (kg)				
Mean	46·8		49·4	
SE	1·3		1·4	
BMI (kg/m^2)				
Mean	19·1		19·9	
SE	0·4		0·4	
Hb (g/l)				
Mean	130·7		128·4	
SE	1·6		1·1	
School year				
7	15	42·9	15	38·5
8	18	51·4	22	56·4
9	2	5·7	2	5·1
Ethnic group				
White	16	45·7	16	41·0
Black	11	31·4	14	35·9
Asian	2	5·7	7	17·9
Other	6	17·1	2	5·1
Analytic class†				
AC 1·1	2	6·1	1	3·1
AC 1·2	3	9·1	5	15·6
AC 2	14	42·4	10	31·3
AC 3	3	9·1	1	3·1
AC 4	4	12·1	1	3·1
AC 5	1	3·0	1	3·1
AC 6	4	12·1	4	12·5
AC 7	1	3·0	3	9·4
AC 8	1	3·0	6	18·8
Education				
Higher degree	4	12·1	11	30·6
Degree	10	30·3	8	22·2
A level	5	15·2	7	19·4
GCSE	6	18·2	7	19·4
Other	8	24·2	3	8·3

AC, analytic class; GCSE, General Certificate of Secondary Education.

* All differences were not statistically significant ($P<0{\cdot}05$; unpaired t test for continuous variables and χ^2 test for categorical variables).

† Socio-economic class based on occupation[28]: AC 1·1, large employers and higher managerial occupations; AC 1·2, higher professional occupations; AC 2, lower managerial and professional occupations; AC 3, intermediate occupations; AC 4, small employers and own account workers; AC 5, lower supervisory and technical occupations; AC 6, semi-routine occupations; AC 7, routine occupations; AC 8, never worked before and long-term unemployed.

Glycaemic index, glycaemic load and blood glucose and salivary cortisol levels

There were no statistically significant differences in the actual time of the day that glucose and cortisol levels were measured at baseline, before, and after the CF tests for all three meals (data not shown). The testing was accurately timed with a stopwatch to start 90 min after breakfast. Cortisol levels were

British Journal of Nutrition

measured first on average 89·8 min after breakfast (minimum 89·4, maximum 90·2 min), followed by glucose levels on average 92·3 min after breakfast (minimum 92·0, maximum 93·0 min). After the CF tests, cortisol levels were measured on average 142·9 min after breakfast (minimum 142·3, maximum 143·5 min), and glucose levels 146·5 min after breakfast (minimum 145·5, maximum 147·5 min). Baseline cortisol levels on the screening day did not differ from baseline cortisol levels on either testing visit (data not shown).

Average blood glucose and salivary cortisol levels in the four GI and GL breakfasts are presented in Table 3. Sex and the order of meal administration were unrelated to these measures. Fig. 1 depicts the 'minus baseline' glucose and cortisol values before and after the CF tests, which differed among the four GI and GL groups. Specifically, high-GI and high-GL meals increased blood glucose levels before the CF tests ($P=0·05$, $P<0·001$, respectively), and high-GL meals increased blood glucose levels after the CF tests ($P<0·001$). High-GI meals also increased cortisol levels both before ($P=0·03$) and after ($P<0·01$) the CF tests.

Glycaemic index, glycaemic load and mood

Table 4 presents average mood states across the four GI and GL breakfast meals. After consuming the low-GI meals, participants reported feeling less nervous ($P=0·04$), more happy ($P=0·04$), more alert ($P=0·05$) and less thirsty ($P=0·05$) compared with after consuming the high-GI meals. After consuming the high-GL meals, participants reported feeling more confident ($P<0·01$), less sluggish ($P=0·01$), less hungry ($P<0·01$) and less thirsty ($P=0·03$) compared with after consuming the low-GL meals (Table 4). These effects were sustained after the CF tests (data not shown). Repeating the analysis with the addition of potential confounders resulted in similar findings (data not shown).

