Breakfast glycaemic index and cognitive function in adolescent schoolchildren

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Abstract

It has been suggested a low glycaemic index (GI) breakfast may be beneficial for some elements of cognitive function (for example memory and attention), but the effects are not clear, especially in adolescents. Thus, the aim of the present study was to examine the effects of a low GI breakfast, a high GI breakfast and breakfast omission on cognitive function in adolescents. Forty-one adolescents (12-14 years old) completed three trials in a randomised cross-over design. Participants consumed a low GI breakfast, a high GI breakfast, or omitted breakfast. A battery of cognitive function tests was completed 30 and 120 min following breakfast consumption and capillary blood samples were taken during the 120 min postprandial period. The findings show there was a greater improvement in response times following a low GI breakfast, compared to breakfast omission on the Stroop (P=0.009) and Flanker (P=0.041) tasks, and compared to a high GI breakfast on the Sternberg paradigm (P=0.013). Furthermore, accuracy on all three tests was better maintained on the low GI trial compared to the high GI (Stroop: P=0.039; Sternberg: P=0.018; Flanker: P=0.014) and breakfast omission (Stroop: P<0.001; Sternberg: P=0.050; Flanker: P=0.014) trials. Following the low GI breakfast, participants displayed a lower glycaemic response (P<0.001) than following the high GI breakfast, but there was no difference in the insulinaemic response (P=0.063) between the high and low GI breakfasts. Therefore, we conclude that a low GI breakfast is most beneficial for adolescents' cognitive function, compared with a high GI breakfast or breakfast omission.

1. Introduction

Breakfast consumption, as opposed to breakfast omission, has a positive impact on cognitive function in adults [1, 2], children [3] and adolescents [4, 5]. In adults, the effects on cognition of breakfasts differing in macronutrient content [6], glycaemic load [7] and glycaemic index (GI) [8-10] have also been examined, with evidence suggesting that low GI foods are beneficial for some aspects of adults' cognitive function, including working memory [8, 10] and attention [10].

Fewer studies have examined the effect of the GI of breakfast on cognitive function of young people and adolescents, and the findings have been equivocal [3]. It has been suggested that adolescent populations are particularly important to study in this field as whilst going through puberty, adolescents undergo rapid growth and changes in metabolism and thus their responses may be different to those of younger children and adults [11, 12]. Furthermore, the academic work completed by adolescents is of a greater complexity than in younger children, compounded by ongoing assessments at school. Therefore, the additional academic stress could exacerbate any nutritional effects on cognitive function [11].

However, only three studies to date have examined the effect of the GI of breakfast on cognitive function in an adolescent population [13-15]. One of these studies has shown that a high GI glucose drink and breakfast omission resulted in a decline in attention and memory during the school morning, but this decline was reduced following the consumption of low GI breakfast cereals [13]. However, nutritional information on the breakfasts was not provided and there was a wide age range of participants (9 to 16 year olds), not all of whom were adolescents. In contrast, another study has shown that 90 min after breakfast consumption, 14-17 year olds were able to remember more items following a high compared to a low GI breakfast [15]. It was suggested that this enhanced memory could be the result of higher blood glucose concentrations following the high GI breakfast, which would be beneficial under the

conditions of divided attention. However, there were no significant differences in blood glucose concentration between the trials and only one element of cognitive function was assessed, namely verbal episodic memory. In the one further study it was reported that performance on a speed of information processing task and a serial sevens task was enhanced following a low GI breakfast, whereas a high GI breakfast was beneficial for immediate word recall [(14)]. However, the breakfasts provided were not matched on key variables, such as energy and carbohydrate content.

Thus, the findings are equivocal regarding the effects of the GI of breakfast on cognitive function in adolescents, with the possibility that the effects of high and low GI breakfasts vary for different elements of cognitive function. Therefore, the aim of the present study was to conduct a randomised control trial, using a crossover design, to assess the effects of a high GI breakfast, a low GI breakfast and breakfast omission on cognitive function in adolescent schoolchildren. The study employed a battery of computer tests to assess various elements of cognitive function. Furthermore, blood glucose and plasma insulin concentrations were measured to allow a possible insight into the mechanisms for any effects of the GI of breakfast on cognitive function in adolescent school children.

