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Review article

The impact of glycaemic load on cognitive performance: A meta-analysis and guiding principles for future research☆

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ABSTRACT

The effect of breakfast glycaemic load (GL) on cognition was systematically examined. Randomised and non-randomised controlled trials were identified using PubMed, Scopus, and Cochrane Library (up to May 2022). 15 studies involving adults (aged 20 – 80 years) were included. Studies had a low risk, or some concerns, of bias. A random-effects meta-analysis model revealed no effect of GL on cognition up to 119 min post-consumption. However, after 120 min, immediate episodic memory scores were better following a low-GL compared to a high-GL (SMD = 0.16, 95% confidence interval [CI] = −0.00 to 0.32, p = 0.05, I2 = 5%). Subgroup analyses indicated that the benefit was greater in younger adults (<35 years) and those with better GT. A qualitative synthesis of 16 studies involving children and adolescents (aged 5 – 17 years) suggested that a low-GL breakfast may also benefit episodic memory and attention after 120 min. Methodological practises were identified which could explain a failure to detect benefits in some studies. Consequently, guiding principles were developed to optimise future study design.

1. Introduction

Several reviews have concluded that breakfast benefits various aspects of cognition in adults, children, and adolescents (Adolphus et al., 2016; Anderson et al., 2020; Galioto and Spitznagel, 2016; Guyatt et al., 2008; Hoyland et al., 2009). However, a more important question has not received the same attention: what type of breakfast optimally enhances acute cognitive performance? Numerous studies have examined this question by manipulating the glycaemic index (GI) of breakfast (Philippou and Constantinou, 2014). GI is a measure of the speed and duration of the increase in blood glucose that results from consuming a set weight of carbohydrate. A related concept is GL, which considers both the GI and the amount of carbohydrate supplied in a food item or meal. GL provides an overall measure of the total glycaemic impact of a specific portion of food and more strongly predicts an individual's glycaemic response than GI (Barclay et al., 2005). For these reasons, the present review focused on the cognitive effects of breakfast GL rather than GI.

It has been hypothesised that a low GL (LGL) breakfast may benefit cognitive performance two to three hours after consumption, reflecting a continuous source of glucose for the brain (Benton et al., 2003; Cooper et al., 2012; Young and Benton, 2014). Conversely, a high GL (HGL) breakfast produces a rapid rise and drop in blood glucose levels which may disrupt cognitive performance, particularly later in the morning as glucose concentrations fall (Nilsson et al., 2009; Young and Benton, 2014). Although this suggestion is conceptually appealing, results have been inconsistent. Some studies have reported that a LGL breakfast benefitted episodic memory, working memory, and attention at various times throughout the postprandial period (Benton et al., 2003; Cooper et al., 2012; Ingwersen et al., 2007; Mahoney et al., 2005; Nabb and Benton, 2006a; Nilsson et al., 2012; Wesnes et al., 2003; Young and Benton, 2014, 2015), whereas other studies have reported that a HGL breakfast benefitted cognitive performance (Dye et al., 2010; Nabb and Benton, 2006a; Smith and Foster, 2008; Young and Benton, 2014).

Abbreviations: GT, glucose tolerance; IGT, impaired glucose tolerance; T2DM, type 2 diabetes mellitus; GL, glycaemic load; LGL, low glycaemic load; MGL, medium glycaemic load; HGL, high glycaemic load; GI, glycaemic index; LGI, low glycaemic index; HGI, high glycaemic index; RCTs, randomised controlled trials; BMI, body mass index; SMD, standardised mean difference; SD, standard deviation; CI, confidence interval; PRISMA, Preferred Reporting Items for Systematic reviews and Meta-Analysis; WHO, World Health Organisation; SUGiRS, Sydney Universities Glycaemic Index Research Service.

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To the best of our knowledge, only one review has examined the effect of breakfast GL on acute cognitive performance (Gilsenan et al., 2009). The authors concluded that there was insufficient evidence to support an effect of breakfast GL on cognitive performance in children, adolescents, and adults. However, several studies have since been published, potentially enabling a quantitative synthesis of the literature (Anderson et al., 2020, 2018, 2021; Deng et al., 2021; Lee et al., 2019; Sanchez-Aguadero et al., 2020; van der Zwaluw et al., 2014; Young and Benton, 2014, 2015). Furthermore, it is plausible that inconsistencies in the literature are due to methodological factors, including differences in the time that cognitive performance was assessed during the postprandial period, sample age, task domain, and glucose tolerance (GT). The impact of these factors on the cognitive effects of breakfast GL has not yet been systematically explored via meta-analysis.

Therefore, we performed an up-to-date systematic review and meta-analysis of the impact of breakfast GL on cognition in children, adolescents, and adults. The primary aim of this meta-analysis was to assess the influence of methodological factors including the timing of testing, sample age, and GT. The secondary aim was to create a series of guiding principles that outline variables that may need to be considered when designing studies in future. It is hoped that the identification of these variables will facilitate a better understanding of the relationship between breakfast GL and cognitive performance.

2. Method

This systematic review and meta-analyses were conducted in accordance with the Preferred Reporting Items for Systematic reviews and Meta-Analysis (PRISMA) guidelines. PRISMA 2020 checklists are provided in Supplementary Document 1 (Table S1 & S2). A study protocol was registered with PROSPERO (CRD42021229575).

2.1. Search strategy and selection criteria

A systematic search for studies published up to 31st May 2022 was conducted using PubMed, Scopus, and Cochrane Library. To identify relevant publications, the following search terms were used: 'cognitive function' or 'cognition' or 'cognitive performance' combined with 'glycaemic index' or 'glycaemic load' or 'breakfast' or 'carbohydrate' or 'glucose' or 'sucrose' or 'isomaltulose'. The search was restricted to English-language articles only, and both British and American spellings of key search terms were used. Reference lists from articles and reviews identified during the electronic search were checked for additional studies. We also used the British Library of Electronic Theses Online Service (http://ethos.bl.uk) to identify unpublished studies. Titles and abstracts were read to check for duplicates and to determine whether the study potentially met the inclusion criteria. Studies that did not fulfil the inclusion criteria or were clearly irrelevant to the review were eliminated. The remaining articles were read to establish their suitability. The systematic search was conducted independently by two authors (C.G and H.Y). Any disagreements were resolved by discussion.

As postprandial glycaemia has a diurnal rhythm, which may influence the cognitive effects of GL, we chose to focus exclusively on studies that manipulated the GL of breakfast (Gibbs et al., 2014; la Fleur et al., 2001). Breakfast was defined as the first meal or drink of the day, consumed between 6 am and 10 am, after an overnight fast. Studies were included if they met the following criteria: (A) randomised controlled trials (RCTs) or non-RCTs (B) studies that investigated the acute cognitive effects of variations in breakfast GL or provided adequate information from which GL could be calculated, (C) published or unpublished studies, (D) studies that used objective measures of cognition, and (E) studies involving children/adolescents (5–17 years) or adults (> 18 years) who were healthy (i.e., no diagnosis of disease) or had impaired glucose tolerance (IGT) or type 2 diabetes mellitus (T2DM). The exclusion criteria were as follows: (A) studies that compared food/drink intake with water, artificial sweeteners, or food/drink omission, (B) studies that compared the chronic cognitive effects of dietary GL or GI, or (C) studies that manipulated the GL or GI of nutritional interventions consumed after breakfast time (e.g., an afternoon snack).

2.2. Data extraction

Two authors independently extracted the following information using a standardised data spreadsheet: first author name, year of publication, participant characteristics (age, gender, & GT status), study characteristics (sample size, type of design, counterbalancing, randomisation, blinding, length of overnight fast, adjustment for confounding factors, length of washout period between test sessions, number of withdrawals, & control for previous days meal consumption/physical activity levels), characteristics of breakfast interventions (GL, GI, macronutrient content, & energy content), timing of blood glucose/cognitive tests, type of cognitive domain/subdomain assessed, name of cognitive test, and results of study.

The GL of a breakfast intervention was calculated using the reported GI value multiplied by the amount of available carbohydrate per serving and divided by 100. If the GI of a meal or drink was not reported, it was estimated using values provided by Atkinson et al. (2021) or Sydney Universities Glycaemic Index Research Service (SUGiRS). The two breakfast interventions with the largest difference in GL were categorised as the HGL or LGL interventions. Remaining meals or drinks were categorised as MGL interventions.

For the meta-analysis, means and standard deviations (SDs) of each cognitive outcome, at each postprandial time point, after the LGL and HGL breakfast intervention were extracted. Sample sizes were recorded and, where possible, both adjusted and unadjusted means were extracted. Authors were contacted when data were missing or only change scores were reported. When an author did not respond, data were estimated from figures when available, or the study was not included in the meta-analysis (see Section 3.2.3.).

2.3. Organisation process

Using the framework described by Harvey (2019), data were first categorised into one of the following cognitive domains and subdomains: memory (episodic, working, visuospatial, & semantic), attention (selective & sustained), processing speed, executive function (reasoning, problem solving & inhibitory control), and psychomotor function. Next, as cognitive performance was measured at various time points throughout the postprandial period, data were further categorised into one of three time windows: early postprandial period (testing commenced between 10 and 59 min), mid postprandial period (60 – 119 min), or late postprandial period (120 min or later). These time windows were chosen to reflect specific points in the typical postprandial glycaemic response.

2.4. Risk of bias and certainty of evidence

Risk of bias (RoB) was assessed by two independent authors using The Cochrane RoB 2 tool (Sterne et al., 2019) for crossover and parallel trials. Disagreements were resolved through discussion. The following sources of bias were assessed: randomisation process (selection bias), deviations from intended interventions (performance bias), missing outcome data (attrition bias), measurement of outcome (measurement bias), selection of the reported results (reporting bias), and overall bias. Studies were classified as either 'low risk of bias', 'high risk of bias', or 'some concerns of bias'. To obtain additional information, theses and study protocols were checked and study authors were contacted where possible.

Certainty of evidence was assessed using the Grading of Recommendations Assessment, Development, and Evaluation (GRADE) approach (Guyatt et al., 2008). Each cognitive subdomain was assessed based on risk of bias, inconsistency, indirectness, imprecision, and

publication bias. There were four possible outcomes: very low, low, moderate, or high.

2.5. Data handling and statistical analysis

Meta-analyses were conducted using a generic inverse variance method in Review Manager 5.3 (RevMan) [Computer programme]. Version 5.3. Copenhagen: The Nordic Cochrane Centre, The Cochrane Collaboration, 2014. All analyses used a random effects model. Effect sizes reflected the standardised mean difference (SMD) between the HGL and LGL breakfast interventions, with 95% confidence intervals (CI). A minimum of three studies per analysis were required. Using the guidelines reported by Cohen (2013), SMDs were interpreted as trivial (< 0.2), small (between 0.2 & 0.6), moderate (between 0.6 & 1.2), or large (between 1.2 & 2.0). A p value of < 0.05 was considered significant, whilst a p value between 0.06 and 0.1 was considered a trend. Heterogeneity was examined using the I^2 statistic, a value above 50% indicated substantial heterogeneity which required exploration.

Studies involving adults were analysed separately from studies involving children and adolescents. To examine the influence of time, three separate meta-analyses were performed for each postprandial time window where possible (early postprandial period = 10 – 59 min, mid-postprandial period = 60 – 119 min, or late postprandial period = 120 min or later). Two a priori subgroup analyses were also performed where data were available. To examine the influence of age in adults, studies were categorised into either the 'younger' or 'older' subgroup

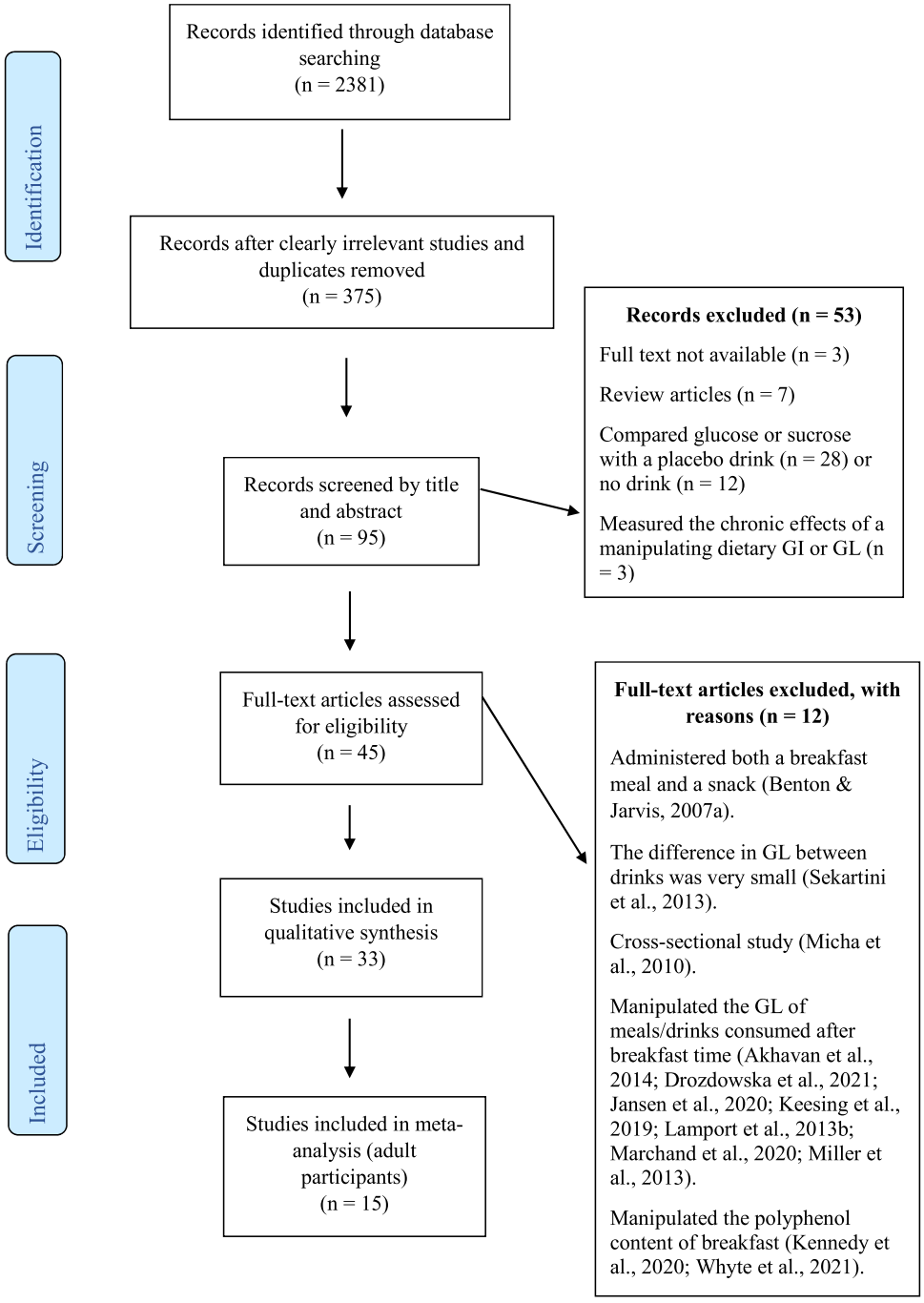

Fig. 1. PRISMA flow diagram of the screening and literature selection process.(Akhavan et al. (2014); Benton, Jarvis (2007a); Drozdowska et al. (2021); Keesing et al. (2019); Kennedy et al. (2020); Marchand et al. (2020); Miller et al. (2013); Sekartini et al. (2013); Whyte et al. (2021)).

based on whether the mean age of the sample was below or above 35 years of age. This cut-off value was chosen because it achieved the most equal subgroup sample sizes, however there is also evidence that certain aspects of cognitive function peak at approximately 35 years of age (Hartshorne and Germine, 2015; Strittmatter et al., 2020). To examine the influence of GT in adults, participants were classified as having 'better' or 'poorer' GT if fasting glucose was below or above 6.1 mmol/L and/or two-hour glucose was below or above 7 mmol/L. Due to an insufficient number of studies, the influence of age and GT was not examined in children and adolescents. For the same reason, the following post-hoc subgroup analyses were not performed: (A) use of dairy (no dairy vs. small quantity of dairy vs. large quantity of dairy) or (B) difference in GL between nutritional interventions (smaller difference vs. larger difference).

Sensitivity analyses were conducted using the leave-one-out method to determine the influence of each individual study on the pooled effect size and p value (Supplementary Document 1, Table S5). We also examined the impact of removing studies that did not match both the macronutrient and energy content of breakfast interventions and compared effect sizes when unadjusted or adjusted means were included in the analysis. Publication bias was assessed by visual inspection of funnel plots; a minimum of 10 studies were required. The Cochrane Handbook for Systematic Reviews of Interventions states that change scores and post-scores should not be analysed as SMDs together. Therefore, separate analyses were performed when necessary. In cases where the same cognitive domain was measured twice within the same postprandial time window, the measurement taken at the time closest to the other studies was used.

3. Results

3.1. Study selection and characteristics

As shown in Fig. 1, 2381 publications were initially identified, of which 45 were potentially eligible. These studies were read fully, and a further 12 studies were excluded. A total of 33 studies met the inclusion criteria, 17 involving adult participants (Table 1) and 16 involving children/adolescents (Table 2). Data were obtained from 15 adult studies for measures of episodic memory, working memory, or attention. We were unable to extract suitable data from Dye et al. (2010) and Kaplan et al. (2000) hence these studies were not included in the meta-analysis. Several other cognitive domains/subdomains were assessed, but these were not quantitatively analysed due to limited data. A detailed discussion of these cognitive outcomes can be found in Supplementary Document 2.