Glycaemic index, glycaemic load and cognitive function

CF testing commenced 103 min (minimum 101, maximum 105 min) after breakfast, and ended 136 min (minimum 133, maximum 138 min) after breakfast. There were no differences in the time that the CF testing started or how long it lasted between the four GI and GL groups ($P>0·05$). Table 5 presents the mean CF scores for the four GI and GL breakfast meals. Repeated-measures ANOVA without potential confounders resulted in only a few significant associations (data not shown). Repeating the analysis with the addition of potential confounders revealed the following: the low-GI meals predicted better performance on the word generation task ($P=0·03$); and the high-GI meals predicted better performance on the Stroop (in the high-GL meals only) ($P=0·03$), speed of information processing ($P=0·01$) and serial sevens task ($P=0·03$). There were no significant differences between males and females, with the exception of the serial sevens task, where males performed better than females.

Discussion

Whereas breakfast skipping is commonly considered to have detrimental effects on memory and learning, our findings

Table 3. Blood glucose and salivary cortisol levels in seventy-four children participating in the study, in the four glycaemic index (GI) and glycaemic load (GL) breakfast meals

(Mean values with their standard errors)

	Breakfast meals										
	High GL				Low GL						
	Low GI		High GI		Low GI		High GI		*P**		
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	GI	GI × GL interaction	GL
Subjects (*n*)	35		35		39		39				
Females	17		17		20		20				
Males	18		18		19		19				
Blood glucose levels (mmol/l)											
Baseline	5·1	0·1	5·1	0·1	5·1	0·1	4·9	0·1			
Before the CF tests	5·5	0·1	5·6	0·1	5·0	0·1	5·0	0·1	0·25	0·28	<0·001
After the CF tests	5·3	0·1	5·4	0·1	5·0	0·1	4·9	0·1	0·96	0·11	0·001
Before minus baseline	0·4	0·1	0·6	0·1	−0·1	0·1	0·0	0·1	0·05	0·58	<0·001
After minus baseline	0·2	0·1	0·4	0·1	−0·1	0·1	−0·1	0·1	0·25	0·35	<0·001
After minus before	−0·1	0·1	−0·2	0·2	0·0	0·1	−0·1	0·1	0·40	0·88	0·24
Salivary cortisol levels (ng/ml)											
Baseline	5·1	0·3	4·9	0·3	4·8	0·3	4·4	0·2			
Before the CF tests	3·9	0·2	3·9	0·2	3·5	0·2	3·6	0·2	0·75	0·28	0·14
After the CF tests	3·7	0·2	3·8	0·2	3·3	0·1	3·6	0·1	0·05	0·27	0·27
Before minus baseline	−1·2	0·2	−1·1	0·2	−1·3	0·2	−0·8	0·2	0·03	0·27	0·70
After minus baseline	−1·6	0·3	−1·2	0·2	−1·5	0·3	−0·8	0·2	<0·01	0·35	0·40
After minus before	−0·3	0·2	−0·1	0·2	−0·1	0·1	0·0	0·1	0·24	0·88	0·53

CF, cognitive function.

* *P* values for repeated-measures ANOVA that was carried out to identify differences in blood glucose and salivary cortisol levels between the four breakfast meals, using GI as the within-subject factor and GL as the between-subject factor. The addition of sex and the order of meal administration as potential confounders resulted in similar findings (data not shown).