2. Methodology

2.1: Study Design

This study was conducted according to the guidelines laid down in the Declaration of Helsinki and all procedures were approved by Loughborough University Ethical Advisory Committee. Participants were recruited from two local schools, and in accordance with the ethical guidelines of the British Education Research Authority for school-based research, school-level consent was obtained from head teachers. In addition, written parental informed consent

was obtained and a health screen questionnaire completed to ensure all participants were in good health.

Each participant undertook a familiarisation session followed by three experimental trials. During familiarisation, which preceded the first experimental trial by seven days, the protocol of the study was explained to participants and they were provided with an opportunity to familiarise themselves with the methods involved. Participants were allowed to repeat the cognitive function tests until they felt comfortable with them, to negate any potential learning effects.

The study employed a randomised crossover design and was order balanced, with participants blind until arrival at school on each day of testing. The experimental trials consisted of a high glycaemic index breakfast (high GI) trial, a low glycaemic index breakfast (low GI) trial and breakfast omission trial (where breakfast was provided upon completion of the protocol). Therefore, participants acted as their own controls and the effects of the different breakfast conditions can be assessed as within-subject factors, yielding greater sensitivity. Trials were scheduled seven days apart and participants reported to school at the normal time. The experimental protocol is shown in figure 1.

(Insert figure 1 here)

Upon arrival at school participants rested in a seated position for 10 min and then a capillary blood sample was taken. The protocol commenced as participants began breakfast on the high and low GI trials, whereas on the breakfast omission trial the protocol commenced after the resting capillary blood sample had been collected. On the high and low GI trials, participants were given 15 min to consume breakfast, whereas on the breakfast omission trial participants rested for 15 min. Capillary blood samples and the cognitive function tests were completed during the subsequent monitoring period. A 120 min monitoring period was selected based

upon recommendations which suggest that this is a sufficient period of time to elicit the different glycaemic responses between the meals [16]. This is also the period of time after which it is suggested the effects of breakfast consumption on cognitive function will become apparent in young people [5, 13, 14, 17].

2.2: Participants

Fifty-two participants aged 12 to 14 years were recruited to participate in the study. However, eleven participants were removed from the study because they were absent from school for one or more of the experimental trials (n = 9), or did not follow the dietary requirements (n = 2). Therefore, forty-one participants completed the study. During familiarisation height, body mass and waist circumference were measured. Height was measured using a Leicester Height Measure (Seca, Hamburg, Germany), accurate to 0.1 cm. Body mass was measured using a Seca 770 digital scale (Seca, Hamburg, Germany), accurate to 0.1kg. These measures allowed the determination of Body Mass Index (BMI), calculated by dividing body mass (kg) by the square of the height (m^2). Waist circumference was measured at the narrowest point of the torso between the xiphoid process of the sternum and the iliac crest, to the nearest 0.1cm. Table 1 provides the physiological characteristics of the participants.

(Insert table 1 here)

2.3: Dietary Control

Participants were asked to consume a meal of their choice the evening before their first experimental trial and then to repeat this meal for each of the subsequent trials. Participants fasted from 10 pm the evening before each experimental trial. In order to maintain euhydration, participants were allowed to drink water ad libitum during this time. In addition, participants avoided any unusually vigorous exercise for 24 h prior to each experimental trial. Prior to each main trial a telephone call was made to participants to remind them of this

information. On the day of each experimental trial, participants were asked to indicate if they had followed the above requirements when they arrived at school.

2.4: Capillary Blood Sample

Capillary blood samples were taken at baseline and 15, 30, 60 and 120 min after breakfast consumption on each trial. Capillary blood samples were preferred to venous blood samples in the present study because they are more sensitive to glycaemic responses and show a lower between subject variation [16, 20-22]. Furthermore, capillary blood samples were more acceptable to the adolescents participating.