Data were obtained from 11 child/adolescent studies for measures of episodic memory, working memory, or attention. However, for several reasons, a meta-analysis of the data was considered inappropriate. Firstly, we were unable to obtain data from five studies (Benton et al., 2007b; Cooper et al., 2012, 2015; Lee et al., 2019; Taib et al., 2012). In some cases, data were available but only for certain cognitive subdomains (Ingwersen et al., 2007; Mahoney et al., 2005; Wesnes et al., 2003). Secondly, three studies only reported change scores (Brindal et al., 2012, 2013; Wesnes et al., 2003). As change scores and post-scores were analysed separately, this reduced the number of studies included in each analysis, often to the point that there were no longer enough studies to perform a meta-analysis (i.e., less than 3 studies). For example, there were not enough studies to analyse the effect of breakfast GL on immediate episodic memory during the early and late postprandial period and delayed episodic memory during the early and mid-postprandial period. Consequently, we chose to only perform a systematic review of the literature, which can be found in Section 3.3.3. For brevity, only the aforementioned cognitive measures are discussed. However, a detailed discussion of the effect of breakfast GL on other aspects of cognition, such as executive function and visuospatial memory, can be found in Supplementary Document 2.

3.2. Studies involving adult participants

3.2.1. Risk of bias and certainty of evidence

The results of the risk of bias assessment are summarised in Supplementary Document 1 (Table S3). Overall, five studies showed a low risk of bias, and 12 studies showed some concerns of bias. Studies were generally judged with some concerns of bias for the following reasons: (A) the method of randomisation and/or allocation concealment was not reported, (B) a pre-registered study protocol was not found; therefore, it is unclear whether statistical analysis plans were changed and/or whether certain cognitive outcomes were selectively reported, and (C) it was unclear whether the researcher(s) administering the cognitive tasks were aware of which breakfast intervention was consumed. For the 'deviations from intended interventions' domain, studies that used a crossover design were judged as having a high risk of bias if participants were clearly not blinded.

The certainty of evidence assessment is reported in Supplementary Document 1 (Table S4). Assessments ranged from very low (working memory & attention) to low (episodic memory). The main issues were risk of bias, as discussed above, and imprecision.

3.2.2. Study characteristics

All studies were randomised, of which four used a parallel design and 13 used a crossover design. Mean age ranged from 20.36 years (Nabb and Benton, 2006a) to 78 years (van der Zwaluw et al., 2014), and sample sizes ranged from 18 (Lamport et al., 2014) to 189 participants (Nabb and Benton, 2006a). The majority of studies recruited healthy participants, several of which examined the influence of GT on the relationship between breakfast GL and cognition (Anderson et al., 2018, 2021; Kaplan et al., 2000; Nabb and Benton, 2006a, 2006b; Nilsson et al., 2009, 2012; van der Zwaluw et al., 2014; Young and Benton, 2014). Two studies recruited participants with clinically diagnosed T2DM (Lamport et al., 2013a; Papanikolaou et al., 2006), and one study recruited participants with IGT (Lamport et al., 2014).

3.2.3. Meta-analyses

Note that Nabb and Benton (2006a) and Nilsson et al. (2009) were excluded from all GT subgroup analyses because the authors defined 'poorer' GT using a particularly low cut-off point. Although Young and Benton (2014) compared the effect of GL on cognitive function across four glucoregulatory groups (see Table 1), data from only the 'poorer' GT and 'better' GT group were analysed. Data were extracted from figures for one study (Papanikolaou et al., 2006).

3.2.3.1. Immediate episodic memory

3.2.3.1.1. The influence of the timing of testing. Forest plots of effect sizes with 95% CI are shown in Fig. 2. During the early postprandial period (15 – 30 min), there was no significant difference in immediate episodic memory scores between the HGL and LGL nutritional interventions (SMD = 0.05, 95% CI = −0.09 to 0.19, p = 0.51, I^2 = 0%), nor during the mid-postprandial period (60–105 min; SMD = 0.08, 95% CI = −0.07 to 0.23, p = 0.31, I^2 = 0%). However, during the late postprandial period (120 – 195 min), immediate episodic memory was significantly better following a LGL breakfast compared to a HGL breakfast (SMD = 0.16, 95% CI = −0.00 to 0.32, p = 0.05, I^2 = 5%). Heterogeneity was low for all analyses.

3.2.3.1.2. The influence of individual differences. Subgroup analyses indicated that individual differences in GT were related to the effect of breakfast GL on immediate episodic memory, but only during the late postprandial period (120 – 195 min; Fig. 3). In those with 'better' GT, performance was significantly better following a LGL breakfast compared to a HGL breakfast (SMD = 0.31, 95% CI = 0.09 to 0.54, p = 0.007, I^2 = 0%), whereas there were no differences in performance in those with 'poorer' GT (SMD = 0.12, 95% CI = -0.21 to 0.45, P = 0.47, I^2 = 0%). Individual differences in age did not influence the

Table 1
Characteristics of studies involving adult participants.

Author (Year)	Participant characteristics	Study design	Breakfast intervention	Cognitive test	Timing of cognitive & blood glucose tests	Results	Comments
Anderson et al. (2018)	86 healthy participants (57 female, 29 male). Mean age = 21.09 (SD = 2.48). GT status = fasting BGLs at each test session (continuous variable).	WS. Randomised. Counterbalanced. Overnight fast. 48-hour minimum washout period. Prior to testing, no exercise or alcohol consumption (24 h).	1. HGL = 237 mL of apple juice (120 kcals, 29 g CHO, 0 g PRO, 0 g fat, 11.3 GL[3]) 2. LGL = 237 mL of 1% fat milk (110 kcal, 12 g CHO, 8 g PRO, 2.5 g fat, 4 GL[3]) 3. Control = water	Go-no-go task (executive function - inhibitory control), RMCPT (working memory), & SCPT (sustained attention).	Cognition = 30, 90, & 120 min. Glucose levels = fasted only.	Go-no-go task = those with fasting BGLs above 104.97 mg/dL made fewer omission errors, at 30 min, after the LGL drink vs. HGL drink. RMCPT = those with higher fasting BGLs displayed better performance (RT & accuracy) 30 min after the LGL drink vs. HGL drink. Opposite pattern occurred for those with lower fasting BGLs.	Drinks had different macronutrient profiles but provided similar amounts of energy. Included BMI & biological sex as covariates. Fasting glucose included as a repeated factor.
Anderson et al. (2021)	44 participants (22 female, 22 male). Mean age = 30.81 years (SD = 8.36). GT status = fasting BGLs at each test session & change in plasma glucose levels from baseline to 30 min after drinking juice.	WS. Randomised. Counterbalanced. Overnight fast. 48-hour minimum washout period. Prior to testing, no exercise or alcohol (24 h), tobacco (1 h), & caffeine (8–12 h). Data were obtained from an open label trial.	1. HGL = 237 mL of apple juice (120 kcal, 29 g CHO, 0 g PRO, 0 g fat, 11.3 GL[3]) 2. LGL = 237 mL of 2% fat milk (122 kcal, 12 g CHO, 8 g PRO, 5 g fat, 4.4 GL[3]) 3. Control = water	CNS Vital Signs battery: Stroop task, symbol digit coding, shifting attention task, CPT, & 4-part CPT. Created five composite scores: working memory, processing speed, executive function, complex attention, & simple attention.	Cognition = 00, 30, 90, & 150 min. Glucose levels = 00, 30, 60, 90, 120, 150, & 180 min.	No effect of GL on any cognitive measure. Complex attention = there was a trend (non-significant) towards a GL X GT interaction. At 30 min, performance was better after consuming the LGL drink in those with higher fasting glucose, whereas performance was better after the HGL drink in those with lower fasting glucose. At 150 min, this pattern reversed.	Drinks had different macronutrient profiles but provided similar amounts of energy. Included biological sex, BMI, & baseline cognitive performance as covariates. Both measures of GT status were included as repeated factors in separate analyses. Assessed the influence of two measures of GT.
Benton et al. (2003)	71 healthy female participants. Mean age 21 years. GT status not assessed.	BS. Randomised. Overnight fast.	1 of 2 meals PLUS sugar-free orange drink, decaffeinated coffee/tea, & skimmed milk, if required. 1. HGL = cereal bar (219.5 kcal, 31.3 g CHO, 3.65 g PRO, 8.85 g fat, 20 GL[4]) 2. LGL = biscuit (230 kcal, 34 g CHO, 3.3 g PRO, 8.8 g fat, 14 GL[4])	WLR task (immediate & delayed episodic memory).	Immediate memory = 30, 90, 150, & 210 min (delayed memory was assessed 10 min after each test). Glucose levels = 00, 20, 50, 80, 140, 200, & 230 min.	Higher global memory scores[1] at 150 & 210 min after consuming the LGL breakfast vs. HGL breakfast. No significant difference at 30 & 90 min.	Meals provided similar amounts of PRO & fat but different amounts of CHO & energy. Differences in performance occurred when BGLs were similar.
Deng et al. (2021)	55 healthy participants (41 female, 14 male). Mean age = 25.5 years (SD = 5.7). GT status not assessed.	WS. Randomised. Counterbalanced. 1-week minimum washout period. Overnight fast. Double-blind. Prior to testing, no vigorous exercise or alcohol (24 h).	1. HGL = carbonated water sweetened with 50 g of sucrose with 250 µl lemon flavouring (32 GL[4]) 2. LGL = carbonated water sweetened with 50 g of isomaltulose with 250 µl lemon flavouring (16 GL[4]) 3. Control =	ROCF (immediate & delayed visuospatial memory), HVLT (WLR - immediate & delayed episodic memory), a self-developed Trail-Making Part B task (attention & executive function), & Stroop task (executive function –	Cognition = 60 min. Glucose levels (measured using a different group of participants who did not undergo cognitive testing) = 00, 30, 60, 90, 120, & 150 min.	No effect of GL on any cognitive measure.	Macronutrient content of drinks were matched. Administered one cognitive test battery, at a time when BGLs were almost identical. Regression adjusted for order of drink consumption, quality of previous night's sleep, & the degree of

(*continued on next page*)

Table 1 (*continued*)

Author (Year)	Participant characteristics	Study design	Breakfast intervention	Cognitive test	Timing of cognitive & blood glucose tests	Results	Comments
			sucralose lemon drink	inhibitory control).			drowsiness & hunger before test
Dye et al. (2010)	24 healthy male participants. Mean age = 23.4 years (range = 18 – 32 years). GT status not assessed.	WS. Randomised. Overnight fast. Counterbalanced. Double-blind. Standardised evening meal. Prior to testing, no exercise or alcohol consumption (24 h).	1. HGL = 429 mL of a milk-based drink sweetened with 50 g of sucrose (325 kcal, 11.2% CHO, 1.3% PRO, 2.1% fat, 32 GL[5]) 2. LGL = 429 mL of a milk-based drink sweetened with 50 g of isomaltulose (325 kcal, 11.2% CHO, 1.3% PRO, 2.1% fat, 16 GL[5]) 3. Control = 429 mL of water	VVLT (immediate & delayed episodic memory, word recognition, & learning of word list), Serial Sevens task (working memory), & a self-developed psychomotor test (psychomotor speed).	Cognition = 00, 35, & 115 min. Glucose levels = continuous glucose monitor inserted at baseline in 12 participants.	Serial Sevens task = faster responses 35 min following the HGL drink vs. LGL drink in those with slower baseline response times. No effect of GL in those with faster baseline response times. No effect of GL on the remaining tests.	Drinks had identical macronutrients & energy profiles. Baseline cognitive performance included as a covariate. Adjusted for the influence of visit & order of drink consumption. Used a milk-based vehicle – insulinotropic.
Ginieis et al. (2018)	49 healthy participants (28 female, 21 male). Mean age of fasting group = 22.6 years (SD = 4.2) & non-fasting group = 24.3 years (SD = 4.9). GT status not assessed.	WS. Randomised. Double-blind. Counterbalanced. 1-week washout period. Participants either fasted overnight or ate & drank as normal.	1. HGL = 26 g of glucose (25 kcal, 0 PRO, 0 fat, 0 fibre, 24.9 GL[5]) 2. MGL = 14.5 g of sucrose (14 kcal, 0 PRO, 0 fat, 0 fibre, 8.7 GL[5]) 3. LGL = 13 g of fructose (12 kcal, 0 PRO, 0 fat, 0 fibre, 1.56 GL[5]) 4. Control = sucralose lemon drink	SRT task (speed of processing), arithmetic processing task (speed of processing & problem solving), & Stroop task (attention & executive function - inhibitory control).	Cognition = 20 min. Glucose levels = 00, 25, & 50 min.	SRT task = slower performance following the HGL drink vs. LGL drink for both the fasted & non-fasted group, & slower performance vs. MGL drink but only in the fasted group. Arithmetic task = slower performance after the HGL drink vs. LGL & MGL drink, but only in the fasted group. Stroop task = slower RTs after the HGL & MGL drink vs. LGL drink for both the fasted & non-fasted group. No differences in error rates between drink conditions.	Drinks matched for PRO, fat, & fibre. Contained different amounts of CHO. Only measured cognition during the early PPP. Adjusted for the influence of order of drink consumption.
Kaplan et al. (2000)	20 healthy elderly participants (10 female, 10 male). Mean age = 72.3 years (SD = 1.4, range = 60 – 82 years). GT status = β cell function, insulin resistance, & glucose AUC.	WS. Randomised. Blind to glucose & placebo condition. Overnight fast. Counterbalanced.	50 g of available CHO from: 1. HGL = 300 mL glucose lemon drink (0 g PRO, 0 g fat, 50 GL[4]) 2. MGL = 312 g of mashed potatoes with 2.5 g of butter to use as required (4 g PRO, 2 g fat, 41.50 GL[4]) 3. LGL = 196 g of barley with 2.5 g of butter to use as required (5 g PRO, 2 g fat, 12.50 GL[4]) 4. Control = 300 mL lemon flavoured saccharin drink.	WLR task (immediate episodic memory) & paragraph recall task (immediate & delayed episodic memory). *During delay periods:* Trail-Making Part B (attention & executive function) & video clip task (sustained attention).	Cognition = 15, 60, & 105 min (testing started shortly after blood glucose sampling). Glucose levels = 00, 15, 60, & 105 min.	No effect of GL on any cognitive measure. Poorer baseline performance & poorer β cell function = associated with enhancements in immediate & delayed paragraph recall after the consumption of 50 g of CHO, regardless of its source, compared to a placebo. Poorer β cell function = associated with improvements in Trails Part B performance after the consumption of 50 g CHO. LGL meal consumption was most strongly	Breakfasts provided identical amounts of available CHO. Barley & mashed potatoes contained similar amounts of PRO & fat. Included biological sex as a between-subjects factor. 91.3% of barley, & 95% of mashed potato, was consumed – possibly contributed to non-significant findings.

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Table 1 (*continued*)

Author (Year)	Participant characteristics	Study design	Breakfast intervention	Cognitive test	Timing of cognitive & blood glucose tests	Results	Comments
						related to improvements in memory performance.	
Lamport et al. (2013a)	24 clinically diagnosed T2DM patients (12 female, 12 male) & 10 healthy controls (6 female, 4 male). Mean age of T2DM = 61 years (SD = 1.9) & controls = 56.2 years (SD = 2). GT status = NGT vs. T2DM.	WS. Randomised. 1-week washout period. Overnight fast. Counterbalanced. Standardised evening meal.	1. HGL = Lucozade energy drink (307 kcal, 75 g CHO, 0 g PRO, 0 g fat, 0 g fibre, 71 GL[3]) 2. LGL = toast, yoghurt, & margarine (307 kcal, 37.3 g CHO, 20.9 g PRO, 9.3 g fat, 5 g fibre, 12 GL[3]) 3. Control = water	VSLT (immediate & delayed visuospatial memory), VVLT (immediate & delayed episodic memory, & word recognition), paragraph recall (immediate & delayed episodic memory), Corsi Block Tapping test (spatial memory), Tower of Hanoi (executive function – planning ability), self-developed psychomotor test (psychomotor skill), & Grooved Peg Board test (psychomotor skill).	Cognition = 30 & 120 min. Glucose levels = 00, 15, 30, 60, 90, 120, 150, & 180 min.	No effect of GL on any cognitive measure.	Breakfasts had different macronutrient profiles but provided identical amounts of energy. Statistically adjusted for the influence of biological sex. Lucozade Energy Original contained 48 mg of caffeine, potentially masking the negative effects of the HGL drink.
Lamport et al. (2014)	18 females with IGT & 47 females with NGT. Mean age of IGT/LWC = 38.56 years (SD = 4.89), IGT/HWC = 41 years (SD = 6.54), NGT/LWC = 36.2 years (SD = 5.2), & NGT/HWC = 37.91 years (SD = 5.96). GT status = WHO criteria for IGT & NGT (fasting glucose <7 mmol/L & 2 h glucose >7.8 & <11.1 mmol/L). Also split participants according to their waist circumference (low = <80 cm, high = >80 cm.	WS. Randomised. 1-week washout period. Overnight fast. Counterbalanced. Standardised evening meal	1. HGL = Lucozade energy drink (307 kcal, 75 g CHO, 0 g PRO, 0 g fat, 0 g fibre, 71 GL[3]) 2. LGL = toast, yoghurt, & margarine (307 kcal, 37.3 g CHO, 20.9 g PRO, 9.3 g fat, 5 g fibre, 12 GL[3]) 3. Control = water.	VSLT (immediate & delayed visuospatial memory), VVLT (immediate & delayed episodic memory, & word recognition), paragraph recall (immediate & delayed episodic memory), Corsi Block Tapping test (spatial memory), Tower of Hanoi (executive function – planning ability), self-developed psychomotor test (psychomotor skill), & Grooved Peg Board test (psychomotor skill).	Cognition = 30 & 120 min. Glucose levels = 00, 15, 30, 60, 90, 120, 150, & 180 min.	VVLT (immediate) = in the IGT/HWC group, more words were recalled during the most demanding trial at 120 min following the LGL breakfast vs. HGL breakfast. VSLT (delayed) = scores were lower after the HGL breakfast at 120 min in the IGT/HWC group compared to NGT/LWC group. This pattern was not observed after consuming the LGL breakfast. The remaining cognitive tasks were not affected by GL.	Breakfasts had different macronutrient profiles but provided identical amounts of energy. NGT group possibly underpowered due to small sample size. Lucozade Energy Original contained 48 mg of caffeine, potentially masking the negative effects of the HGL drink.
Nabb and Benton (2006a)	189 female participants. Mean age = 20.36 (SD = 3.48) GT status = fasting BGLs below or above 5 mmol/L.	BS. Randomised. Overnight fast.	1 of 8 meals containing low or high CHO (24 or 59 g), fat (1 or 16 g), & PRO (2 or 10 g), & a sugar-free orange drink, decaffeinated coffee/tea, & skimmed milk, if required. Kcal range = 114 – 407, CHO range = 24.2–59.6 g, PRO range = 1.7–9.9 g, fat range = 1–16.5 g, GL range = 12.23–52.66[3].	Self-developed WLR task (immediate & delayed episodic memory), Hick paradigm (SRT & CRT – speed of processing), & RIPT (sustained attention).	Cognition = 30, 75, & 120 min. Glucose levels = 00, 20, 50, 95, & 140 min.	WLR task = better GT/LP had higher global memory scores[1] vs. better GT/HP & poorer GT/LP. Those who ate LP and had better GT also had the lowest BGLs. Global memory scores[1] were higher in those with better GT/LCLF vs. poorer GT/LCLF. Hick paradigm = better GT/HCLP had faster decision times vs. better GT/LCLP.	Macronutrient & energy composition of certain meals differed.