British Journal of Nutrition

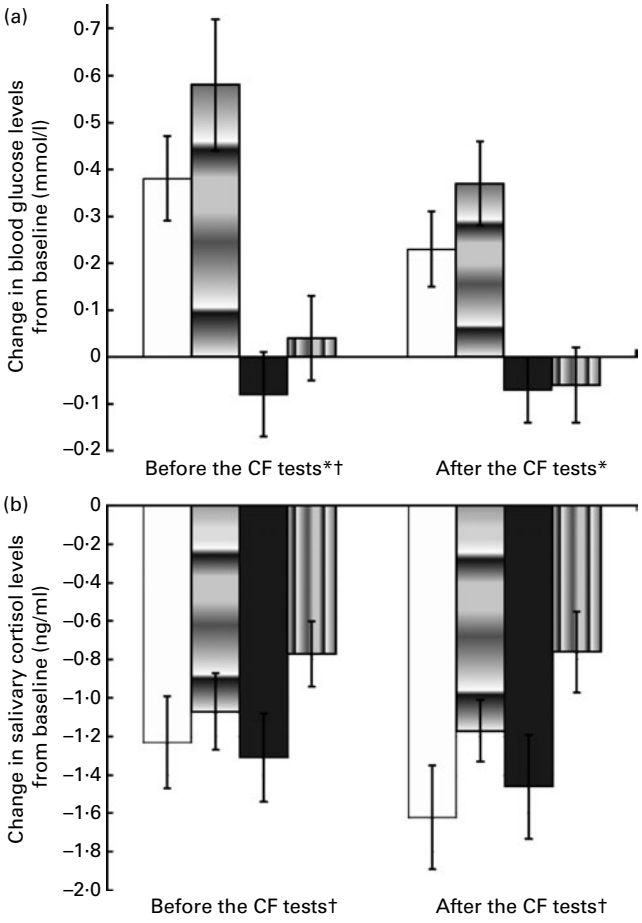

Fig. 1. Change in blood glucose (a) and salivary cortisol (b) levels from baseline levels in seventy-four children participating in the study, in the four glycaemic index (GI) and glycaemic load (GL) breakfast meals: low-GI high-GL (□); high-GI high-GL (▤); low-GI low-GL (■); high-GI low-GL (◧). Values represent the change from baseline levels at two time points: before and after the administration of the cognitive function (CF) tests; that is, 92–147 min after breakfast for glucose levels (a) and 90–143 min after breakfast for cortisol levels (b). Values are means, with standard errors represented by vertical bars. Repeated-measures ANOVA was carried out to identify differences in blood glucose levels between the four breakfast meals, using GI as the within-subject factor, and GL as the between-subject factor. The addition of sex and the order of meal administration as potential confounders resulted in similar findings (data not shown). *Statistically significant GL differences ($P<0·05$). † Statistically significant GI differences ($P<0·05$).

indicate that the type of breakfast consumed can also affect both mood and cognitive performance. The effects of breakfast composition on CF in school children are currently not well characterised, nor have the mechanisms mediating any observed effects been elucidated. The present randomised controlled feeding trial considered the use of both GI and GL to assess the effects of breakfast on mood and CF in adolescents, and measured glucose and cortisol levels to elucidate potential underlying mechanisms. The findings of the present study highlight the potential of a low-GI high-GL breakfast meal for improved learning, possibly mediated through its effects on glucose and cortisol levels.

The high-GL meals administered had by definition higher energy content compared with the low-GL meals, driven mainly by differences in carbohydrate content; protein and fat content was relatively similar across all four GI and GL meals. Thus, any observed GL effects cannot be strictly differentiated from potential differences in energy and macronutrient content *per se*. In contrast, within the same GL group, high- and low-GI meals had similar energy and macronutrient composition, separating any GI effects from potential energy and macronutrient content differences. Therefore, the results of the present research should be interpreted in that context.

These breakfast meals differing in their GI and GL were capable of inducing differences in glucose levels, as measured 90 min after breakfast administration; high-GI and high-GL meals increased glucose levels, as would be expected based on physiological responses to meals differing in GI and GL[51]. Of note, the effects of GL on glycaemia 90 min after breakfast administration were more profound compared with the effects of GI. It could be that differences in glucose levels due to GI are more pronounced in the earlier postprandial period (blunted over time), a finding further reinforced by the lack of significant GI effects approximately 2.5 h after breakfast administration. Furthermore, the addition of milk in a mixed meal, which was higher in content in the high-GI meals, could have potentially resulted in a lower GI[52], and thus smaller detectable differences in blood glucose responses due to GI. On the contrary, 2.5 h after breakfast administration the high-GL meals still significantly predicted increased glucose levels.

These meals differing in their GI and GL should not be expected to affect cortisol levels, as cortisol is associated with response to stress. Indeed, we have previously shown that meals differing in their GI and GL do not affect cortisol levels when stress is not present[27]. Cortisol levels fall progressively throughout the morning. Therefore, since the high-GI meals predicted higher cortisol levels both before and after the CF tests, this suggests that low-GI meals may be associated with reduced response to stressful stimuli (such as CF testing).