Participants' hands were warmed via submersion in warm water to increase capillary blood flow. A Unistik single use lancet (Unistik Extra, 21G gauge, 2.0 mm depth, Owen Mumford Ltd., UK) was used and the blood collected into two 300 µl EDTA coated microvettes (Sarstedt Ltd., UK). Two 25 µl whole blood samples were removed using 25 µl plain pre-calibrated glass pipettes (Hawksley Ltd., UK), immediately deproteinised in 250 µl of 2.5% ice cooled perchloric acid in 1.5 ml plastic vials and centrifuged at 7000 rev.min^{-1} for 4 minutes (Eppendorph 5415C, Hamburg, Germany). The remaining whole blood was also centrifuged at 7000 rev.min^{-1} for 4 min (Eppendorph 5415C, Hamburg, Germany) and the plasma removed and placed into 500 µl plastic vials. All samples were frozen at -20 ºC until analysis.

Blood glucose concentrations were determined using a commercially available kit (GOD-PAP method, GL 2610, Randox, Ireland) and were analysed spectrophotometrically (Cecil CE393 digital grating spectrophotometer, Cambridge, UK). Plasma insulin concentrations were determined using an enzyme-linked immuno-sorbent assay (ELISA) (Mercodia Ltd., Sweden). Incremental area under the curve (IAUC) for blood glucose and plasma insulin was calculated using previously described methods [23].

2.5: Cognitive Function Tests

The battery of cognitive function tests was administered via a laptop computer and took approximately 15 min to complete. The battery of tests included a Stroop test, the Sternberg Paradigm and a Flanker task. Written instructions appeared on the screen at the start of each test, which were repeated verbally by an investigator. Each cognitive function test was preceded by 3-6 practice stimuli, where feedback was provided regarding whether the participants' response was correct or not. This allowed the participants to re-familiarise themselves with each of the tests and ensure that instructions were fully understood. Results from these practice stimuli were discarded and once the test started no feedback was provided. The cognitive function tests were found to be suitable (avoiding floor or ceiling effects) for the study population during familiarisation and were administered in the following order:

2.5.1: Stroop Test

The Stroop test measures the sensitivity to interference and the ability to suppress an automated response and is a widely used measure of executive function [24, 25]. The Stroop test consisted of two levels (baseline and complex). Both levels involved a test word being placed in the centre of the screen, with the target and distractor presented randomly on the right or left of the test word. The target position was counterbalanced for the left and right side within each level of the test. The participant was asked to respond as quickly as possible, using the left and right arrow keys, to identify the position of the target word.

The baseline level contained 20 stimuli, where the test word was printed in white and the participant had to select the target word, from the target and distractor, which were also printed in white. The colour-interference level contained 40 stimuli and involved the participant selecting the colour the test word was written in, rather than the actual word (which was an incongruent colour), again using the right and left arrow keys to identify the

target. The choices remained on the screen until the participant responded. The variables of interest were the response times of correct responses and the proportion of correct responses made.

2.5.2: Sternberg Paradigm

The Sternberg Paradigm [26] is a test of working memory and has three levels. Each level used a different working memory load; one, three or five items. On the baseline (number) level, the target was always the number '3'. This level contained 16 stimuli and provides a measure of basic information processing speed. The three- and five-item levels had target lists of three and five letters respectively, each containing 32 stimuli.

At the start of each level, the target items were displayed together with instructions to press the right arrow key if the stimulus was a target item and the left arrow key otherwise. The correct responses were counterbalanced on each level between the right and left arrow keys. The choice stimuli were presented on the centre of the screen with an inter-stimulus interval (ISI) of 1 second, during which the screen was blank. The choices remained on the screen until the participant responded. The variables of interest were the response times of correct responses and the proportion of correct responses made.