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Table 1 (*continued*)

Author (Year)	Participant characteristics	Study design	Breakfast intervention	Cognitive test	Timing of cognitive & blood glucose tests	Results	Comments
						RIPT = better GT/HCHF made more correct responses vs. better GT/LCHF. Poorer GT/LCHF also made more correct responses vs. better GT/LCHF.	
Nabb and Benton (2006b)	168 female participants. Mean age = 20.41 (SD = 1.99). GT status = fasting BGLs below or above 6 mmol/L.	BS. Randomised. Overnight fast.	1 of 8 meals containing low, medium, or high CHO (10/30/50 g) & fibre (1.5/6/13 g), & a sugar-free orange drink, decaffeinated coffee/tea, & skimmed milk, if required. Kcal range = 81.80–274.90, CHO range = 14.45–49.84 g, PRO range = 4.26–14.06 g, fat range = 0.34–2.08 g, GL range = 3.01–35.45[5].	Self-developed WLR task (immediate & delayed episodic memory), Hick paradigm (SRT & CRT – speed of processing), & RIPT (sustained attention).	Cognition = 30 & 90 min. Glucose levels = 00, 20, 50, 80, & 110 min.	WLR task = fewer words forgotten[2] in those with poorer GT/LC vs. poorer GT/HC. Higher global memory scores[1] in those with poorer GT/medium fibre vs. poorer GT/low fibre. Hick paradigm = in those with better GT, decision times were faster when medium CHO or high CHO was consumed with low fibre. No effect of GL on sustained attention.	Macronutrient & energy composition of certain meals differed. Did not assess cognitive performance during the late PPP.
Nilsson et al. (2009)	40 healthy participants (20 female, 20 male). Mean age = 59 years (range = 49 – 70 years). GT status = above or below median split of BGLs 3-hours after 50 g bolus. (5.4 mmol/L).	WS. Randomised. Counterbalanced. Overnight fast. Standardised evening meal. 1-week minimum washout period.	1. Simulated HGL = 50 g of glucose in 450 mL of water consumed as a bolus (within 10 – 12 min) 2. Simulated LGL = 50 g of glucose in 450 mL of water, divided into six equal parts & sipped every 30 min for 150 min	Self-developed working memory test (verbal working memory) & picture test (visual selective attention & RT).	Working memory = 35, 90, 120, & 150 min. Selective attention = 170 min. Glucose levels = 00, 15, 35, 45, 60, 90, 150, 170, & 180 min.	Working memory task = better accuracy scores 90 min after the LGL drink vs. HGL drink. At 35 min, there was an order effect, whereby performance was better on the second day of testing. Analysis of day 1 data indicated that performance was similar at 35 min, but better 90 & 120 min after the HGL drink vs. LGL drink. Selective attention task = better accuracy scores 170 min after consuming the LGL drink vs. HGL drink. No differences in RT occurred.	GL of drinks could not be calculated due to the method of manipulating breakfast GL. Did not report whether there was an interaction between GT & GL. Order of meal consumption included as a between-subjects factor, & GT included as a covariate.
Nilsson et al. (2012)	40 healthy participants (28 female, 12 male). Mean age = 62.9 years (SD = 5, range = 49–71 years). GT status = above or below median split of glucose incremental AUC.	WS. Randomised. Counterbalanced. Overnight fast. Standardised evening meal. 1-week minimum washout period.	50 of available starch from: 1. HGL = 124 g of white wheat flour-based bread (100 GI) 2. LGL = 179 g of white wheat flour-based bread supplemented with guar gum (45 GI)	Self-developed working memory test (verbal working memory) & picture test (selective attention & RT).	Working memory = 90, 135, 180, & 225 min. Selective attention = 75, 120, 165, & 210 min. Glucose levels = 00, 15, 30, 45, 60, 90, 120, 150, 180, 210, & 240 min	Selective attention task = better accuracy scores 120 min after the LGL bread vs. HGL bread. When only the most difficult part of the test was analysed, the difference in performance was greater. Specifically,	Meals provided similar amounts of macronutrients & energy. Did not report whether there was an interaction between GT & GL. Order of meal consumption included as a between-subjects factor

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Table 1 (*continued*)

Author (Year)	Participant characteristics	Study design	Breakfast intervention	Cognitive test	Timing of cognitive & blood glucose tests	Results	Comments
					(measured using another group of participants).	accuracy scores were better after consuming the LGL bread vs. HGL bread at each time point (75–210 min). No effect of GL on sustained attention RTs or working memory scores.	
Papanikolaou et al. (2006)	21 clinically diagnosed T2DM patients (11 female, 10 male). Mean age = 65 years (SD = 7.29). Fifteen participants were medicated (taken directly before meal consumption)	WS. Randomised. 1-week washout period. Overnight fast.	50 g of available CHO from: 1. HGL = white bread, cheese, & tomato sauce (37 GL^6) 2. LGL = pasta, cheese, & tomato sauce (22 GL^6) 3. Control = water	HVLT (WLR - immediate & delayed episodic memory) & WMS (paragraph recall - immediate & delayed episodic memory). *During first & second delays:* Digit span forward task (working memory), Trail-Making test (Part A = attention & processing speed, Part B = attention & executive function), & Test of Everyday Attention (Part A = sustained attention, Part B = auditory selective attention).	Cognition = 15, 62, & 100 min. Glucose levels = 00, 5, 15, 62, 100, & 138 min.	HVLT = better immediate recall, & delayed recall at 100 min, after consuming the LGL meal vs. HGL meal. WMS = delayed paragraph recall (62 &100 min) was better after consuming the LGL meal vs. HGL meal. Digit span forward test = performance better after the LGL meal vs. HGL meal, but only during the first delay (prior to 62 min). Trails Part B = larger improvement in performance from the first to the second administration of the test after consuming the LGL meal vs. HGL meal. No effect of GL on Test of Everyday Attention & Trails Part A performance.	Meals provided identical amounts of available CHO, but different amounts of PRO & fat. No control group – unclear what effects may have occurred in healthy participants. Regression included HbA1c values, depression scores, intelligence scores, & visit as covariates where appropriate (also checked whether BMI & age needed to be included).
Sanchez-Aguadero et al. (2020)	40 healthy participants (20 female, 20 female). Mean age = 28.1 years (range = 20–40 years). GT status not assessed.	WS. Randomised. 1-week washout period. Participants required to maintain stable dietary habits between test sessions. Limited physical activity, smoking, & alcohol consumption 24 – 48 h prior to testing.	1. HGL = white bread, jam, grape juice, & water (315 kcal, 72 g of CHO, 3.9 g PRO, 0.9 g fat, 1.6 g fibre, 46.08 GL^4) 2. LGL = low fat yoghurt, an apple, three walnuts,72% dark chocolate, & water (356 kcal, 31.5 g CHO, 9.7 g PRO, 19.9 g fat, 6 g fibre, 9.26 GL^4) 3. Control = water	WLR (immediate & delayed episodic memory), phonological fluency task (semantic memory), & Trail-Making test (Part A = attention & processing speed, Part B = attention & executive function).	Cognition = 00, 60, & 120 min. Glucose levels = 00, 60, & 120 min.	Phonological fluency = at 120 min, there was a decline in phonological fluency scores after the LGL breakfast but not the HGL breakfast. No effect of GL on the remaining tasks.	Meals had different macronutrient & energy profiles. Statistically adjusted for age & educational level. There was a hypoglycaemic undershoot 60 min after consuming the LGL breakfast, which is not typically observed.
van der Zwaluw et al. (2014)	43 older adults with self-reported memory complaints (27 female, 16 male). Mean age – 77.7 years (SD = 5.6). GT status = above or below median split of incremental AUC after glucose consumption.	WS. Randomised. 1-week minimum washout period. Overnight fast.	1. HGL = 250 mL of water sweetened with 100 g of sucrose & lemon flavouring (0 g PRO, 0 g fat, 0 g fibre, 65 GL^5) 2. LGL = 250 mL of water sweetened with 50 g of glucose & lemon flavouring (0 g	Administered a large battery of tests: RAVLT, digit span forwards & backwards, TAP (LDST, Flexibility, & Alertness subtests), story recall subset of the Rivermead Behavioural	Cognition = 15 min. Glucose levels = 00, 15, 30, 60, & 90 min.	Working memory = better performance after the HGL drink vs. LGL drink. No significant difference in attention & information processing composite scores. However, within	Drinks provided identical amounts of PRO & fat. The HGL drink contained twice as many calories & CHO. Assessed cognitive performance at one time point. Both drinks produced similar

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Table 1 (*continued*)

Author (Year)	Participant characteristics	Study design	Breakfast intervention	Cognitive test	Timing of cognitive & blood glucose tests	Results	Comments
			PRO, 0 g fat, 0 g fibre, 50 GL[5]) 3. Control = water with artificial sweeteners	Memory tests, PAL test, Stroop test, & phonological fluency test. Created four composite scores: episodic memory, working memory, attention & information processing speed, & executive functioning.		this domain, performance on the flexibility subtest of the TAP was faster after the HGL drink vs. LGL drink. No effect of GL on the remaining cognitive tests/ compositive scores.	glycaemic responses (no significant difference in BGLs at any time point).
Young and Benton (2014)	155 healthy participants (96 female, 58 male). Mean age = 55.35 years (SD = 10.63, range = 45–80 years). GT status = OGTT performed on a separate day (poorer GT or better GT = above or below 7 mmol/L at 120 min, then further divided into above or below fasting glucose).	BS. Randomised. Double-blind.	1. HGL = breakfast sweetened with 15 g of glucose, & an orange drink sweetened with 25 g of glucose (275 kcal, 56.4 g CHO, 9.3 g PRO, 1.45 g fat, 45.4 GL[3]) 2. MGL = breakfast sweetened with 15 g of sucrose, & an orange drink sweetened with 25 g of sucrose (275 kcal, 56.4 g CHO, 9.3 g PRO, 1.45 g fat, 34.9 GL[3]) 3. LGL = breakfast sweetened with 15 g of isomaltulose, & an orange drink sweetened with 25 g of isomaltulose (275 kcal, 56.4 g CHO, 9.3 g PRO, 1.45 g fat, 24.3 GL[3])	Self-developed WLR task (immediate & delayed episodic memory), phonological fluency task (semantic memory), Serial Sevens task (working memory), RIPT (sustained attention), & Hick paradigm (SRT & CRT – speed of processing).	Cognition = 30, 105, & 195 min.	WLR task = the better GT/above baseline group had better memories 30, 105, & 195 min after consuming the LGL breakfast vs. MGL breakfast, & 105 & 195 min after consuming the LGL breakfast vs. HGL breakfast. The better GT/ below baseline group had higher episodic memory scores 195 min after consuming either the LGL or MGL breakfast vs. HGL breakfast. The poorer GT/ above baseline group had higher episodic memory scores 30 min after consuming the HGL breakfast vs. LGL breakfast. Serial Sevens task = the better GT/ above baseline group made more errors 195 min after consuming the HGL breakfast vs. LGL breakfast. No other effects reported.	Meals had identical macronutrient & energy profiles. Did not measure BGLs. GT included as a between-subjects factor, & cognitive performance on day 1 as a covariate (also checked whether age, biological sex, & BMI needed to be included as covariates).

Note. 1 = calculated by summing immediate & delayed memory scores, 2 = difference between immediate & delayed memory scores, 3 = GL values reported by study authors, 4 = GL values calculated using reported GI values multiplied by amount of CHO or available CHO, 5 = GL values calculated using published GI tables, 6 = GL values taken from Philippou and Constantinou (2014).
BS = between-subjects design, WS = within-subjects design, LWC = low waist circumference, HWC = high waist circumference, OGTT = oral glucose tolerance test, BMI = body mass index, BGLs = blood glucose levels, AUC = area under the curve, 00 = baseline, GT = glucose tolerance, IGT = impaired glucose tolerance, NGT = normal glucose tolerance, T2DM = type 2 diabetes mellitus, RT = reaction time, SRT = simple RT, CRT = choice RT, WLR = word list recall, CHO = carbohydrate, PRO = protein, LP = low protein, HP = high protein, LC = low carbohydrate, HC = high carbohydrate, LF = low fat, HF = high fat, LGL = low glycaemic load, MGL = medium glycaemic load, HGL = high glycaemic load, RAVLT = Rey Auditory Verbal Learning Test, HVLT = Hopkins Verbal Learning Test, WMS = Wechsler Memory Scale, TAP = Test for Attentional Performance, LDST = Letter Digit Substitution Test, PAL = Paired Associate Learning, RIPT = Rapid Information Processing Task, VVLT = Visual Verbal Learning Test, VSLT = Visual Spatial Learning Test, ROCF = Rey-Osterrieth Complex Figure, CPT = continuous performance test, RMCPT = running-memory CPT, SCPT = standard CPT, PPP = postprandial period.

effect of breakfast GL on immediate episodic memory.

3.2.3.2. Delayed episodic memory

3.2.3.2.1. The influence of the timing of testing. As shown in Fig. 4, there was no effect of breakfast GL on delayed episodic memory during the early postprandial period (35–59 min; SMD = 0.09, 95% CI = −0.08 to 0.27, p = 0.30, I^2 = 6%), nor during the mid-postprandial period (62–119 min; SMD = 0.11, 95% CI = −0.02 to 0.24, p = 0.10, I^2 = 0%). However, during the late postprandial period (150–220 min), there was a trend towards better performance following a LGL breakfast compared to HGL breakfast (SMD = 0.14, 95% CI = −0.01 to 0.30, p = 0.07, I^2 = 0%). Heterogeneity was low for all analyses.

Table 2
Characteristics of studies involving children and adolescents.

Author (Year)	Participant characteristics	Study design	Breakfast intervention	Cognitive test	Timing of cognitive & blood glucose tests	Results	Comments
Anderson et al. (2020)	84 healthy children (46 female, 38 male). Mean age = 10.18 years (SD = 1.35, range = 8–12 years). GT status = fasting BGLs at the beginning of each test session (analysed as a continuous variable using a linear mixed model).	WS. Randomised. Counterbalanced Overnight fast. 1-week minimum washout period. Experimenter blinded to breakfast conditions.	1. HGL = 237 mL of apple juice (120 kcal, 29 g CHO, 0 g PRO, 0 g fat, 10 GL[1]) 2. LGL = 237 mL of 1% fat milk (110 kcal, 12 g CHO, 8 g PRO, 2.5 g fat, 4 GL[1])	Go-no-go task (executive function - inhibitory control). RMCPT (working memory). SCPT (sustained attention).	Cognition = 00, 30, 90, & 120 min. Glucose levels = 00, 30, 60, 90, & 120 min.	Go-no-go task = in those with higher fasting BGLs, RTs were faster after consuming the LGL drink vs. HGL. The difference in performance increased as fasting BGLs increased. No impact on accuracy scores. RMCPT = in females, consumption of the HGL drink improved accuracy vs. LGL drink, whereas the opposite pattern emerged for males (trend only). No impact on speed scores. SCPT = in females, consumption of the LGL drink was associated with faster performance, whereas the opposite pattern emerged for males (trend only). No impact on accuracy scores.	Drinks had different macronutrient profiles but provided similar amounts of energy. Statistically adjusted for the influence of visit, biological sex, & GT.
Benton et al. (2007b)	19 healthy children (10 female, 9 male). Mean age = 6 years & 10 months (range = 5 – 7 years). GT status not assessed.	WS. Randomised. Unbalanced. Overnight fast. No washout period (four-week breakfast club). School-based study (two days of testing per dietary condition)	Breakfast club provided one of three meals (based on the average amount consumed): 1. HGL = Cornflakes with semi-skimmed milk, two spoons of sugar, one waffle, & one tablespoon of maple syrup (196 kcal, 33.9 g CHO, 4.7 g PRO, 1.7 g fat, 17.86 GL[1]) 2. MGL = scrambled egg, one slice of bread, low fat spread, & jam (168 kcal, 21.7 g CHO, 8.9 g PRO, 5.2 g fat, 12.09 GL[1]) 3. LGL = low calorie yoghurt, ham, cheese, bread, & low fat spread (157 kcal, 5.7 g CHO, 10.8 g PRO, 10.2 g fat, 2.85 GL[1])	British Ability Scale – object name recall (immediate & delayed episodic memory). British Ability Scale – object location recall (immediate & delayed visuospatial memory). Paradigm of Shakow (sustained attention).	Cognition = between 140 and 210 min.	No effect of GL on cognition (ANOVA). Object name recall = negative correlation between immediate word recall & GL. A lower GL predicted better performance, whereas PRO, fat, & CHO did not. Paradigm of Shakow = positive correlation between the number of lapses of attention (difficult trials only) & GL. A lower GL predicted better sustained attention (difficult trials only). No associations between GL & immediate/delayed visuospatial memory & delayed episodic memory.	Breakfasts had different macronutrient & energy profiles. Only administered one cognitive test battery. Did not measure BGLs. Statistically tested for the influence of biological sex & order of meal consumption.
Brindal et al. (2012)	39 healthy children (13 female, 26 male).	WS. Randomised. Overnight fast.	1) HGL = white bread, margarine, vegemite or jam, &	Administered an extensive battery of cognitive tests: SRT	Cognition = 00, 60, 120, & 180 min.	No effect of GL on any of the cognitive tasks.	Meals provided similar amounts of fat & energy but