Mood was also affected by the meal administered. The observed effects were not confounded by sex, visit, age, height, weight, BMI, blood glucose and salivary cortisol values. Specifically, in the high-GL meals participants reported feeling more confident, less sluggish, less hungry, and less thirsty; that is, they had improved mood before the CF tests. Similarly, in the low-GI groups participants reported feeling more happy and alert, and less nervous and thirsty. Therefore, the present findings suggest that a low-GI high-GL breakfast improves mood approximately 90–140 min later. The effects of high-GL meals, particularly the satiating effects, cannot be strictly differentiated from the potential effects of higher energy and macronutrient content *per se* in the high-GL meals. There was also a GL and GI effect on how thirsty the children reported feeling. Since the liquid volume of the meals administered was the same between all meals, and the water consumed by the participants during the testing controlled for (none of them had water after the meal) it might in fact reflect a satiating effect. The satiating effects of a low-GI *v.* a high-GI breakfast meal have already been documented, and it has also been suggested that changes in blood levels rather that the levels *per se* are strongly related

Table 4. Mood states in seventy-four children participating in the study, in the four glycaemic index (GI) and glycaemic load (GL) breakfast meals†
(Mean values with their standard errors)

	Breakfast meals										
	High GL				Low GL						
	Low GI		High GI		Low GI		High GI		*P**		
Mood scales	Mean	SE	Mean	SE	Mean	SE	Mean	SE	GI	GI × GL interaction	GL
Friendly	0·5	0·1	0·3	0·1	0·5	0·1	0·5	0·1	0·59	0·44	0·48
Nervous	−0·6	0·2	−0·2	0·2	−0·4	0·2	−0·1	0·1	0·04	0·79	0·35
Drowsy	−0·6	0·2	−0·4	0·1	−0·4	0·2	−0·3	0·1	0·34	0·89	0·37
Happy	0·5	0·1	0·2	0·1	0·3	0·1	0·1	0·1	0·04	1·00	0·28
Calm	0·0	0·1	0·2	0·2	0·3	0·1	0·0	0·1	0·75	0·06	0·68
Uncertain	−0·1	0·1	−0·1	0·1	−0·3	0·1	−0·3	0·1	0·76	0·91	0·22
Sad	0·1	0·1	−0·1	0·1	0·1	0·1	−0·1	0·1	0·06	0·97	0·53
Energetic	0·9	0·2	0·4	0·2	0·5	0·2	0·4	0·2	0·09	0·21	0·41
Muddled	−0·1	0·1	−0·1	0·1	−0·1	0·1	0·0	0·1	0·76	0·42	0·66
Relaxed	0·4	0·2	0·3	0·2	0·1	0·1	0·2	0·1	0·97	0·35	0·23
Dissatisfied	−0·1	0·1	0·0	0·0	0·1	0·1	−0·1	0·1	0·93	0·06	0·34
Alert	0·5	0·2	0·2	0·2	0·6	0·2	0·3	0·2	0·05	0·98	0·63
Confident	0·4	0·2	0·3	0·1	0·1	0·1	−0·2	0·1	0·27	0·71	<0·001
Tired	−0·6	0·2	−0·7	0·1	−0·6	0·2	−0·6	0·2	0·61	0·90	0·91
Angry	−0·1	0·1	0·0	0·1	0·0	0·1	0·0	0·1	0·22	0·36	0·49
Contented	0·1	0·2	−0·1	0·2	−0·3	0·2	0·2	0·2	0·47	0·07	0·75
Lively	0·6	0·2	0·5	0·2	0·5	0·2	0·2	0·1	0·24	0·69	0·27
Tense	−0·1	0·1	−0·1	0·2	−0·2	0·2	−0·1	0·1	0·86	0·86	0·65
Sluggish	−0·6	0·2	−0·3	0·1	−0·1	0·1	−0·1	0·1	0·26	0·35	0·01
Clearheaded	0·3	0·2	0·2	0·2	0·2	0·2	0·3	0·2	0·67	0·56	1·00
Hungry	−2·1	0·2	−2·0	0·2	−1·5	0·2	−1·2	0·2	0·12	0·42	<0·01
Thirsty	−1·6	0·2	−1·1	0·2	−0·9	0·2	−0·8	0·2	0·05	0·38	0·03

* *P* values for repeated-measures ANOVA that was carried out to identify differences in mood states before the cognitive function tests between the four breakfast meals, using GI as the within-subject factor, and GL as the between-subject factor. The addition of the order of meal administration, sex, age, height, weight, BMI, and glucose and cortisol levels at baseline as potential confounders resulted in similar findings (data not shown).
† Mood state values represent 'minus baseline' levels.

to satiety[53]; similarly, for high-GL meals[54]. These findings suggesting that high-GL and low-GI meals decrease fatigue and increase alertness are in agreement with what has been previously hypothesised[15].