2.5.3: Flanker Task

The Flanker task assesses aspects of attention and has two levels, congruent and incongruent. On the congruent level, five arrows appear on the screen, all pointing in the same direction (left or right). The participant is asked to select the arrow key pointing in the same direction as the arrows. On the incongruent level, the arrows point in different directions and the participant selected the arrow key pointing in the same direction as the central arrow. On both levels, the arrows were presented in green on a black background, after a varied delay of 400 to 4000 ms. The items remained on the screen until the participant responded. The variables

of interest were the response times of correct responses and the proportion of correct responses made.

2.6: Breakfast

Breakfast was provided after the resting measures had been taken and participants had 15 min to consume breakfast. The high and low GI breakfasts both contained 1.5 $g.kg^{-1}$ body mass available carbohydrate and were matched for energy, protein and fat content. Water was provided at the start of the protocol on the high GI (150 ml) and breakfast omission (350 ml) trials, to ensure that total water intake was the same between trials. Furthermore, 150 ml of water was provided after 60 min on each trial. The breakfast composition for a 50 kg participant is shown in table 2.

(Insert table 2 here)

2.7: Statistical Analysis

The blood glucose and plasma insulin data were analysed using SPSS (Version 16, SPSS Inc., Chicago, Il, USA) via two-way Analysis of Variance (ANOVA) for repeated measures (trial by session time).

The cognitive function data were analysed using R (www.r-project.org, version 2.9.1). Linear mixed effects models were used to analyse the data, corrected for repeated measures with a random effect for each participant. Response time analyses were performed using the nlme package and accuracy analyses were performed with the lme4 package with a binomial outcome data distribution to properly account for the binomial (correct/incorrect) accuracy scores. All analyses were conducted using a three-way trial by session time by test level interaction. Where the three-way interaction was not significant, a two-way trial by session time interaction was conducted. For all analyses, significance was set as $P < 0.05$.

3. Results

3.1: Cognitive Function Tests

All participants completed all cognitive function tests at each time point (n = 41 for all analysis). For all timed cognitive tests the response times were first log-transformed to normalise the distributions, which exhibited the right-hand skew typical of human response times. Minimum response time cut-offs were then chosen based on what may reasonably be expected to be the fastest possible human response to the given stimuli (200 – 300 ms, depending on task complexity) to exclude unreasonably fast responses, which relate to response key presses before stimuli have even been perceived. Maximum response time cut-offs were determined so as to remove unreasonably long right-hand tails for a normal distribution, corresponding to 5 standard deviations individually for each test and test level.

3.1.1: Stroop Test

Response Times: Only response times of correct responses were used for analysis. Using the methods previously described responses faster than 250 ms for both test levels and slower than 2500 ms for the baseline level and 4000 ms for the complex level were removed.

Response times were quicker following the high GI breakfast when compared to the low GI breakfast (main effect of trial, $t(1,13537) = 2.1$, $P = 0.031$). Response times following the high GI breakfast tended to be quicker 120 min following breakfast consumption when compared to breakfast omission, an effect specific to the complex level, but this did not reach statistical significance (trial by session time by test level interaction, $t(1,13530) = 1.8$, $P = 0.079$, figure 2). Furthermore, response times following the low GI breakfast were quicker 120 min following breakfast consumption when compared to breakfast omission and again this effect was specific to the complex level (trial by session time by test level interaction, $t(1,9019) = 2.6$, $P = 0.009$, figure 2). However, the pattern of change in response times across

the morning between the high and low GI trials was not different (trial by session time by test level interaction and trial by time interaction, both $P > 0.05$).

(Insert figure 2 here)

Accuracy: Students achieved more correct responses following the low GI breakfast compared to following both the high GI breakfast (main effect of trial, effect size = 0.011, $z(1,14820) = 2.1$, $P = 0.039$) and breakfast omission (main effect of trial, effect size = 0.274, $z(1,14820 = 3.6$, $P < 0.001$). However, there was no significant difference in the proportion of correct responses between the high GI and breakfast omission trials (main effect of trial, $P = 0.150$).