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Table 2 (*continued*)

Author (Year)	Participant characteristics	Study design	Breakfast intervention	Cognitive test	Timing of cognitive & blood glucose tests	Results	Comments
	Mean age = 11.6 years (SD = 0.7, range = 10 – 12 years). GT status not assessed.	Tested on consecutive days. Laboratory-based study.	fruit drink. (313 kcal, 50 g CHO, 7 g PRO, 9 g fat, 33 GL[1]) 2) MGL = low fat yogurt, full fat cheese, white bread, vegemite or jam, & fruit drink. (312 kcal, 45 g CHO, 14 g PRO, 9 g fat, 24 GL[1]) 3) LGL = full fat milk, low fat yogurt, full fat cheese, white bread, & vegemite or jam. (315 kcal, 38 g CHO, 18 g PRO, 10 g fat, 18 GL[1])	task, CRT task, odd-man-out RT task, attention switching task, letter cancellation task, RAVLT WLR, WISC digit span backward task, & visual inspection time task. Created six composite scores: speed of processing, attention switching, perceptual speed, short-term memory, working memory, & inspection time.	Glucose levels = continuous glucose monitor inserted at baseline.		different amounts of PRO & CHO. Used a milk-based vehicle -insulinotropic. Included biological sex, BMI, z-score, age, baseline cognitive scores, & visit as covariates.
Brindal et al. (2013)	40 healthy children (21 female, 19 male). Mean age = 11.6 years (SD = 0.13, range = 10 – 12 years). GT status = median split of blood glucose responses to the glucose drink.	WS. Randomised. Double-blind. Overnight fast. Tested on consecutive days. Laboratory-based study. No vigorous exercise prior to testing.	1. HGL = 65 g of glucose with water (254 kcal, 0 g PRO, 0 g fat, 65 GL[1]) 2. MGL = 200 g of whole milk & 32 g of glucose (259 kcal, 42 g CHO, 7 g PRO, 8 g fat, 35 GL[1]) 3. LGL = 400 g of whole milk (260 kcal, 19 g CHO, 13 g PRO, 15 g fat, 5 GL[1])	Administered a large battery of cognitive tests: SRT task, CRT task, odd-man-out RT task, attention switching task, letter cancellation task, RAVLT WLR, WISC digit span backward task, & visual inspection time task. Created six composite scores: speed of processing, attention switching, perceptual speed, short-term memory, working memory, & inspection time.	Cognition = 00, 60, 120, & 180 post-breakfast. Glucose levels = continuous glucose monitor inserted at baseline.	Short term memory = there was an interaction between breakfast GL and biological sex. Relative to baseline, females recalled more words overall after consuming the MGL or LGL drink vs. HGL drink.	Drinks provided similar amounts of energy but different amounts of PRO, fat, & CHO. Used a milk-based vehicle – insulinotropic. Included biological sex, BMI z-score, age, GT status, baseline cognitive scores, & visit as covariates.
Cooper et al. (2012)	41 healthy children (23 female, 18 male). Mean age = 12.8 years (SD = 0.4, range = 12 – 14 years). GT status not assessed.	WS. Randomised. Counterbalanced. Overnight fast. 1-week washout period. School-based study. Same meal consumed evening before testing. No unusually vigorous exercise for 24 h.	1.5 g of available CHO per kg body mass. For a 50 kg participant: 1. HGL = Cornflakes, 1% fat milk, white bread, & margarine (422 kcal, 75 g CHO, 14.3 g PRO, 7.2 g fat, 54 GL[1]) 2. LGL = Muesli, 1% fat milk & apple (420 kcal, 75 g CHO, 15.5 g PRO, 6.4 g fat, 36 GL[1]) 3. No breakfast.	Stroop task (executive function - inhibitory control). Sternberg task (working memory/ speed of processing). Flanker task (selective attention).	Cognition = 30 & 120-minutes. Glucose levels = 00, 15, 30, 60, & 120 min.	Stroop task = overall RTs were faster following the HGL meal vs. the LGL meal. Conversely, there was a larger decline in accuracy scores from 30 to 120 min after the HGL meal vs. LGL meal. Sternberg task = RTs remained similar across the morning following the HGL meal, whereas there was a larger improvement across the morning following the LGL meal. Accuracy scores on the complex trials were maintained across the morning following the LGL meal but declined following the HGL meal. No difference in accuracy scores	Meals provided identical amounts of CHO, & similar amounts of energy, PRO, & fat.

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Table 2 (*continued*)

Author (Year)	Participant characteristics	Study design	Breakfast intervention	Cognitive test	Timing of cognitive & blood glucose tests	Results	Comments
						on the easier levels. Flanker task = on the complex trials, accuracy scores were better maintained across the morning following the LGL breakfast vs. HGL breakfast.	
Cooper et al. (2015)	42 healthy adolescents (22 female, 20 male). Mean age = 12.4 (SD = 0.5, range = 11–13 years). GT status not assessed.	Mixed design (WS = exercise or rest & BS = HGL or LGL meal). Randomised Counterbalanced. Overnight fast. 1-week washout period. School-based study. Same meal consumed evening before testing. No unusually vigorous exercise for 24 h.	1.5 g of available CHO per kg body mass. For a 50 kg participant: 1. HGL = Cornflakes, 1% fat milk, white bread, & margarine (422 kcal, 75 g CHO, 14.3 g PRO, 7.2 g fat, 54 GL[1]) 2. LGL = Muesli, 1% fat milk & apple (420 kcal, 75 g CHO, 15.5 g PRO, 6.4 g fat, 36 GL[1]) 3. No breakfast	Stroop task (executive function - inhibitory control). Sternberg task (working memory/ speed of processing). Flanker task (selective attention)	Cognition = 30 & 120-minutes. Glucose levels = 00, 30, 60, & 120 min.	Stroop task = no effect of GL alone. On the complex trials, RT improved across the morning after the LGL breakfast on both exercise & rest days. The largest improvement was when the LGL breakfast was combined with exercise. No difference in performance accuracy. Sternberg task = RT improved across the morning after the LGL meal, regardless of exercise type, whereas RT only improved after the HGL meal on exercise days. Flanker task = no effect of GL alone.	Meals provided identical amounts of CHO, & similar amounts of energy, PRO, & fat. Statistically tested for the influence of order of meal consumption.
Ingwersen et al. (2007)	64 healthy children (38 female, 26 male). Mean age = 9.3 years (range = 6 – 11 years). Two age groups = 6–8 years & 9 – 11 years. GT status not assessed.	WS. Randomised. Counterbalanced. Tested on consecutive days. Overnight fast. School-based study.	1. HGL = Coco Pops plus 125 mL of semi-skimmed milk (133 kcal, 29.8 g CHO, 1.6 g PRO, 0.9 g fat, 23 GL[2]) 2. LGL = All Bran cereal plus 125 mL of semi-skimmed milk (98 kcal, 16.1 g CHO, 4.9 g PRO, 1.6 g fat, 7 GL[2]) 3. No breakfast.	CDR Computerised Assessment Battery: WLR, SRT, CRT, digit vigilance, visuospatial & numeric working memory, word recognition, & picture recognition. Created composite scores: speed of attention, speed of memory, accuracy of attention, secondary memory, & working memory.	Cognition = 00, 10, 70, & 130 min.	Accuracy of attention = at 130 min, there was a sharp decline in scores following the HGL meal, whereas performance was maintained after the LGL meal. No difference at 10 & 70 min. Secondary memory = at 10 & 130 min, scores were better after the LGL vs. HGL meal. No difference at 70 min. No effect of GL on the remaining composite scores/ tests.	Meals provided similar amounts of fat but different amounts of PRO, CHO, & energy. Did not measure BGLs. Statistically tested for the influence of biological sex.
Ingwersen (2011) Unpublished study from thesis.	38 healthy children (19 female, 19 male). Mean age = 9 years & 5 months (range = 8 – 10 years). GT status not assessed.	BS. Randomised. Overnight fast. School-based study.	1. HGL = Coco Pops plus 125 mL of semi-skimmed milk (133 kcal, 29.8 g CHO, 1.6 g PRO, 0.9 g fat, 23 GL[2]) 2. LGL = All Bran cereal plus 125 mL of semi-skimmed milk (98 kcal, 16.1	SRT & CRT task (speed of information processing), Corsi Block Tapping test (spatial memory), Continuous Attention Task (sustained attention), & odd-	Cognition = 00, 10, 70, & 130 min.	No effect of GL on any cognitive measure.	Meals provided similar amounts of fat but different amounts of PRO, CHO, & energy. Did not measure BGLs.

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Table 2 (*continued*)

Author (Year)	Participant characteristics	Study design	Breakfast intervention	Cognitive test	Timing of cognitive & blood glucose tests	Results	Comments
			g CHO, 4.9 g PRO, 1.6 g fat, 7 GL^2) 3. No breakfast	one-out task (working memory)			
Lee et al. (2019)	22 healthy children (7 female, 15 male). Mean age = 12.4 years (SD = 0.3). GT status not assessed.	WS. Randomised. Counterbalanced. Minimum four-day washout-period. Overnight fast. Rescheduled test session if previous days physical activity level or sleep duration deviated from normal routine.	50 g of available CHO from one of five meals* : 1. HGL = mashed potatoes with 17 g of unsalted butter (426 kcal, 5.2 g PRO, 20.7 g fat, 35.50 GL^3) 2. MGL = white rice with 25.9 g of unsalted butter added whilst boiling (413 kcal,5.6 g PRO, 20.7 g fat, 34 GL^3) 3. MGL = French fries cooked in canola oil (424 kcal, 4.5 g PRO, 20.7 g fat, 31.50 GL^3) 4. MGL= oven-baked hash browns (515 kcal, 4.8 g PRO, 29.8 g fat, 28 GL^3) 5. LGL = baked beans with 24.5 g of unsalted butter (475.8 kcal, 15.5 g PRO, 20.7 g fat, 20 GL^3) 6. No breakfast	WLR task (immediate episodic memory). Modified map task (visuospatial memory). Digit span forwards & backwards test (working memory) Finding A's test (speed of information processing).	Cognition = 10, 30, 60, 120, & 180 min. Glucose levels = 00, 10, 30, 60, 120, & 180 min.	WLR task = overall, more words recalled after French fries vs. mashed potatoes & white rice. No effect of GL on the remaining tests.	Some meals contained similar amounts of energy, fat, & PRO.
Mahoney et al. (2005) Study 1.	30 healthy children (15 female, 15 male). Age range = 9 – 11 years. GT status not assessed.	WS. Non-randomised. Counterbalanced. Experimenter blind to breakfast conditions. Overnight fast. Minimum 1-week washout period. School-based study.	1. HGL = 36 g of ready-to-eat oatmeal with half cup skimmed milk (200 kcal, 36 g CHO, 22 g sugar, 5 g PRO, 1.5 g fat, 37.02 GL^3) 2. LGL = 43 g of oatmeal with half cup skimmed milk (200 kcal, 38 g CHO, 19 g sugars, 8 g PRO, 2 g fat, 31.66 GL^3) 3. No breakfast	Self-developed spatial map test (visuospatial memory), digit span forwards & backwards test (working memory), Rey Complex Figure Test (visual perception), CPT (visual & auditory attention), & paragraph recall task (episodic memory).	Cognition = 60 min.	Digit span backward test = in females, more digits recalled after the LGL breakfast vs. HGL breakfast. No difference in performance in boys. No effects of GL on the remaining tests.	Meals provided identical amounts of energy, & similar amounts of CHO & fat. Statistically tested for the influence of biological sex. Only administered one cognitive test battery. Did not measure BGLs.
Mahoney et al. (2005) Study 2.	30 healthy children (15 female, 15 male). Age range = 6 – 8 years. GT status not assessed.	WS. Non-randomised. Counterbalanced. Experimenter blind to breakfast conditions. Overnight fast. Minimum 1-week washout period. School-based study.	1. HGL = 36 g of ready-to-eat cereal with half cup skimmed milk (200 kcal, 36 g CHO, 22 g sugar, 5 g PRO, 1.5 g fat, 1 g fibre, 37.02 GL^3) 2. LGL = 43 g of oatmeal with half cup skimmed milk (200 kcal, 38 g CHO, 19 g sugars, 8 g PRO, 2 g fat, 3 g fibre, 31.66 GL^3) 3. No breakfast	Self-developed spatial map test (visuospatial memory), digit span forwards & backwards test (working memory), Rey Complex Figure Test (visual perception), CPT (visual & auditory attention), & paragraph recall task (episodic memory).	Cognition = 60 min.	Digit span backward test = in females, more digits were recalled after the LGL breakfast vs. HGL. No effect in boys. CPT (auditory) = higher number of CR/fewer misses after LGL breakfast vs. HGL breakfast. No effect of GL on the remaining tests.	Meals provided identical amounts of energy, & similar amounts of CHO & fat. Statistically tested for the influence of biological sex. Only administered one cognitive test battery. Did not measure BGLs.
Micha et al. (2011)	74 healthy children (37 female, 37 male). Mean age = 12.6	Mixed design (WS = HGI or LGI & BS = HGL or LGL). Randomised.	1) HGL/LGI = Alpen muesli, milk, apple juice, & sugar (470 kcal,	Word generation task (semantic memory). WLR task	Cognition = started between 101 and 105 min post-	Inclusion of confounding variables increased the number of	Some meals contained similar amounts of macronutrients &

(*continued on next page*)

Table 2 (*continued*)

Author (Year)	Participant characteristics	Study design	Breakfast intervention	Cognitive test	Timing of cognitive & blood glucose tests	Results	Comments
	years (SD = 0.1, range = 11–14 years). Created 32 matched pairs based on school year, sex, height, weight, mean age, & BMI.	Double-blind. Counterbalanced. Overnight fast. Two-week washout period. Same meal consumed evening before testing. No vigorous exercise for 24 h School-based study.	86.6 g CHO, 14 g PRO, 7.1 g fat, 41 GL^1) 2) HGL/HGI = Cornflakes, milk, apple juice, & sugar (470 kcal, 90.4 g CHO, 14 g PRO, 5.3 g fat, 55 GL^1) 3) LGL/LGI = Alpen muesli, milk, & sugar (281 kcal, 43.2 g CHO, 12.5 g PRO, & 6.4 g fat, 21 GL^1) 4) LGL/HGI = Cornflakes, milk, & sugar (276 kcal, 45.2 g CHO, 12 g PRO, 5.1 g fat, 28 GL^1)	(immediate & delayed episodic memory), Stroop task (executive function - inhibitory control), Matrices (visual reasoning), number search task (speed of information processing), & Serial Sevens task (working memory).	breakfast & finished 133–138 min post-breakfast. Glucose levels = 00, 92, & 147 min.	significant results. Serial Sevens task = HGI meals predicted better performance. Stroop task = HGI meals predicted faster performance. Number search task = HGI meals predicted better performance. Word generation task = LGI meals predicted better performance. No effect of GL on the remaining tests.	energy. Included order of meal consumption, biological sex, BMI, height, age, weight, baseline mood, & baseline cortisol/ glucose levels as covariates. Did not report Stroop accuracy scores. Faster RTs may reflect more impulsive responses.
Smith and Foster (2008)	38 healthy participants (19 female, 19 male). Mean age = 15.65 years (SD = 0.9, range = 14 – 17 years). GT status not assessed.	BS. Randomised. Overnight fast.	1. HGL = Cornflakes with 125 mL milk (172 kcal, 31.2 g CHO, 6.5 g PRO, 2 g fat, 24 GL^2) 2. LGL = All Bran with 125 mL milk (158 kcal, 20.5 g CHO, 8.8 g PRO, 2.8 g fat, 6 GL^2)	CVLT, WLR task (immediate, short delay, & long delay episodic memory) Completed a secondary motor task whilst encoding word lists.	Cognition = 20 (immediate recall), 60 (short-delay free/cued recall), & 100 min (long-delay free/cued recall). Glucose levels = 00, 10, 50, & 90 min.	Participants in the HGL group recalled more words after the long delay vs. LGL group.	Breakfasts provided similar amounts of fat but different amounts of PRO, CHO, & energy. No difference in BGLs between groups at any time point.
Taib et al. (2012)	30 healthy children (12 female, 18 male). Mean age = 5.58 years & 4 months. GT status not assessed.	WS. Randomised. Counterbalanced. Double-blind. Overnight fast. One-week washout period. School-based study. Children maintained a standard pattern of activity prior to testing.	1. HGL = glucose -maltodextrin drink (160 kcal, 50 g CHO, 40 GL^2) 2. MGL = standard GUM (170 kcal, 26.40 g CHO, 5.88 PRO, 5.32 g fat, 20 GL^2) 3. MGL = reformulated GUM (174 kcal, 26.48 g CHO, 5.88 g PRO, 5.32 g fat, 14 GL^2) 3. LGL = isomaltulose GUM (170 kcal, 26.44 g CHO, 5.88 g PRO, 5.36 g fat, 13.76 GL^2)	CDR Computerised Assessment Battery: visuospatial working memory, numeric working memory, & picture recognition. Also created two composite scores using speed measures (speed of attention) & accuracy measures (accuracy of attention) from SRT, CRT, & digit vigilance tasks.	Cognition – 00, 60, 120, & 180 min.	Speed of attention = scores declined across the morning. However, scores improved 180 min after consuming the isomaltulose-GUM drink (non-significant). Working memory = spatial working memory scores declined across the morning following the consumption of all drinks; the decline was significantly smaller following the consumption of glucose. Numeric working memory also declined across the morning following the consumption of all drinks; the decline was smaller following the isomaltulose-GUM drink. Delayed picture recognition = overall performance declined across the morning in all groups except the isomaltulose-GUM	GUM drinks had similar macronutrient & energy profiles. Did not measure BGLs. Used a milk-based vehicle – insulinotropic. Baseline cognitive performance for each visit included as a covariate.