CF was particularly unaffected by GL, and the observed GI effects were valid across GL groups, not supporting a potential role for energy and macronutrient content on the specific measures of cognitive performance. The addition of baseline measurements of mood, blood glucose and cortisol levels as possible confounders strengthened the findings, suggesting that individual differences in these measures are important confounding factors that should be taken into account. Performance on four out of seven tests was predicted by GI, possibly mediated through its effects on mood, glucose and cortisol levels before CF administration. Specifically, low GI improved performance on a word generation task (declarative

Table 5. Cognitive function test scores in seventy-four children participating in the study, in the four glycaemic index (GI) and glycaemic load (GL) breakfast meals
(Mean values with their standard errors)

	Breakfast meals										
	High GL				Low GL						
	Low GI		High GI		Low GI		High GI		*P**		
Cognitive function tests	Mean	SE	Mean	SE	Mean	SE	Mean	SE	GI	GI × GL interaction	GL
Word generation task (no. of words)	16·0	0·8	15·2	0·8	15·2	0·7	14·1	0·8	0·03	0·36	0·66
Word recall, immediate (no. of words)	6·7	0·4	6·6	0·3	7·2	0·3	7·3	0·3	0·93	0·55	0·14
Time of completion in Stroop task† (s)	47·3	2·0	44·9	1·7	47·2	1·5	47·5	1·6	0·19	0·03	0·58
Matrices (no. of matrices)	11·8	0·4	12·2	0·4	12·3	0·4	12·0	0·4	0·77	0·18	0·76
Speed of information processing (no. of hits)	12·7	0·7	13·8	0·7	12·4	0·7	13·9	0·7	0·01	0·20	0·71
Serial sevens (no. of subtractions)	16·3	1·8	17·2	1·7	15·1	1·9	16·2	1·8	0·03	0·71	0·56
Word recall, delayed (no. of words)	4·5	0·4	4·8	0·3	5·1	0·4	5·4	0·4	0·30	0·88	0·19

* *P* values for repeated-measures ANOVA analysis with GI as the within-subject factor and GL as the between-subject factor. Potential confounders included: the order of administration of the breakfast meals, sex, age, height, weight, BMI, mood, glucose and cortisol levels at baseline.
† For the Stroop task, lower scores represent better performance, as performance was measured in seconds; therefore, the quicker the completion, the better the performance.

British Journal of Nutrition

verbal memory), and high GI improved performance on the Stroop task, a speed of information processing and a serial sevens task (all assessing vigilance). Matrices performance was unrelated to GI and GL, possibly because it reflects acquired information and learned material over a longer period of time, leaving little potential for learning, and for a short-term impact of GI and GL to take place. The reason why word recall (immediate and delayed) was not related to either GI or GL could be because the task was not sensitive enough to detect differences in GI and/or GL (i.e. perhaps the words selected were not as difficult). Indeed, previous studies looking into glucose administration and CF have not always shown an effect on this task[40,55,56], while others have[19].

Only recently have GI or GL been used as a tool to assess the effects of carbohydrate-containing foods or meals on CF or mood[7,19–21]. Across all of these intervention studies, it seems that there are inconsistencies regarding all cognitive domains, including declarative verbal memory and vigilance, as well as mood. These inconsistencies can be partially attributed to not accounting for both GI and GL (particularly for mood), and to not trying to control for potentially important confounding factors. Indeed, in our pilot cross-sectional study of sixty children that considered both GI and GL, associations were observed with both measures of carbohydrate quality[22]. There should be a distinction between a low glycaemic response as determined by both GI and GL (the recommended approach), and a low glycaemic response as determined solely by GI or GL. The literature to date generally predicts that a low glycaemic response could be beneficial for CF and mood, but it does not distinguish between a high, intermediate, and a truly low glycaemic response (i.e. the lowest among the meals compared when both the GI and GL are taken into account).