On the high GI trial, there was a greater decrease in accuracy across the morning when compared to the low GI trial (trial by session time interaction, effect size = 0.024, $z(1,14820) = 2.1$, $P = 0.033$, figure 3). However, this effect was not specific to the test level (trial by session time by test level interaction, $P = 0.121$). There were no other significant interactions between the different conditions and the testing time and/or the test level (all $P > 0.05$).

(Insert figure 3 here)

3.1.2: Sternberg Paradigm

Response Times: Only response times of correct responses were used for analysis. Using the methods previously described, responses faster than 200 ms and slower than 2000 ms for all test levels were removed.

Overall, participants responded quicker following breakfast omission compared to following both the high GI breakfast (main effect of trial, $t(1,17468) = 3.6$, $P < 0.001$) and the low GI breakfast (main effect of trial, $t(1,17468) = 2.5$, $P = 0.011$). However, whilst response times remained similar across the morning following the high GI breakfast, there was a greater

improvement in response times across the morning following the low GI breakfast (trial by session time interaction, t(1,17438) = 2.5, P = 0.013, figure 4).

(Insert figure 4 here)

Accuracy: Overall, participants achieved a greater proportion of correct responses following the low GI breakfast when compared to breakfast omission (main effect of trial, effect size = 0.010, z(1,19520) = 2.1, P = 0.036), but there was no difference between the low GI and high GI or the high GI and breakfast omission trials (main effects of trial, P = 0.118 and P = 0.586 respectively).

Whilst accuracy was similar across the morning between the trials on the easier levels (figures 5a and 5b), on the more complex levels of the Sternberg paradigm accuracy was better maintained across the morning following the low GI breakfast when compared to the high GI breakfast (trial by session time by test level interaction, effect size = 0.040, z(1,19520) = 3.1, P = 0.002, figure 5c). There was also a tendency for accuracy to be better maintained across the morning following the low GI breakfast when compared to the breakfast omission trial, again this effect was only evident on the more complex levels (trial by session time by test level interaction, effect size = 0.025, z(1,19520) = 2.0, P = 0.051, figure 5c).

(Insert figure 5 here)

3.1.3: Flanker Task

Response Times: Only response times of correct responses were used for analysis. Using the methods previously described responses faster than 100 ms and slower than 2500 ms were removed.

Overall, response times between the trials were not significantly different (main effects of trial: high GI vs. low GI, P = 0.497; high GI vs. breakfast omission, P = 0.909); low GI vs.

breakfast omission, P = 0.634). There was a greater improvement in response times across the morning following the low GI breakfast when compared to breakfast omission (trial by session time interaction, t(1,13630) = 2.0, P = 0.045, figure 6). Apart from this trial by session time interaction, response times across the morning were similar between the trials on both test levels (all other interactions, P > 0.05).

(Insert figure 6 here)

Accuracy: Overall, there was no significant difference in the proportion of correct responses between the trials (main effects of trial: high GI vs. low GI, P = 0.931; high GI vs. breakfast omission, P = 0.859; low GI vs. breakfast omission, P = 0.805). However, on the incongruent (more complex) level, accuracy was better maintained across the morning following the low GI breakfast compared to the high GI breakfast (trial by session time by test level interaction, effect size = 0.033, z(1,14700) = 2.5, P = 0.014, figure 7b) and breakfast omission (trial by session time by test level interaction, effect size = 0.042, z(1,14700), P = 0.001, figure 7b).

(Insert figure 7 here)

3.2: Capillary Blood Samples

Blood Glucose: Blood glucose concentrations and the pattern of response across the morning were different between the trials (main effect of trial, time and trial by time interaction, all P < 0.001). However, because the differences between breakfast omission and breakfast consumption were expected, the following results consider only the high GI and low GI trials, with the breakfast omission trial shown on the figures only for illustration purposes.