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Table 2 (*continued*)

Author (Year)	Participant characteristics	Study design	Breakfast intervention	Cognitive test	Timing of cognitive & blood glucose tests	Results	Comments
						group. Speed scores improved from baseline following the glucose drink only.	
Wesnes et al. (2003)	29 healthy children (15 female, 14 male). Mean age = 12.2 years (range = 9 – 16 years). GT status not assessed.	WS. Randomised. Counterbalanced. Tested on consecutive days. Overnight fast. Laboratory-based study.	1. HGL = 38.3 g of glucose in 330 mL orange-flavoured drink (38 GL^3) 2. LGL = Shreddies plus 125 mL of semi-skimmed milk (38.3 g total CHO, 15 GL^3) 3. LGL = Cheerios plus 125 mL of semi-skimmed milk (28.7 g total CHO, 15 GL^3) 4. No breakfast	CDR Computerised Assessment Battery: WLR, SRT, CRT, digit vigilance, visuospatial & numeric working memory, word recognition, & picture recognition. Created composite scores: speed of memory, speed of attention, accuracy of attention, working memory, & secondary memory.	Cognition = 00, 30, 90, 150, & 210 min.	Speed of attention & secondary memory = scores declined across the morning following the consumption of a glucose drink or no breakfast, whereas the consumption of either LGL breakfast reduced the decline by more than half. Immediate WLR = relative to baseline, immediate WLR declined by 27% 210 min after consuming the glucose drink, whereas scores increased by 5% after Shreddies & 3% after Cheerios. No effect of GL on the remaining tests.	Macronutrient & energy content of meals not reported. Did not measure BGLs. Large age range of sample.
Young and Benton (2015)	75 healthy children from four different schools (47 female, 28 male). Mean age = 8 years & 8 months (range = 5 – 11 years). GT status not assessed.	WS. Randomised Counterbalanced. Overnight fast. Double-blind. 1-week minimum washout period. School-based study.	1. HGL = Cornflakes, skimmed milk, & glucose-sweetened low calorie yoghurt, fruit, & an orange drink (337 kcal, 73.g CHO, 9.2 g PRO, 1.9 g fat, 59.8 GL^1) 2. LGL = Cornflakes, skimmed milk, & isomaltulose-sweetened low calorie yoghurt, fruit, & an orange drink (337 kcal, 73.3 g CHO, 9.2 g PRO, 1.9 g fat, 31.63 GL^1)	British Ability Scale – object name recall (immediate & delayed episodic memory), British Ability Scale – object location recall (immediate & delayed visuospatial memory), Paradigm of Shakow (sustained attention), British Ability Scale (speed of information processing), & RTs.	Cognition = 60 & 180 min. Speed of information processing task also tested at baseline.	Information processing speed = order of meal consumption interacted with breakfast GL. No difference in performance on day 1. However, on day 2, overall performance was better after the LGL meal vs. HGL meal. Object name recall (immediate) = similar performance at 60 min. However, at 180 min, performance following the LGL meal was maintained, whereas performance declined following the HGL meal. Object location recall = order of meal consumption interacted with breakfast GL. No difference in performance on day 1. However, on day 2, overall performance was better after the LGL meal vs. HGL meal. No effect of GL on RTs or sustained attention.	Meals had identical macronutrient & energy profiles. Did not measure BGLs. Biological sex & order of meal consumption were included as additional between-subjects factors. Age, baseline cognitive performance (speed of processing only), & social deprivation were included as covariates.

Note. 1 = GL values reported by study authors, 2 = GL values calculated using reported GI values multiplied by amount of CHO or available CHO, 3 = GL values calculated using published GI tables. * = estimated GL values are not consistent with participants glycaemic responses.
BS = between-subjects design, WS = within-subjects design, 00 = baseline, GL = glycaemic load, LGL = low GL, HGL = high GL, MGL = medium GL, GI = glycaemic index, CHO = carbohydrate, PRO = protein, GT = glucose tolerance, BMI = body mass index, BGLs = blood glucose levels, GUM = growing up milk, WLR = word list recall, RT = reaction times, SRT = simple RT, CRT = choice RT, CDR = cognitive drug research, CPT = continuous performance task, SCPT = standard CPT, RMCPT = running memory CPT, CVLT = California Verbal Learning Test, RAVLT = Rey Auditory Verbal Learning Test, WISC = Wechsler Intelligence Scale for Children.

3.2.3.2.2. The influence of individual differences. Individual differences in GT were related to the effect of breakfast GL on delayed episodic memory, but only during the late postprandial period (150–220 min; Fig. 5). In the 'better' GT subgroup, there was a trend towards better delayed episodic memory following the consumption of a LGL breakfast compared to a HGL breakfast (SMD = 0.22, 95% CI = −0.01 to 0.44, p = 0.06, I^2 = 0%), whereas no trend was observed in the 'poorer' GT subgroup (SMD = 0.21, 95% CI = −0.12 to 0.54, p = 0.20, I^2 = 0%).

Subgroup analyses by age could not be performed during the early postprandial period due to an insufficient number of studies. Age was related to the effect of GL on delayed episodic memory, but only during the mid-postprandial period (Fig. 6). Specifically, performance was significantly better after a LGL breakfast compared to a HGL breakfast in the 'younger' subgroup (SMD = 0.18, 95% CI = 0.01 – 0.35, p = 0.04, I^2 = 0%), but not the 'older' subgroup (SMD = −0.00, 95% CI = −0.21 to 0.21, p = 0.99, I^2 = 0%). To check whether this was due to the inclusion of participants with T2DM in the 'older' subgroup, a separate analysis was performed with data from these participants excluded. There was still no significant effect of breakfast GL in the 'older' subgroup (SMD = −0.08, 95% CI = −0.33 to 0.17, p = 0.53, I^2 = 0%).

3.2.3.3. Accuracy of working memory

3.2.3.3.1. The influence of the timing of testing. For brevity, forest plots, effect sizes, and 95% CI are included in Supplementary Document 1 (Fig. S1). There were no significant differences in performance between the HGL and LGL nutritional interventions during the early (30 – 35 min; p = 0.30), mid (90 – 105 min; p = 0.32), or late postprandial period (120 – 195 min; p = 0.78). There was also no evidence of heterogeneity (I^2 = 0%).

3.2.3.3.2. The influence of individual differences. Individual differences in GT and age were not related to the effect of breakfast GL on accuracy of working memory.

3.2.3.4. Speed of attention

3.2.3.4.1. The influence of the timing of testing. For brevity, forest plots, effect sizes, and 95% CI are included in Supplementary Document 1. The Rapid Information Processing Task (RIPT) was used in three studies (Nabb and Benton, 2006a, 2006b; Young and Benton, 2014). This task detects changes in performance over time by measuring attention every minute for five minutes. To reduce the number of data points taken from these studies, data from the first and fifth minute were extracted, and separate analyses were performed for each minute. When one-minute RIPT reaction time scores were included in the analysis (Fig. S2), there was no significant effect of breakfast GL during the early (15 – 35 min; p = 0.52), mid (60 – 105 min; p = 0.77), or late postprandial period (120 – 195 min; p = 0.21). Similarly, when five-minute RIPT reaction time scores were included in the analysis (Fig. S3), there was no effect of breakfast GL during the early (15 – 35 min; p = 0.57), mid (60 – 105 min; p = 0.64), or late postprandial period (120 – 195 min; p = 0.26). Heterogeneity was not substantial for any analysis.

3.2.3.4.2. The influence of individual differences. Individual differences in GT and age were not related to the effect of breakfast GL on speed of attention.

3.2.3.5. Accuracy of attention

3.2.3.5.1. The influence of the timing of testing. Forest plots, effect sizes, and 95% CI can be found in Supplementary Document 1. When one-minute RIPT reaction time scores were included in the analysis (Fig. S4), there was no effect of breakfast GL on accuracy of attention during the early (30 – 35 min; p = 0.84). mid (60 – 105 min; p = 0.48), or late postprandial period (120 – 195 min; p = 0.54). Similarly, when five-minute RIPT reaction time scores were included in the analysis (Fig. S5), there was no effect of GL during the early (30 – 35 min; p = 0.81), mid (60 – 105 min; p = 0.91), or late postprandial period (120 – 195 min; p = 0.71). There was no evidence of substantial heterogeneity.

3.2.3.5.2. The influence of individual differences. Individual differences in GT and age were not related to the effect of breakfast GL on accuracy of attention.

3.2.3.6. Sensitivity analyses. The results of the leave-one-out analysis are reported in Supplementary Document 1 (Table S5). For brevity, the impact of individually removing studies on significant/trending analyses will only be discussed here. With regards to immediate episodic memory (late postprandial analysis), removal of 13 out of 18 studies reduced the pooled effect size and resulted in the analysis no longer being significant. Removal of Benton et al. (2003) most strongly affected the pooled effect size and significance of the analysis, followed by the better GT data from Young and Benton (2014) and Sanchez-Aguadero et al. (2020). Conversely, removal of some data from Nabb and Benton (2006a) and Lamport et al. (2014) reduced the significance value and increased the pooled effect size (Table S5). With regards to delayed episodic memory (late postprandial analysis), removal of Benton et al. (2003) also produced the largest change in significance and pooled effect size, followed by the better GT data from Young and Benton (2014) and Sanchez-Aguadero et al. (2020).

In most cases, removal of studies that did not match the macronutrient and energy composition of breakfast interventions lowered p values and increased effect sizes (data not reported). For accuracy of attention scores, removal of these studies revealed a trend towards a beneficial effect of a LGL breakfast during the late postprandial period (SMD = 0.23, 95% CI = −0.01 to 0.48, p = 0.06, I^2 = 0%). Adjusted and unadjusted means were obtained from one study (Sanchez-Aguadero et al., 2020). The inclusion of adjusted or unadjusted means did not influence effect sizes (data not reported).

3.2.3.7. Publication bias. Funnel plots were generated for immediate episodic memory, delayed episodic memory, accuracy of attention, and speed of attention (Supplementary Document 1). Due to an insufficient number of studies, we could not generate funnel plots for accuracy of working memory scores. There was some degree of asymmetry for accuracy of attention (early & late postprandial period), speed of attention (early & late postprandial period) and delayed episodic memory (early postprandial period).

3.2.3.8. Summary of results.

- The influence of the timing of testing: immediate episodic memory was significantly better after a LGL breakfast, compared to a HGL breakfast, but only during the late postprandial period (120 – 195 min). There was a similar non-significant trend for delayed episodic memory, whereby performance was better during the late postprandial period (150 – 220 min) following a LGL breakfast relative to a HGL breakfast.

- The influence of individual differences in GT: during the late postprandial period, immediate episodic memory was significantly better

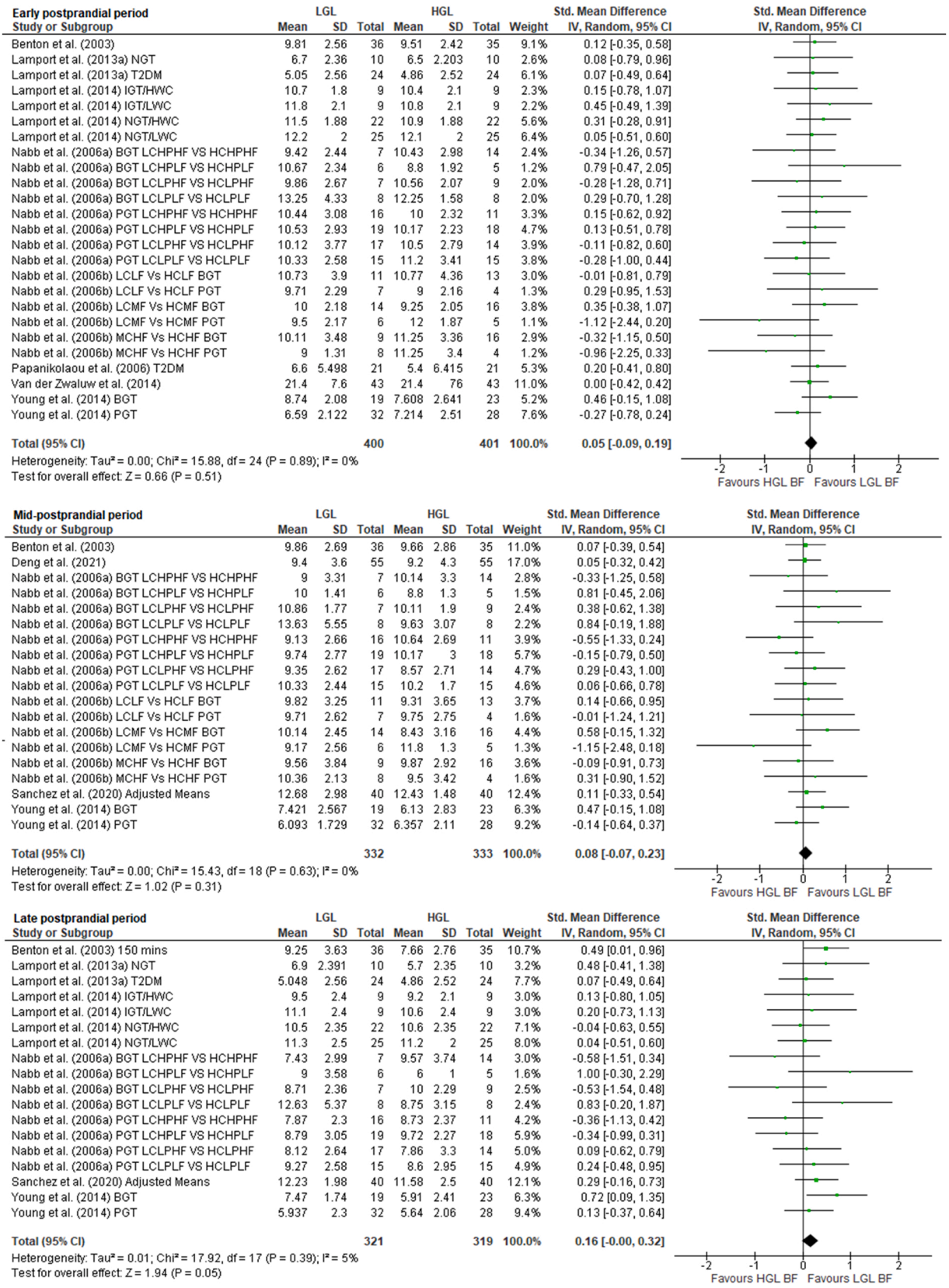

Fig. 2. Forest plot of the effect of glycaemic load on immediate episodic memory for each postprandial time window. NGT = normal glucose tolerance, T2DM = type 2 diabetes mellitus, IGT = impaired glucose tolerance, HWC = high waist circumference, LWC = low waist circumference, BGT = better glucose tolerance, PGT = poorer glucose tolerance, LC = low carbohydrate, HC = high carbohydrate, LP = low protein, HP = high protein, LF = low fat, and HF = high fat. Note that Nabb and Benton (2006b) manipulated the carbohydrate and fibre content of meals hence LF = low fibre, HF = high fibre, and MF = medium fibre.

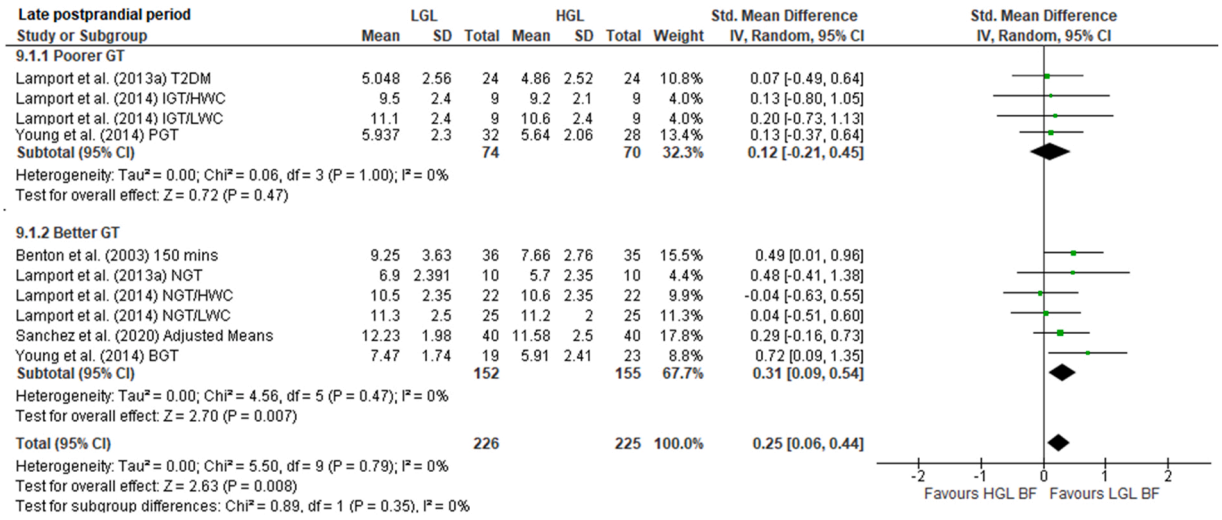

Fig. 3. Forest plot of the effect of glycaemic load on immediate episodic memory during the late postprandial period in participants with poorer GT or better GT. NGT = normal glucose tolerance, T2DM = type 2 diabetes mellitus, IGT = impaired glucose tolerance, HWC = high waist circumference, LWC = low waist circumference, BGT = better glucose tolerance, and PGT = poorer glucose tolerance.

following a LGL breakfast, but only in those with 'better' GT. No differences were observed in those with 'poorer' GT. A similar non-significant trend was observed for delayed episodic memory, whereby performance was better after a LGL breakfast, in those with 'better' GT, during the late postprandial period. No trend was observed in the 'poorer' GT subgroup.