The present findings are in support of what has been previously hypothesised[23]: that glucose and cortisol levels, as a result of the meal administered and of the arousing situation (i.e. CF testing), interact to bring about effects on CF and mood. It could be argued that a high-GI meal and, as a result of that, higher blood glucose levels could result in stronger activation of the hypothalamic–pituitary–adrenal axis in anticipation of potentially demanding or stressful situations, reflected by the higher cortisol levels and participants reporting feeling more nervous before the tests, and thus better performance on vigilance tasks (i.e. how quickly information is being processed). On the contrary, a low-GI meal, and as a result of that lower blood levels, could result in lower activation of the hypothalamic–pituitary–adrenal axis in anticipation of potentially demanding or stressful situations, reflected by the lower cortisol levels and participants reporting feeling less nervous before the tests, and thus showing better performance on memory tasks. This proposed mechanism is consistent with the view that fasting, and, as a result, lower blood glucose levels, has been shown to result in a blunted hypothalamic–pituitary–adrenal axis response[57]. Therefore, it seems that blood glucose levels as a result of the meal administered mediate the cortisol response under demanding situations, subsequently affecting cognitive performance. It thus appears that the GI effect is domain specific, across GL. In a school environment, this may equate to an ability to retain newly acquired information and to access and recall information already stored in memory, which may be more important for learning than how quickly information is processed.

The present study had limitations. First of all, participants were matched between the low- and the high-GL group, increasing the power of the study, but resulting in each participant receiving only two of the four test meals. Exposing the students to all four test meals would pose different limitations, potentially more damaging to the integrity of the study. Doubling the number of the visits (i.e. five in total with the screening) would increase the drop-out rates, which were high in any case. It would also increase participant effects, such as expectancy effects and familiarity with the tasks (and the meals), which could potentially result in ceiling effects or loss of interest. Second, like other studies in the field[7,19,20,23,58], we did not have a baseline measure of performance, as the interest was in short-term differences of high- or low-GI and -GL meals on CF, and not on whether there is an improvement or decline in overall CF as a result of a meal. Third, in all these studies, the GI calculations were based on published values[47], which may have introduced error in the estimation of the exposure. However, any resulting exposure misclassification would be more likely to attenuate the significant associations observed here[59]. Finally, the tests were administered in the same order for every participant and on both occasions. It could be argued that by administering the tests in the same order, there may be an interaction between the tests which might have endangered or obscured an effect of GI or GL. It was thought, however, that the likelihood of interactions between tests (and hence any advantages of randomisation) was small, and that the possible benefits of randomisation would be outweighed by possible disadvantages, principally the complex logistics associated with creating different versions of the test administration booklet for each child, which then raised the risk of loss of adherence to the test protocol.

The present findings are likely to be physiologically and psychologically representative of the general school population aged 11–14 years. While the present study does not include a random sample of the entire UK school population, it is a population-based sample of adolescent school children from five different schools with a wide variety of abilities and social and ethnic mix. Furthermore, there is no strong reason to suspect that the biological effects of the glycaemic potency of breakfast in these adolescent school children will be different from the effects in adolescent school children in general. The low response rate (< 10 %) could be an issue of internal validity (i.e. selection bias). The potential selection biases are hard to overcome, since the many ways the respondents differ from non-respondents cannot be known.

The importance of breakfast *v.* no breakfast in school life and performance has been long established. Our findings further demonstrate that the carbohydrate profile of breakfast may be of importance. Our findings also identify specific gaps in our understanding of how the glycaemic potency of

British Journal of Nutrition

breakfast influences CF and mood, particularly potential effects of GI and GL on mood, satiety and cognition; and of specific physiological responses (i.e. glucose, cortisol) that could be underlying these relationships, highlighting the need for further investigation of such effects. Considering the beneficial effects of low-GI and high-GL meals on mood, and of low-GI meals on the ability to preserve acquired information and to readily use stored information, our findings suggest that on balance a low-GI high-GL meal may be advantageous in a learning environment. These findings may be particularly relevant to school breakfast policies, as consumption of breakfast meals with specific carbohydrate profiles may help to improve the learning and academic potential of children.

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