Blood glucose concentration was significantly higher on the high GI trial, compared to the low GI trial (main effect of trial, F(1,40) = 44.4, P < 0.001). As expected, blood glucose concentrations increased after both the high and low GI breakfasts, peaking at 30 min, before

returning towards resting concentrations (main effect of time, $F(4,160) = 138.3$, $P < 0.001$). However, blood glucose concentrations reached a higher peak at 30 min on the high GI trial compared to the low GI trial (7.01 vs. 6.46 $mmol.l^{-1}$ respectively) and remained higher 60 and 120 min following breakfast (60 min: 5.23 vs. 4.71 $mmol.l^{-1}$; 120 min: 5.01 vs. 4.69 $mmol.l^{-1}$, both $P < 0.001$). This produced a significant interaction between trial and time (trial by time interaction, $F(4,160) = 5.9$, $P < 0.001$, figure 8). Furthermore, blood glucose incremental area under the curve (IAUC) was also greater following the high GI breakfast compared to following the low GI breakfast (116.6 vs. 80.9 $mmol.l^{-1}.120\ min^{-1}$ respectively, $P < 0.001$).

(Insert figure 8 here)

Plasma Insulin: Plasma insulin concentrations and the pattern of response across the morning were different between the trials (main effect of trial, time and a trial by time interaction, all $P < 0.001$). However, because the differences between breakfast omission and breakfast consumption were expected, the following results consider only the high GI and low GI trials, with the breakfast omission trial shown on the figures only for illustration purposes.

Plasma insulin concentration was significantly higher on the high GI trial, compared to the low GI trial (main effect of trial, $F (1,40) = 4.3$, $P = 0.045$). As expected, plasma insulin concentrations increased after both the high and low GI breakfasts, peaking at 30 min before returning towards resting concentrations (main effect of time, $F (4,160) = 68.1$, $P < 0.001$). However, there was no difference in the pattern of change in plasma insulin concentration across the morning between the high and low GI trials (trial by time interaction, $F (4,160) = 0.5$, $P = 0.507$, figure 9), nor was there a difference in plasma insulin IAUC following the high and low GI breakfasts (36590 vs. 31651 $pmol.l^{-1}.120\ min^{-1}$ respectively, $P = 0.063$).

(Insert figure 9 here)

4. Discussion

The main finding of the present study is that a low glycaemic index (GI) breakfast enhanced cognitive function in adolescents, when compared to both a high GI breakfast and breakfast omission. Across all three cognitive function tests (Stroop test, Sternberg paradigm and Flanker task), a low GI breakfast enhanced both response times and accuracy later in the morning when compared to a high GI breakfast, breakfast omission, or both, particularly on the more cognitively demanding levels of the tests employed. Ingestion of the low GI breakfast also resulted in a lower peak blood glucose concentration when compared to a high GI breakfast, produced a smaller overall glycaemic response and tended to produce a smaller overall insulinaemic response.

4.1: Stroop Test

Response times on the Stroop test were quicker overall on the high GI trial, when compared to the low GI trial. Furthermore, on the incongruent (more complex) level of the Stroop test, there was a greater improvement in response times across the morning following a low GI breakfast when compared to breakfast omission (figure 2b). Accuracy was also better maintained across the morning following a low GI breakfast when compared to a high GI breakfast (figure 3).

Another study to examine the effects of the GI of breakfast on performance on the Stroop test reports that a high GI breakfast was more beneficial than a low GI breakfast, but only in the group who had consumed a high glycaemic load (GL) breakfast [28]. It has also been reported that neither the GI nor GL of breakfast affects adolescents' performance on the Stroop test [14]. However, the earlier studies suffered from a number of methodological weaknesses, including; providing high and low GL meals that were not matched for energy content [14,28], not reporting whether response times and/or accuracy were assessed on the Stroop test [28] and furthermore, not employing a crossover design, with participants consuming only the high or

low GL breakfasts [14,28]. In comparison, in the present study participants performed all trials in a randomised crossover design and the breakfasts were matched on key variables such as energy and carbohydrate content.