- The influence of individual differences in age: during the mid-postprandial period (62 – 119 min), delayed episodic memory was significantly better following a LGL breakfast, but only in the 'younger' subgroup. No differences were observed in the 'older' subgroup.

- There was no effect of breakfast GL on accuracy of working memory, accuracy of attention, or speed of attention.

3.3. Studies involving children or adolescents

As mentioned above, data from studies conducted in children were not deemed suitable for meta-analysis. However, children are an important population in which to consider the cognitive consequences of the GL of breakfast. Therefore, we qualitatively reviewed the literature to identify promising avenues for future research as well as factors to be considered in study design.

3.3.1. Risk of bias

The results of the risk of bias assessment are summarised in Supplementary Document 1 (Table S6). Overall, four studies showed a low risk of bias and 12 studies showed some concerns of bias. Studies were generally judged with some concerns of bias for the same reasons reported in Section 3.2.1. For the 'bias arising from period and carryover effects' domain, studies were judged as having some concerns of bias or a high risk of bias if the study was unbalanced and/or participants were tested on consecutive days. For the 'deviations from intended outcome' domain, studies were judged as showing a high risk of bias if participants were clearly not blinded.

3.3.2. Study characteristics

Participants mean age ranged from 5.58 years (Taib et al., 2012) to 15.65 years (Smith and Foster, 2008), and sample sizes ranged from 19 (Benton et al., 2007b) to 84 participants (Anderson et al., 2020). One study was unpublished (Ingwersen, 2011). Two studies used a parallel design, two used a mixed-subjects design, and 12 used a crossover design. All studies were randomised, other than both studies by Mahoney et al. (2005).

3.3.3. The effect of breakfast GL on cognitive performance

3.3.3.1. Episodic memory. Twelve studies assessed episodic memory. As shown in Table 2, three studies reported no effect of breakfast GL during the early postprandial period (Lee et al., 2019; Smith and Foster, 2008; Wesnes et al., 2003). In contrast, Ingwersen et al. (2007) reported that episodic memory scores were higher 10 min after consuming a LGL breakfast compared to HGL breakfast.

During the mid-postprandial period, 10 studies reported no effect of breakfast GL (Brindal et al., 2012, 2013; Ingwersen et al., 2007; Lee et al., 2019; Mahoney et al., 2005; Micha et al., 2011; Taib et al., 2012; Wesnes et al., 2003; Young and Benton, 2015). Smith and Foster (2008) were the only authors to report an effect of breakfast GL within this time window (100 min post-breakfast), whereby delayed episodic memory was better in the HGL group compared to the LGL group. The authors suggested that the beneficial effect of a HGL breakfast on delayed memory may be due to the increased availability of glucose to the brain during encoding. However, there were no significant differences in blood glucose levels between the two groups at any postprandial time point, suggesting that differences in glycaemia may not account for differences in cognitive performance.

Nine studies measured episodic memory during the late postprandial period (120 min or later), of which five reported that breakfast GL did not influence performance (Brindal et al., 2012, 2013; Lee et al., 2019; Micha et al., 2011; Taib et al., 2012). Using an ANOVA, Benton et al. (2007b) also found that breakfast GL did not influence the memory of young children 140 min post-breakfast. However, there was a significant negative correlation between GL and immediate episodic memory scores. Furthermore, a lower GL predicted better performance, whereas the amount of protein, fat, and carbohydrate did not. Young and Benton (2015) also recruited a sample of children. Although immediate recall was similar 60 min post-breakfast, performance was significantly better during the second test battery (180 min) following the consumption of a LGL breakfast. Furthermore, performance only declined from the first test battery to the second test battery after the consumption of a HGL breakfast.

Ingwersen et al. (2007) also found no effect of breakfast GL during the mid-postprandial period (70 min). However, during the late

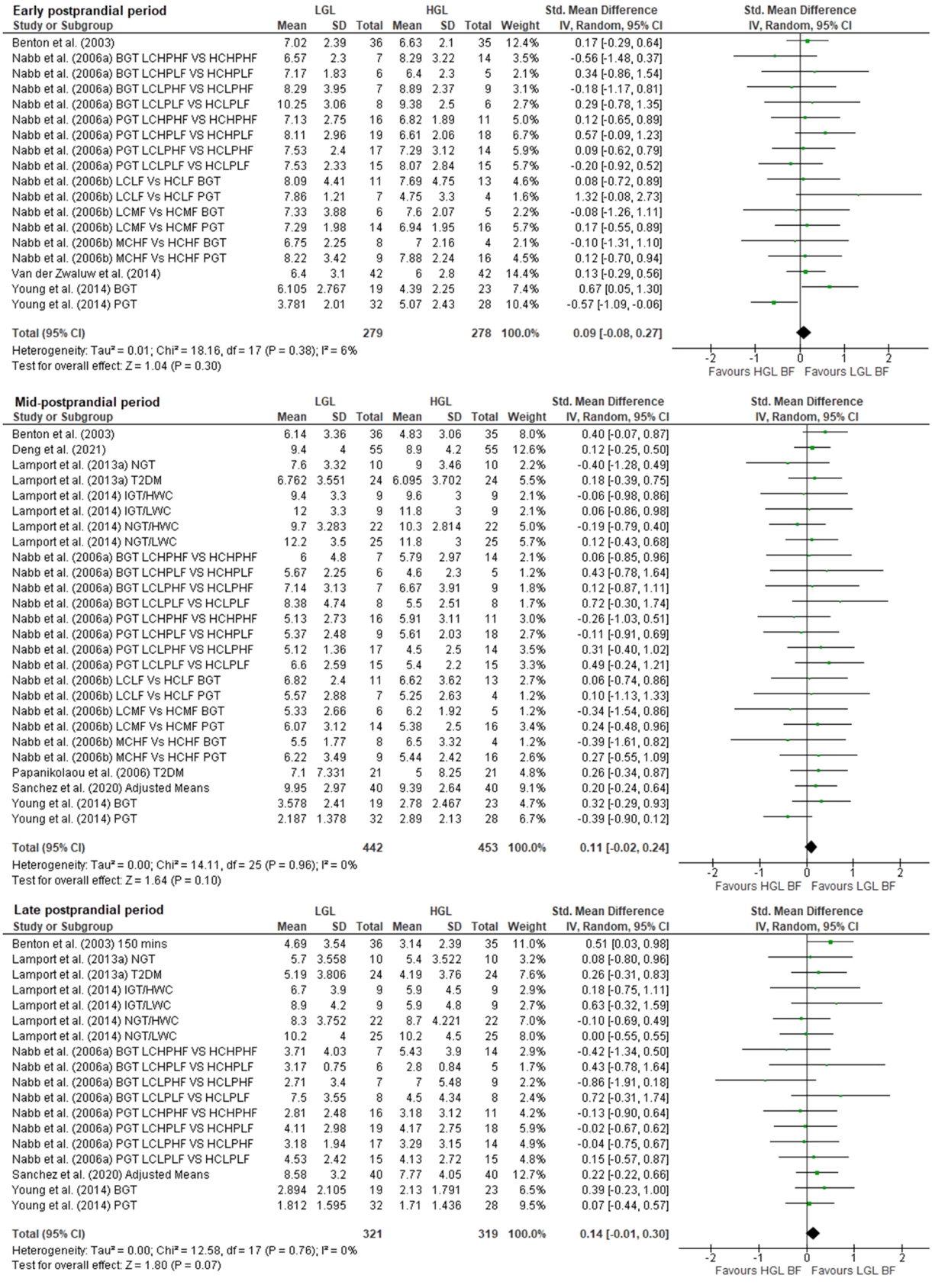

Fig. 4. Forest plot of the effect of glycaemic load on delayed episodic memory for each postprandial time point. NGT = normal glucose tolerance, T2DM = type 2 diabetes mellitus, IGT = impaired glucose tolerance, HWC = high waist circumference, LWC = low waist circumference, BGT = better glucose tolerance, PGT = poorer glucose tolerance, LC = low carbohydrate, HC = high carbohydrate, LP = low protein, HP = high protein, LF = low fat, and HF = high fat. Note that Nabb and Benton (2006b) manipulated the carbohydrate and fibre content of meals hence LF = low fibre, HF = high fibre, and MF = medium fibre.

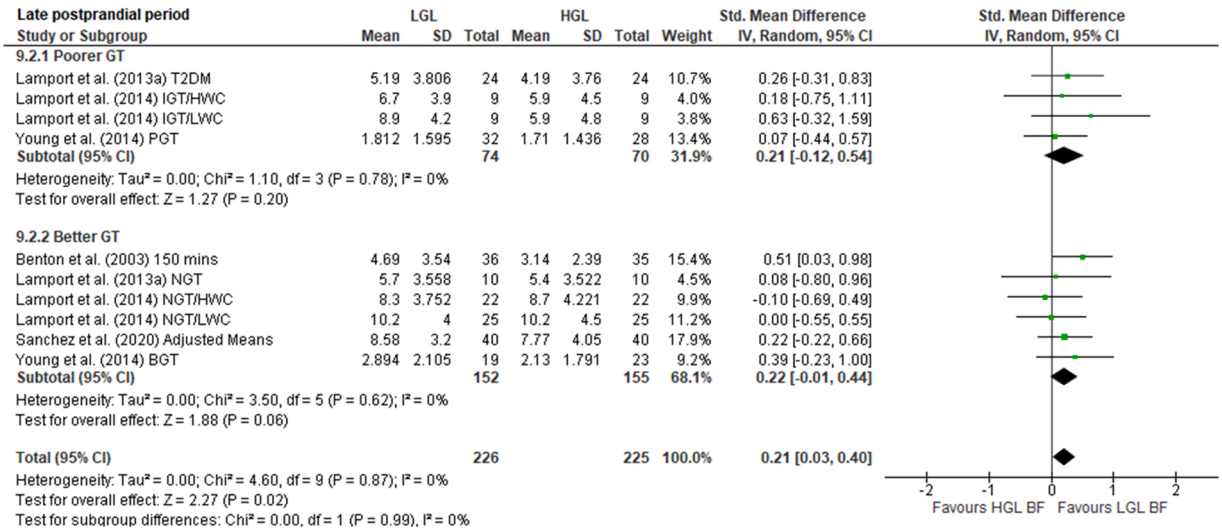

Fig. 5. Forest plot of the effect of glycaemic load on delayed episodic memory during the late postprandial period in participants with poorer GT or better GT. NGT = normal glucose tolerance, T2DM = type 2 diabetes mellitus, IGT = impaired glucose tolerance, HWC = high waist circumference, LWC = low waist circumference, BGT = better glucose tolerance, and PGT = poorer glucose tolerance.

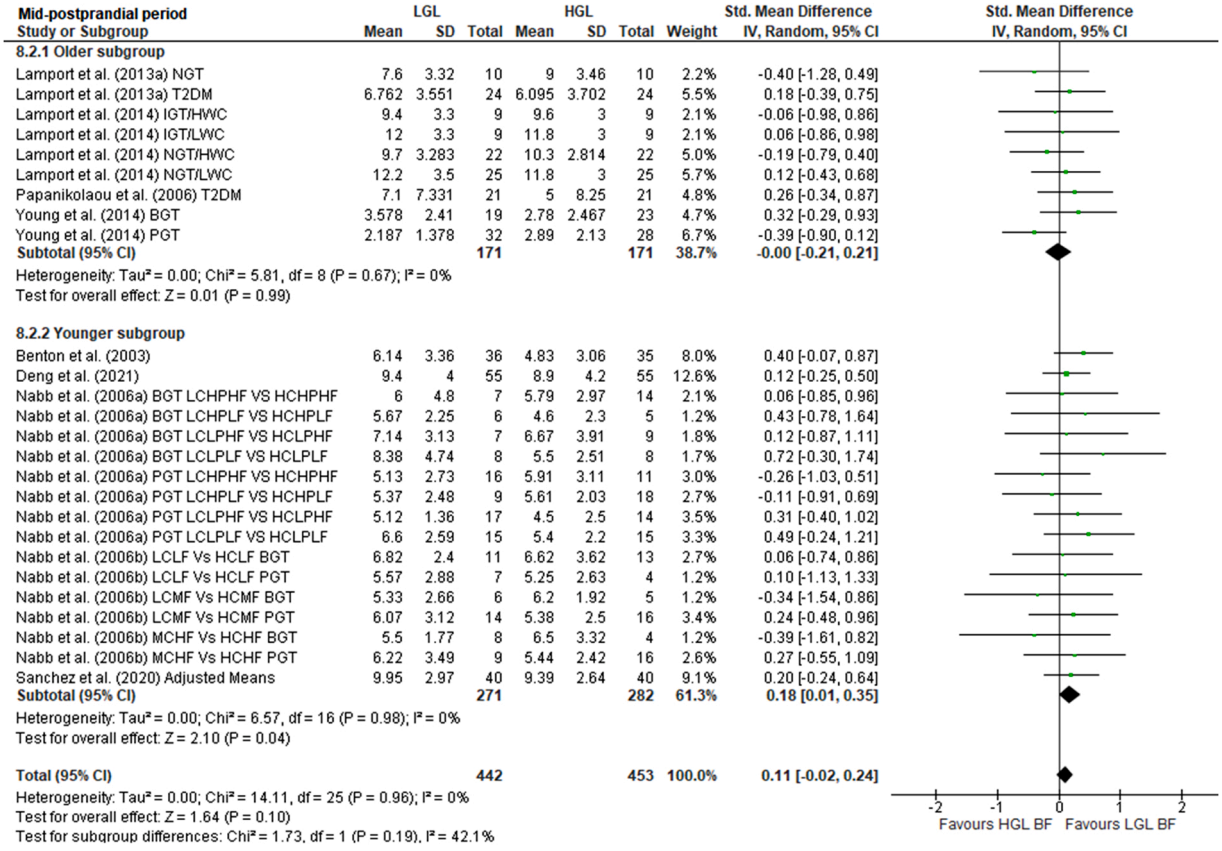

Fig. 6. Forest plot of the effect of glycaemic load on delayed episodic memory during the mid-postprandial period in studies with a mean age above or below 34 years. NGT = normal glucose tolerance, T2DM = type 2 diabetes mellitus, IGT = impaired glucose tolerance, HWC = high waist circumference, LWC = low waist circumference, BGT = better glucose tolerance, PGT = poorer glucose tolerance, LC = low carbohydrate, HC = high carbohydrate, LP = low protein, HP = high protein, LF = low fat, and HF = high fat. Note that Nabb and Benton (2006b) manipulated the carbohydrate and fibre content of meals hence LF = low fibre, HF = high fibre, and MF = medium fibre.

postprandial period (130 min), task accuracy was better after consuming a LGL rather than HGL breakfast. Similarly, Wesnes et al. (2003) found that a LGL breakfast benefited performance, but only during the late postprandial period. Immediate recall declined by 27% during the final test battery (210 min) after consuming a HGL breakfast but improved by 3 – 5% after consuming a LGL breakfast. The ratio of significant to non-significant findings during the early, mid, or late postprandial period are shown in Table 3.

Three studies reported significant effects of breakfast GL that were not time dependent. Taib et al. (2012) reported an overall decline in

Table 3
The ratio of significant to non-significant findings reported by studies involving children and adolescents.

	Early PPP (0–59 min)	Mid PPP (60–119 min)	Late PPP (120 min +)
Episodic memory[1]	1/4	1/11	4/9
Working memory[2]	0/7	2/10	3/11
Attention reaction times[3]	0/5	0/8	1/8
Attention accuracy	0/6	1/10	3/11

Note. Only studies that reported an effect of breakfast GL at a specific time point were included in this table. A main effect of breakfast GL was reported by 1 = Brindal et al. (2013), Lee et al. (2019), and Taib et al. (2012), 2 = Taib et al. (2012), and 3 = Anderson et al. (2020) and Taib et al. (2012). PPP = postprandial period.

delayed memory, across the morning, after the consumption of all drinks other than an isomaltulose-sweetened drink (lowest GL). Interestingly, overall task speed improved across the morning after the consumption of a glucose drink (highest GL) compared to reformulated growing-up milk. In contrast, Wesnes et al. (2003) and Ingwersen et al. (2007) reported that task speed was not influenced by breakfast GL. Brindal et al. (2013) reported that the effect of breakfast GL interacted with participant's biological sex. Relative to baseline, females recalled more words overall after consuming a LGL or MGL breakfast compared to a HGL breakfast. There was no effect of GL in male children. No effect of time was also reported by Lee et al. (2019). However, participants recalled more words overall after consuming a meal with a lower estimated GL (French fries) compared to a higher estimated GL (mashed potatoes or white rice). As glycaemic responses were higher after the consumption of French fries than mashed potatoes, it suggests that estimated GL values are incorrect. Therefore, these findings should be interpreted with caution.

3.3.3.2. Working memory. A total of 13 studies assessed working memory. Nine studies reported that breakfast GL did not influence task performance during the early postprandial period (Anderson et al., 2020; Cooper et al., 2012, 2015; Ingwersen, 2011; Ingwersen et al., 2007; Lee et al., 2019; Wesnes et al., 2003), mid postprandial period (Anderson et al., 2020; Brindal et al., 2012, 2013; Ingwersen, 2011; Ingwersen et al., 2007; Lee et al., 2019; Taib et al., 2012; Wesnes et al., 2003), and/or late postprandial period (Anderson et al., 2020; Brindal et al., 2012, 2013; Ingwersen, 2011; Ingwersen et al., 2007; Lee et al., 2019; Taib et al., 2012; Wesnes et al., 2003).

Both studies by Mahoney et al. (2005) found an effect of breakfast GL during the mid-postprandial period. Older (9 – 11 years) and younger (6 – 8 years) female children performed better 60 min after consuming a LGL breakfast compared to a HGL breakfast. Breakfast GL did not significantly influence the performance of male children. Although no effect of time was reported, Anderson et al. (2020) also reported an interaction between biological sex and breakfast GL. Overall task performance was better, in females, after consuming a HGL drink compared to a LGL drink. The opposite pattern occurred in males, but this was not significant. The reason for these conflicting findings is unclear - participants in Mahoney et al. (2005) and Anderson et al. (2020) were of a similar age and there was a similar difference in GL between the LGL and HGL breakfast interventions.

One study reported that a HGI breakfast predicted better working memory performance during the late postprandial period (Micha et al., 2011). Two studies reported that a LGL breakfast was associated with better performance during the late postprandial period (Cooper et al., 2012, 2015). Although reaction times were similar 30 min post-breakfast, there was a greater improvement in task speed 120 min after consuming a LGL breakfast compared to a HGL breakfast (Cooper et al., 2012). On the complex levels of this task, accuracy scores were maintained across the morning following a LGL breakfast but declined following a HGL breakfast. In a later study, Cooper et al. (2015) reported a similar finding, whereby reaction times improved across the morning (from 30 to 120 min) after consuming a LGL meal, regardless of whether participants exercised. However, performance only improved after a HGL meal if participants exercised.

Taib et al. (2012) reported that a LGL breakfast benefitted overall task performance. Relative to baseline, numeric working memory scores declined across the morning in all drink conditions. However, the decline was significantly smaller after consuming an isomaltulose-sweetened drink (lowest GL) compared to a glucose drink (highest GL) or reformulated growing-up milk. As shown in Table 2, the GL of the isomaltulose-sweetened milk and reformulated milk were very similar and so it is unlikely that differences in GL accounted for this finding. The authors also reported that a HGL drink benefitted spatial working memory. Specifically, the overall decline across the morning was significantly smaller after the consumption of glucose compared to all three LGL drinks.

3.3.3.3. Speed of attention. Eleven studies measured speed of attention, of which nine reported no specific effect of breakfast GL during the early postprandial period (Anderson et al., 2020; Cooper et al., 2012, 2015; Ingwersen, 2011; Ingwersen et al., 2007), mid-postprandial period (Anderson et al., 2020; Brindal et al., 2012, 2013; Ingwersen, 2011; Ingwersen et al., 2007; Mahoney et al., 2005; Taib et al., 2012), and/or late postprandial period (Anderson et al., 2020; Brindal et al., 2012, 2013; Cooper et al., 2012, 2015; Ingwersen, 2011; Ingwersen et al., 2007; Taib et al., 2012). One study reported that a LGL breakfast benefitted task speed, but only during the late postprandial period. Wesnes et al. (2003) reported a significant decline in performance, relative to baseline, 210 min after consuming a HGL drink. However, this decline was reduced by more than half following the consumption of a LGL breakfast.

Two studies reported significant effects of breakfast GL that were not time dependent. Taib et al. (2012) reported that performance declined across the morning. However, the overall decline was significantly greater following the consumption of standard growing-up milk compared to isomaltulose-sweetened growing-up milk. Furthermore, at 180 min, there was a non-significant improvement in performance, but only after the consumption of isomaltulose-sweetened milk. Although there was no specific effect of time, Anderson et al. (2020) reported an interaction between breakfast GL and biological sex. Responses were faster overall after the consumption of a LGL drink, compared to a HGL drink, but only in female participants. The opposite pattern emerged for males, but this was non-significant.

3.3.3.4. Accuracy of attention. Thirteen studies measured accuracy of attention. Ten studies reported that breakfast GL did not influence performance during the early postprandial period (Anderson et al., 2020; Cooper et al., 2012, 2015; Ingwersen, 2011; Ingwersen et al., 2007; Wesnes et al., 2003), mid-postprandial period (Anderson et al., 2020; Brindal et al., 2012, 2013; Ingwersen, 2011; Ingwersen et al., 2007; Taib et al., 2012; Wesnes et al., 2003; Young and Benton, 2015), and/or late postprandial period (Anderson et al., 2020; Brindal et al., 2012, 2013; Cooper et al., 2015; Ingwersen, 2011; Taib et al., 2012; Wesnes et al., 2003; Young and Benton, 2015).

During the mid-postprandial period, Mahoney et al. (2005) reported an interaction between age and breakfast GL. Younger children (6 – 8 years) made more correct responses on an auditory attention task 60 min after consuming a LGL breakfast rather than a HGL breakfast. In contrast, no differences in performance were found in older children (9 – 11 years). Furthermore, breakfast GL did not influence visual attention performance. Ingwersen et al. (2007) also examined the effect of age

using the same age groups, however no age effects were observed.

Three studies found a beneficial effect of a LGL breakfast during the late postprandial period. In Cooper et al. (2012), accuracy scores on the more complex trials were similar during the first test battery (30 min). However, during the second test battery (120 min), scores were better maintained after consuming a LGL breakfast compared to a HGL breakfast. Similarly, Ingwersen et al. (2007) reported that there was a sharp decline in performance 130 min after consuming a HGL breakfast, whereas performance was maintained at this time after consuming a LGL breakfast. Although no effect of breakfast GL was reported using an ANOVA, Benton et al. (2007b) found that the number of lapses of attention (difficult trials only) correlated positively with GL. A lower GL also predicted better sustained attention (difficult trials only).

3.3.4. Summary of results

- There was very limited evidence to suggest that breakfast GL influenced cognitive performance within the first hour after consuming breakfast.
- There was some evidence to suggest that a LGL breakfast may protect against a decline in episodic memory, accuracy of attention, and speed of attention during the late postprandial period (120 min post-breakfast or later).
- Task difficulty, age, and biological sex might influence the relationship between breakfast GL and cognitive performance.

4. Discussion

4.1. Adult meta-analysis

Studies comparing HGL and LGL breakfasts have produced mixed results. An obvious hypothesis is that certain methodological factors determine the outcome. Therefore, for the first time, this meta-analysis considered a range of possible factors that may influence the response to the glycaemic influence of breakfast.

As summarised in Section 2.4.8, there were several lines of evidence to suggest that a LGL breakfast benefits cognitive performance in a time-dependent manner. During the late postprandial period (120 min or later), a LGL breakfast was significantly associated with better immediate episodic memory (Fig. 2). A similar non-significant trend was also observed for delayed episodic memory during the late postprandial period (150 −220 min; Fig. 4). In addition, the beneficial effect of a LGL breakfast on immediate and delayed episodic memory was influenced by individual differences in age (Fig. 6) and GT (Figs. 3 & 5). However, the sensitivity analysis showed that the removal of most studies, particularly Benton et al. (2003), Young and Benton (2014), and Sanchez-Aguadero et al. (2020), reduced the effect size of the analyses shown in Figs. 2 and 4, highlighting the need for more research in this area to confirm or refute these conclusions.

There was no effect of breakfast GL on speed of attention, accuracy of attention, or accuracy of working memory across all three postprandial time windows. These results suggest that the effect of breakfast GL may be subdomain-specific. In line with this, previous reviews have reported that episodic memory is more responsive to breakfast manipulations than other cognitive domains and subdomains (Galioto and Spitznagel, 2016; Hoyland et al., 2008; Smith et al., 2011; Wasyluk et al., 2019). However, it is important to note that fewer studies assessed working memory than episodic memory in the present review. In addition, a wider variety of tests were used to measure attention and working memory, potentially influencing the findings.

Nonetheless, these findings are consistent with the hypothesis that a LGL breakfast, which provides a steady and continuous supply of glucose to the brain, may be more advantageous for acute cognitive performance than a HGL breakfast (Nilsson et al., 2012; Papanikolaou et al., 2006; Young and Benton, 2014). It is difficult to assess the validity of this hypothesis because many studies did not measure peripheral glucose levels. Furthermore, in those studies that did, some reported cognitive differences when glucose levels were similar (Benton et al., 2003; Nilsson et al., 2012), and others reported no cognitive differences when glucose levels were markedly different (Kaplan et al., 2000; Lamport et al., 2013a; Sanchez-Aguadero et al., 2020). Although there is a positive correlation between blood glucose and extracellular glucose (Rostami and Bellander, 2011; van de Ven et al., 2012), the concentration of glucose in the brain is approximately 20–30% of that in the blood (Béland-Millar et al., 2017), and there is a time lag of up to 30 min between changes in blood glucose and changes in extracellular glucose (Abi-Saab et al., 2002; Gruetter et al., 1998). Cognitive demand can also influence extracellular glucose levels (McNay et al., 2000). Therefore, a failure to observe concurrent cognitive and glycaemic differences does not necessarily disprove this hypothesis. Perhaps the beneficial effect of a LGL relative to HGL breakfast is not directly related to glycaemia, but rather associated aspects of metabolism that appear over time, including changes to concentrations of cortisol, insulin, glucagon, glucagon-like pepetide-1, acetylcholine, glutamate, or serotonin (Adolphus et al., 2016; Hoyland et al., 2009).

Previous reviews have suggested that a LGL breakfast may be particularly advantageous to vulnerable groups, including older adults or individuals with poorer glucoregulation (Galioto and Spitznagel, 2016; Lamport et al., 2009; Sünram-Lea and Owen, 2017). In contrast, subgroup analyses indicated that a LGL breakfast may exert a greater effect in younger adults or those with 'better' GT. Specifically, a LGL breakfast benefitted immediate episodic memory, during the late postprandial period (120 min or later), in the 'better' but not the 'poorer' GT subgroup. A similar non-significant trend was observed for delayed episodic memory during the late postprandial period. Subgroup analyses also showed that a LGL breakfast benefitted delayed episodic memory, during the mid-postprandial period (62 – 119 min), in the 'younger' subgroup but not the 'older' subgroup. The finding that age effects were only observed during the mid-postprandial period is surprising, as all other effects were observed during the late postprandial period.

As the mechanisms underlying the acute cognitive effects of GL are currently unclear, it is difficult to speculate why these subgroup effects occurred. However, it is plausible that such mechanisms are hampered in those with 'poorer' GT or those aged above 35 years old. For example, it has been suggested that the beneficial effect of a LGL breakfast may be due to the generation of a smoother postprandial insulin profile (Benton et al., 2003). Glucose intolerance is associated with impaired insulin action and secretion (Abdul-Ghani et al., 2006) and endothelial dysfunction (Convit, 2005). The transport of insulin and glucose across the blood brain barrier, and between intracellular and extracellular fluid in the brain, is thus hindered in glucose intolerant individuals (Lamport et al., 2013a; Young and Benton, 2014). This may result in an insensitivity to the cognitive effects of GL. The prevalence of glucose intolerance and endothelial dysfunction also increases with age, which may also contribute to age effects.

Consistent with this suggestion, a double-blind, well-controlled study by Young and Benton (2014) reported that a LGL breakfast benefitted episodic and working memory in middle aged and older adults (45 – 80 years old) with 'better' but not 'poorer' GT. The picture is, however, complicated as a beneficial effect of a LGL breakfast on episodic memory has been demonstrated in older adults with T2DM (Papanikolaou et al., 2006) and IGT (Lamport et al., 2014), and young healthy adults with 'poorer' GT (Nabb and Benton, 2006b). However, it is unclear whether GT interacted with the effects of breakfast GL as Papanikolaou et al. (2006) did not recruit a healthy control group. Furthermore, most participants in Papanikolaou et al. (2006) were treated with metformin or sulphonylureas. These medications improve GT by enhancing insulin secretion and suppressing hepatic glucose production, which may have interacted with the effects of breakfast GL.

Alternatively, the absence of a significant beneficial effect in the 'older' subgroup may be due to the inclusion of participants with a wide range of ages. Specifically, the mean age of the 'older' subgroup ranged

from 36.6 years (Lamport et al., 2014) to 65 years (Papanikolaou et al., 2006), whereas the mean age of the 'younger' subgroup ranged from 20.36 years (Nabb and Benton, 2006a) to 28.1 years (Sanchez-Aguadero et al., 2020). It is plausible that the wide age range of the 'older' subgroup introduced variability, which can reduce statistical power and mask significant effects (Jiang et al., 2010; Netz et al., 2019). For example, advancing age is associated with increased interindividual differences in baseline nutritional status, GT, and cognitive, physical, and sensory function (Asamane et al., 2020; Ferrucci and Kuchel, 2021; Mungas et al., 2010; Zulman et al., 2011). Further research aimed at understanding individual differences in the response to GL is clearly warranted.

4.2. Child and adolescent qualitative analysis

Due to a lack of data, and the use of different types of scores, a meta-analysis of the effect of breakfast GL in children and adolescents was not possible. Instead, we performed a systematic review of 16 studies. Although the cognitive effects of manipulating breakfast GL have been discussed in previous systematic reviews, the influence of the timing of testing was only briefly considered (Adolphus et al., 2016; Álvarez-Bueno et al., 2019; Hoyland et al., 2009). In contrast, we systematically examined the effect of breakfast GL in relation to the timing of testing.

There was no clear and robust effect of breakfast GL on episodic memory, working memory, and attention during the early, mid, or late postprandial period. There was some evidence to suggest that a LGL breakfast benefited episodic memory, particularly during the late postprandial period (120 min post-breakfast or later), which is consistent with the results of the present meta-analysis. No study reported an effect of breakfast GL on accuracy and speed of attention during the early postprandial period, and no study reported that a HGL breakfast positively influenced attention. The effect of breakfast GL on working memory was more heterogeneous, with some studies reporting an advantage of a LGL breakfast (Cooper et al., 2012, 2015; Mahoney et al., 2005; Taib et al., 2012), and other studies reporting an advantage of a HGL breakfast (Anderson et al., 2020; Micha et al., 2011; Taib et al., 2012).

A recent meta-analysis assessed the effect of breakfast GI, rather than GL, on the cognitive performance of children and adolescents. Álvarez-Bueno et al. (2019) reported that breakfast GI did not influence immediate memory, delayed memory, and attention. However, subgroup analyses revealed that delayed memory scores were significantly higher after a LGI breakfast, compared to HGI breakfast, in children but not adolescents. Álvarez-Bueno et al. (2019) were able to perform a meta-analysis of the effect of breakfast GI because they took a less rigorous approach to the meta-analysis than we aimed to perform. For example, change scores and post-scores were analysed together, subdomains of memory were analysed as one group (e.g., working memory & episodic memory), and the effect of the timing of testing was not examined. It is unclear how these factors influenced their conclusions, however, our qualitative synthesis indicated that they might be important.

Overall, there was some evidence to suggest that a LGL breakfast exerted a positive effect on episodic memory and accuracy of attention during the late postprandial period. This pattern of results is illustrated in Table 3. However, the quality of evidence was mixed, with most studies showing some concerns of bias. Furthermore, a range of experimental methods were used, giving rise to different methodological limitations. For example, two studies were not randomised, and most studies administered breakfast interventions that were not matched for macronutrient or energy content. A detailed discussion of these methodological limitations can be found in Section 4.3.

4.3. Guiding principles

This review highlighted considerable methodological variability between studies that may have contributed to the inconsistent literature. Consequently, a series of guiding principles were developed to guide study design and, in turn, facilitate a better understanding of the relationship between breakfast GL and acute cognitive performance (Fig. 7).

4.3.1. Sample heterogeneity

Research has repeatedly shown that participants respond in different ways to the same nutritional interventions (Lampe et al., 2013). As such, an analysis of the average cognitive response to variations in breakfast GL may fail to reveal the range of responses produced (Blundell et al., 2010). Although there are many other relevant factors, this section discusses the importance of considering age, biological sex, and body mass index (BMI), whereas GT is discussed separately in Section 4.3.2.

The meta-analysis revealed that age influenced the beneficial effect of a LGL breakfast on delayed episodic memory in adults. Therefore, null findings in studies with large age ranges may reflect a failure to test for age effects rather than no effect of breakfast GL. Similarly, some studies analysed children and adolescents as one group (Cooper et al., 2015; Wesnes et al., 2003). However, children and adolescents should ideally be analysed separately given the abundance of metabolic, behavioural, and hormonal changes associated with puberty (Kawakubo et al., 2011). The rate of cerebral glucose utilisation is also higher in young children (4 – 10 years) compared to adolescents (Chugani, 1998), potentially making young children more susceptible to changes in postprandial glycaemia. Indeed, Álvarez-Bueno et al. (2019) reported that delayed episodic memory scores were significantly higher after a LGI breakfast, compared to HGI breakfast, in children but not adolescents. More work is clearly needed to determine the influence of age, ideally by directly comparing different age groups within the same study.

As shown in Table 1, few studies assessed whether measures of obesity influenced the relationship between breakfast GL and cognitive function in adults. This is surprising given the strong association between obesity, cognitive dysfunction, and GT throughout adulthood (Fellows and Schmitter-Edgecombe, 2018). Although a larger number of studies involving children and adolescents included BMI as a covariate, there was no evidence to suggest that BMI moderated the effect of breakfast GL on cognitive performance (see Table 2). However, other than Anderson et al. (2020), participants BMIs were within the normal, healthy range. As glycaemic responses to HGI meals are greater in overweight adolescents and adults, compared to normal weight individuals (Yalçın et al., 2017; Zakrzewski and Tolfrey, 2012), it is possible that BMI or other measures of obesity exert a moderating effect on the relationship between GL and cognition.

We were unable to perform subgroup analyses according to biological sex. However, several studies have reported that female children (ranging from 6 to 12 years of age) were more susceptible to variations in breakfast GL than male children (Anderson et al., 2020; Brindal et al., 2013; Mahoney et al., 2005). This finding may be due to sex differences in insulin sensitivity and cortisol levels, both of which have been suggested to underlie the effect of GL on acute cognitive performance (Cooper et al., 2012; Lamport et al., 2013a). In adults, no study reported that sex moderated the cognitive effects of breakfast GL. It has previously been reported that the consumption of glucose enhanced episodic memory in older men but not older women (Craft et al., 1994). Therefore, further exploration of this factor is warranted.