It has previously been suggested that higher blood glucose concentrations are associated with better performance on the Stroop test [29]. However, studies from which this conclusion was drawn focused on a nutritional intervention (e.g. breakfast or lunch provision) versus continued fasting [30]. Similarly, in our previous work we have found that breakfast consumption (which was associated with higher blood glucose concentrations) improved performance on the Stroop test compared to breakfast omission [5]. However, the present study compares two nutritional interventions (high and low GI breakfasts) with breakfast omission, extending the previous work that examined nutritional interventions versus fasting.

Thus, while the enhanced performance following both the high and low GI breakfasts, compared to following breakfast omission, may be mediated by the higher blood glucose concentrations [29], when comparing the high and low GI trials it seems that the higher blood glucose concentrations enhance response times, but they are to the detriment of accuracy (possibly causing a speed-accuracy trade-off). Alternatively, blood glucose concentrations (within the postprandial ranges following the high and low GI breakfasts) may not be the only determinant of performance on the Stroop test, and other factors such as improved insulin sensitivity following a low GI breakfast [31] may also play a role in determining performance. However, the present study does not allow us to provide details of the mechanistic pathways determining cognitive performance, rather it only allows us to speculate on such mechanisms.

4.2: Sternberg Paradigm

There was a greater improvement in response times across the morning on the Sternberg paradigm, a test of working memory, following a low GI breakfast compared to a high GI

breakfast (figure 4). Furthermore, accuracy was better maintained across the morning following a low GI breakfast compared to following both the high GI breakfast and breakfast omission trials, but this was only evident on the more complex level (figure 5c).

The findings of the present study are consistent with an earlier study in 9 to 16 year olds which showed a greater improvement in response times across the morning following a low GI breakfast, compared to both a high GI breakfast and breakfast omission, but in the earlier study the accuracy of working memory was not investigated [13]. The accuracy of working memory has been examined previously in children, with 9 to 11 year old females showing an enhanced accuracy following a low GI breakfast as opposed to a high GI breakfast. However, there were no effects of the different breakfasts in the 9 to 11 year old males or in 6 to 8 year old males or females [32]. Thus, the present study is the first to examine the effects of the GI of breakfast on both the speed and accuracy of working memory in an adolescent population.

It has been previously suggested that the improvement in working memory following a low GI breakfast could be due to better maintenance of blood glucose concentrations after a 'simulated' low GI breakfast [10]. However, in the present study, following the 'real-life' low GI breakfast, blood glucose concentrations were lower than following the high GI breakfast, thus contradicting the suggestion that maintenance of higher blood glucose concentrations within normal postprandial ranges is a key determinant of working memory performance.

4.3: Flanker Task

There was a greater improvement in response times across the morning on the Flanker task, which is a test of selective attention, following a low GI breakfast when compared to breakfast omission (figure 6). Furthermore, accuracy on the incongruent (more difficult) level was better maintained across the morning following a low GI breakfast when compared to both the high GI breakfast and breakfast omission (figure 7b).

The improvement in accuracy on the Flanker task across the morning following the low GI breakfast is consistent with findings based on classroom observations in 6 to 7 year olds who spent more time on task and demonstrated fewer lapses in attention following a low GI breakfast compared to a high GI breakfast [17]. Furthermore, in 9 to 16 year olds completing an attentional task as part of the Cognitive Drug Research battery of cognitive tests, the accuracy of attention declined across the morning following a high GI breakfast, but accuracy was better maintained following a low GI breakfast [13]. These findings are in line with those of the present study, but the present study extends findings by using a more widely used test of attention (Flanker task) and focussing on adolescence, a time during which the frontal lobes thought to govern executive functions have been found to undergo a final bout of development [33], whereas earlier studies focused on young people in general.

4.4: Glycaemic and Insulinaemic Responses

The glycaemic and insulinaemic responses to meals of differing GI have not been previously reported in adolescent populations. In the present study, adolescents exhibited a larger overall glycaemic response following a high GI breakfast when compared to the low GI breakfast (as determined by IAUC). These findings are consistent with those in adult populations [34]. It has also been suggested that high GI foods result in a higher insulinaemic response in adults [34]. However in the adolescents tested in the present study, there was no difference in the overall insulinaemic response following the high GI compared to the low GI breakfast (as determined by IAUC). One potential explanation for the similar insulinaemic response to the high and low GI trials is the matched milk content of the breakfasts, because of the well documented insulinotrophic effect of milk [35]. Therefore, the expected differences in insulinaemia (based on findings in adults) could have been masked by the matched milk content of the meals.

4.5: Summary and Future Research Directions

The main finding of the present study is that across a range of cognitive function tests, including the domains of working memory and attention, in adolescents a low GI breakfast enhanced both response times and accuracy later in the morning when compared to a high GI breakfast and breakfast omission, particularly on the more cognitively demanding levels of the cognitive function tests. Furthermore, the low GI breakfast produced a smaller overall glycaemic response when compared to the high GI breakfast.

Overall, we conclude that a low GI breakfast is more beneficial, than both a high GI breakfast and breakfast omission, for cognitive function in adolescent schoolchildren across the school morning. However, further work is required to examine the optimal timing of breakfast and the effects of different macronutrients on cognitive function during the school morning. Furthermore, where possible given the ethical constraints of working with young people, more detailed mechanistic work should be undertaken to suggest potential mechanisms for nutritional effects on cognitive function.

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Figure 1: Experimental protocol

Figure 2: Response times across the high GI (HGI), low GI (LGI) and breakfast omission (NBF) trials on the baseline (figure 2a) and complex (figure 2b) levels of the Stroop test (n = 41).

(LGI vs. NBF: trial by session time by test level interaction, p = 0.009)

Figure 3: Accuracy across the morning on the high GI (HGI), low GI (LGI) and breakfast omission (NBF) trials on the Stroop test (n = 41).

(LGI vs. HGI: trial by session time interaction, p = 0.033).

Figure 4: Response times across the morning on the high GI (HGI), low GI (LGI) and breakfast omission (NBF) trials on the Sternberg paradigm (n = 41).

(LGI vs. HGI: trial by session time interaction, p = 0.013).

Figure 5: Accuracy across the morning on the number (figure 5a), three-letter (figure 5b) and five-letter (figure 5c) levels of the Sternberg paradigm on the high GI (HGI), low GI (LGI) and breakfast omission (NBF) trials (n = 41).

(LGI vs. HGI: trial by session time by test level interaction, p = 0.002,

LGI vs. NBF: trial by session time by test level interaction, p = 0.051).

Figure 6: Response times across the morning on the high GI (HGI), low GI (LGI) and breakfast omission (NBF) trials on the Flanker task (n = 41).

(LGI vs. NBF: trial by session time interaction, p = 0.045).

Figure 7: Accuracy across the morning on the congruent (figure 7a) and incongruent (figure 7b) levels of the Flanker task on the high GI (HGI), low GI (LGI) and breakfast omission (NBF) trials (n = 41).

(LGI vs. HGI: trial by session time by test level interaction, p = 0.014,

LGI vs. NBF: trial by session time by test level interaction, p = 0.001)

Figure 8: Blood glucose concentrations across the high GI (HGI), low GI (LGI) and breakfast omission (NBF) trials. Data are mean ± SEM (n = 41).

(LGI vs. HGI: trial by time interaction: $p < 0.001$, * HGI > LGI: $p < 0.001$).

Figure 9: Plasma insulin concentrations across the high GI (HGI), low GI (LGI) and breakfast omission (NBF) trials. Data are mean ± SEM (n = 41).

(LGI vs. HGI: trial by time interaction: p = 0.507, * HGI > LGI: p = 0.008).