4.3.2. Individual differences in glucose tolerance

The importance of investigating the influence of GT was highlighted in the present meta-analysis. Studies have also reported that GT moderated the effect of breakfast GL on attention, inhibitory control, working memory, and visuospatial memory (Anderson et al., 2018; Lamport et al., 2014; Nabb and Benton, 2006a, 2006b; Young and Benton, 2014). However, despite its obvious importance, many studies

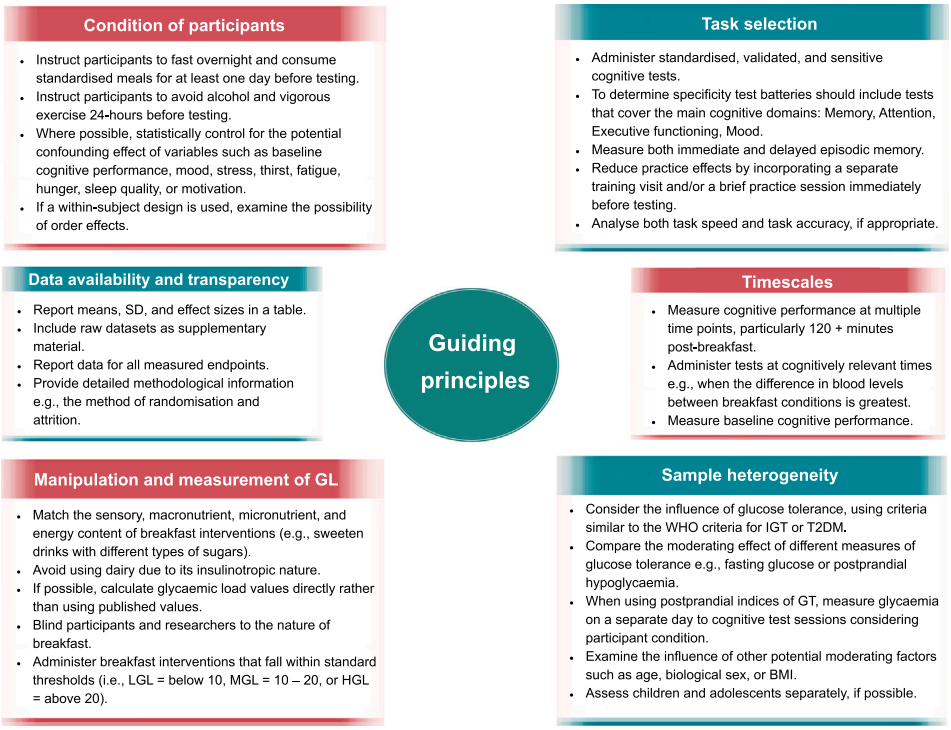

Fig. 7. Six guiding principles for research examining the impact of breakfast GL on cognition.

did not measure GT. In those studies that did, some defined 'poorer' GT using the WHO criteria for IGT or T2DM (Lamport et al., 2014, 2013a), whereas others used the median split of the sample (Brindal et al., 2013; Nilsson et al., 2009; van der Zwaluw et al., 2014). Although the latter approach can provide valuable information, definitions of 'poorer' or 'better' GT are sample dependent which limits comparisons between studies. As such, researchers may benefit from using criteria in line with the WHO for impaired fasting glucose, IGT, or T2DM.

Various measures of GT were also used including fasting glucose, 2-h glucose, or change in glucose levels from baseline to 30 min. To categorise participants as having 'poorer' or 'better' GT, the present meta-analysis used the following definition: fasting glucose below or above 6.1 mmol/L or 2-h glucose below or above 7 mmol/L. Due to an insufficient number of studies, we were unable to analyse the influence of fasting glucose and 2-h glucose separately. Although these measures are related, they reflect different aspects of metabolism and therefore it is questionable whether such measures should have been combined (Meyer et al., 2006). For example, both elevated fasting and 2-h glucose levels are associated with an increased risk of T2DM and cardiovascular disease (de Vegt et al., 2001). However, elevated fasting glucose levels are primarily due to hepatic insulin resistance and impaired basal insulin secretion and first-phase insulin release, whereas elevated 2-h glucose levels are primarily due to muscle insulin resistance and impaired first- and second-phase insulin release (Meyer et al., 2006).

It is yet to be established whether certain measures of GT exert a stronger moderating effect on the relationship between GL and cognition than others. A study by Owen et al. (2013) reported that fasting glucose levels moderated the glucose facilitation effect whereas 2-hour glucose levels did not. Future research would therefore benefit from comparing the moderating effect of different indices of GT. The influence of the susceptibility to postprandial hypoglycaemia remains relatively unexplored (Young and Benton, 2014), but provides an interesting avenue for future work. Given that the demands of a cognitive task influence postprandial blood glucose levels (Donohoe and Benton, 1999; Scholey et al., 2001), studies that utilise postprandial measures of GT may benefit from measuring glycaemia, via an OGTT, on a separate day to cognitive test sessions.

The findings from a recent study by Anderson et al. (2018) also suggest that research may benefit from analysing GT as a continuous, rather than dichotomous, variable. Anderson et al. (2018) compared the cognitive effects of a breakfast drink containing milk or apple juice in young adults. Using a linear mixed model, the authors identified specific fasting glucose levels where cognitive differences between breakfast conditions were observable. Importantly, these levels varied depending on the nature of the task (working memory, attention, or inhibitory control) and outcome measure (speed vs. accuracy), indicating that the domain specific response to GL might reflect a variability in the threshold at which specific domains are impacted.

4.3.3. *Selection of tests*

Apart from episodic memory, a range of cognitive tests have been used to measure the same cognitive subdomain. This observation suggests that tests may have been selected due to convenience rather than their sensitivity to previous nutritional interventions (Adolphus et al., 2021). As such, a null finding may be due to a lack of test sensitivity rather than a lack of effect of breakfast GL. For example, in order to measure attention, Ingwersen et al. (2007) created a composite score using reaction time and digit vigilance scores, whereas Ingwersen (2011) administered a Continuous Attention Task. Although the same breakfasts were administered in both studies, and children were of a similar age, only Ingwersen et al. (2007) reported that breakfast GL significantly influenced task performance. The authors suggested that the discrepant findings may be due to differences in cognitive demand and hence task sensitivity.

Future studies would benefit from using standardised, validated tests that are known to be sensitive to the subtle, but important, effects of nutritional interventions (Adolphus et al., 2017). Based on the results of this meta-analysis, word list recall tasks are sensitive to the effect of breakfast GL on episodic memory in adults. Both immediate and delayed episodic memory should be measured, and words matched for the number of syllables, the frequency with which they occur in English, the number of abstract and concrete words, and image-ability (Young and Benton, 2014). Due to the wide range of tests used to measure other cognitive domains and subdomains, it is difficult to state whether a test

is sensitive to the effects of breakfast GL. Although performance on the Serial Sevens task was significantly influenced by variations in breakfast GL (Dye et al., 2010; Micha et al., 2011; Young and Benton, 2014), this task should be avoided due to its reliance on mathematical skill and the likelihood of significant practise effects (Karzmark, 2000).

The results of a recent systematic review by Peters et al. (2020) may inform task selection. The authors found that the medial temporal and frontal lobes and networks, which underpin episodic memory and attentional processes, may be preferentially affected by carbohydrate consumption. Despite the sensitivity of episodic memory to glycaemic manipulations, as evidenced in the present meta-analysis, many studies did not measure this subdomain. It would be useful if future work continued to assess episodic memory so that firm conclusions could be made regarding the conditions that elicit beneficial effects of LGL or HGL breakfasts.

Studies would also benefit from considering the influence of practice effects, which are a particular issue for tests involving memory and learning (Bartels et al., 2010). Practice effects tend to occur mostly between the first and second administration of a test (Bell et al., 2018). Using parallel versions of the same test, the influence of practice effects can therefore be reduced by incorporating a separate test familiarisation visit and a brief practice session immediately before testing begins (Bell et al., 2018). Practice sessions can also minimise the negative impact of stress and anxiety, due to a lack of task familiarity, on performance. However, it is important that the length of a practice session is appropriate so that fatigue effects do not impact performance (Süss and Schmiedek, 2000).

The final factor that needs consideration is the nature of outcome measures. Some studies only measured task speed (Deng et al., 2021; Micha et al., 2011). However, faster performance does not necessarily equate to better performance as speed may increase at the expense of accuracy, which is suggestive of an impulsive response style (Schmitt et al., 2005). To avoid misleading conclusions, measures of both speed and accuracy should be reported where possible, especially as studies reported that variations in breakfast GL influenced one outcome measure but not the other (Cooper et al., 2012, 2015; Ingwersen et al., 2007; Nilsson et al., 2012; Wesnes et al., 2003).

4.3.4. Manipulation and measurement of GL

A major limitation of the literature to date, and hence the present meta-analysis, is that most breakfast interventions differed not only in terms of GL but also macronutrient and energy composition. This limits the extent to which findings can be attributed to differences in GL, as the provision of different amounts of energy, fat, protein, and carbohydrate can also impact cognitive performance (Fischer et al., 2002; Kaplan et al., 2001). The importance of matching the macronutrient and energy content of meals was highlighted in Section 3.2.4.6, whereby inclusion of studies that matched the macronutrient and energy content of meals revealed a trend towards a beneficial effect of a LGL breakfast on accuracy of attention scores during the late postprandial period. Similarly, the polyphenol, vitamin, and mineral content of breakfast interventions often differed, all of which can acutely modulate cognitive performance (Huskisson et al., 2007; Philip et al., 2019). To gain a better understanding of the impact of breakfast GL on cognitive performance, future research would benefit from matching the macronutrient and micronutrient content of meals or drinks. Studies have accomplished this by sweetening the same meal or beverage with different types of sugar (Deng et al., 2021; Dye et al., 2010; Young and Benton, 2014, 2015) or by administering two types of rice varying in GL (Jansen et al., 2020). Manipulating GL using these methods would also allow studies to be blinded.

Another factor that needs consideration is the GL of breakfast interventions. As the GL of meals and drinks varied considerably between studies, standard GL thresholds could not be applied (i.e., LGL = below 10, MGL = 10 – 20, or HGL = above 20). Instead, within each study, the two meals or drinks with the largest difference in GL were categorised as the HGL and LGL breakfast interventions. This resulted in large variability in the GL of LGL breakfast interventions, which ranged from 1.56 (Ginieis et al., 2018) to 50 (van der Zwaluw et al., 2014), and HGL breakfast interventions, which ranged from 11.3 (Anderson et al., 2018, 2021) to 71 (Lamport et al., 2014, 2013a). To facilitate more precise comparisons in future, research would benefit from administering breakfast interventions that fall within the thresholds stated above. Dose-response studies could also be conducted using a range of glycaemic loads to determine the optimal GL of breakfast.

The difference in GL between LGL and HGL breakfast interventions also varied considerably. The smallest difference in GL was six (Benton et al., 2003) and the largest difference was 59 (Lamport et al., 2014, 2013a). It is unclear what impact this has on the relationship between breakfast GL and cognitive performance as significant effects were reported after consuming breakfasts with smaller and larger differences in GL. Due to a limited number of studies, we were unable to determine whether differences in GL influenced the results. However, there was some evidence to suggest that when the GL of breakfast was manipulated using different types of sugars, studies tended to demonstrate significant effects when there was a larger difference in GL. That is, when glucose was compared with isomaltulose or fructose (Ginieis et al., 2018; Taib et al., 2012; Young and Benton, 2014, 2015), rather than when sucrose was compared with isomaltulose (Deng et al., 2021; Dye et al., 2010). However, this suggestion requires further investigation.

Many studies estimated the GL/GI of meals using published values. We also used this method when required. However, there are several issues with using published values. For example, depending on the type of food consumed, published values can overestimate the actual GI of a food by 22–55% (Dodd et al., 2011). The GI of the same two foods can vary depending on the degree of ripeness, country of origin, variety, or cooking/storage methods (Aston et al., 2008; Henry et al., 2005). Furthermore, it is questionable whether published values, calculated using adult samples, are applicable to children and adolescents. Although it is more costly, future studies would benefit from calculating GL values directly, on a separate day to cognitive test sessions. This would enable researchers to verify beforehand that HGL and LGL breakfast interventions produce significant differences in postprandial glycaemia, an issue that occurred in some studies (Smith and Foster, 2008; van der Zwaluw et al., 2014).

Lastly, the use of dairy products needs to be reconsidered. Dairy products are insulinotropic hence the addition of dairy to meals can shorten postprandial glucose profiles and produce lower GL values than anticipated (Blaak et al., 2012). This is problematic when the objective of a study is to compare the cognitive consequences of different glycaemic profiles. It is plausible that by using a dairy-based vehicle, the difference in postprandial blood glucose levels between two meals is reduced to the point where it is no longer cognitively relevant (Blaak et al., 2012). We intended to perform subgroup analyses to determine whether the amount of dairy used influenced the findings, however an insufficient number of studies were available. Nonetheless, dairy products should be avoided where possible.

4.3.5. Timescales

Cognitive performance was measured at various times throughout the postprandial period, a factor that may have played a key role in producing conflicting literature. The meta-analysis revealed multiple lines of evidence to suggest that the beneficial effect of a LGL breakfast in adults emerges during the mid-postprandial period (60 – 119 min) and, in particular, the late postprandial period (120 min or later). Studies in children and adolescents have reported similar findings, whereby a significant beneficial effect of a LGL breakfast typically occurred between 120 and 210 min post-breakfast consumption (Cooper et al., 2012, 2015; Ingwersen et al., 2007; Wesnes et al., 2003; Young and Benton, 2015). These findings suggest that a LGL breakfast may attenuate decrements in cognitive performance across the morning. As such, future studies would benefit from assessing cognitive performance

at multiple time points, especially during the late postprandial period (120 min or later).

In many cases, participants did not undergo cognitive testing when the difference in blood glucose levels between breakfast conditions were greatest, times that are more likely to be cognitively relevant. For example, Deng et al. (2021) administered a cognitive test battery 60 min post-breakfast. Blood glucose levels after the HGL (GL = 32) and LGL (GL = 16) drink were almost identical at 60 min, possibly contributing to the lack of significant results. If GL values are calculated directly, on separate days to cognitive test sessions, then this information could be used to select the most appropriate time points to administer test batteries. This information would be particularly useful for researchers that choose to administer one test battery to reduce participant burden or school disruption. Lastly, the majority of studies included in this review did not measure baseline cognitive performance. However, one study reported that the effect of breakfast GL was influenced by baseline cognitive performance (Dye et al., 2010), suggesting that effects may have been masked in studies that did not statistically account for baseline performance. Measuring baseline performance would also assist future meta-analyses, as change scores can be calculated by review authors when necessary.

4.3.6. Condition of participants and controlling for confounding factors

In order to attribute differences in cognitive performance to difference in GL, it is critical that the influence of factors that might distort true effects are excluded or minimised (Schmitt et al., 2005). As shown in Tables 1 and 2, a phenomenon that was rarely considered is the second meal cognitive effect, whereby the composition of one meal influences glycaemic and cognitive responses to a subsequent meal. For example, Lamport et al. (2013b) reported that the consumption of a HGL evening meal, compared to a LGL evening meal, was associated with better episodic memory following the consumption of a HGL breakfast. An overnight fast may be insufficient to control for the potential confounding effect of an evening meal. This also applies to evening alcohol consumption, which has been shown to interact with the effect of breakfast GL on memory in adults (Benton and Nabb, 2004). Similarly, despite evidence showing that exercise can reduce mean 24-hour glucose levels (Munan et al., 2020), few studies standardised participants 24-hour physical activity levels. Given these findings, it is critical that studies instruct participants to fast overnight, consume standardised meals the day before testing, and avoid alcohol and vigorous exercise in the 24 h preceding testing.

Additional factors that can influence glucose metabolism and/or cognitive performance include mood, stress, illness, fatigue, hydration, hunger, quality of sleep, and motivation (Micha et al., 2010; Schmitt et al., 2005). This is especially the case for young children (Isaacs and Oates, 2008). Differences in GL may influence cognitive performance indirectly via some of these factors, hence it is important that studies consider their influence (Adolphus et al., 2016). In addition, it is likely that many participants included in the present meta-analysis underwent cognitive testing in a state of caffeine and/or nicotine withdrawal. This is less of a problem if a crossover design is used as the effect of withdrawal on cognitive performance is constant across conditions. Nonetheless, nicotine and excessive caffeine use should form part of the exclusion criteria.

The type of study design used should also be carefully considered. One of the main advantages of using a crossover design is that breakfast interventions are evaluated in the same group of participants thus reducing the confounding effect of between-person variability (Harris and Raynor, 2017). However, results can be complicated by order effects - for example, despite including a one-week washout period, three studies reported that cognitive effects only occurred when breakfast interventions were consumed in a specific order (Nilsson et al., 2009, 2012; Young and Benton, 2015). Furthermore, if breakfast conditions are not blinded, participants pre-existing knowledge or beliefs about the cognitive effects of a specific food (e.g., sugary cereal) may impact task performance (Adolphus et al., 2016).

In contrast, parallel designs reduce the risk of expectancy, fatigue, and order effects but increase the risk of between-subject variability distorting results. It is common practice for researchers to statistically test for baseline differences between groups. However, a covariate can be balanced between groups, according to a non-significant p value, but still exert a meaningful influence on the relationship between a treatment and outcome (Knol et al., 2012; Peterson et al., 2017). This is especially true for studies with small samples, often leading to the omission of important covariates (De Boer et al., 2015). Ideally, factors that are known to influence the cognitive effects of nutritional manipulations (e.g., baseline cognitive performance or socioeconomic status) should be identified a priori and incorporated into statistical models as covariates (Peterson et al., 2017). By adjusting for known covariates, whether significant or not, the effect estimate will be more precise and closer to the 'true' effect (De Boer et al., 2015).

4.3.7. Data availability and transparency

For this area of research to evolve, there needs to be more transparency and consistency when reporting results. Indeed, limited data availability and the use of different scores (i.e., post scores or change scores) prevented a meta-analysis of child and adolescent studies. It would therefore be beneficial if future studies reported means, effect sizes, and SD in a table and, ideally, raw datasets as supplementary material. This would facilitate a more accurate and robust synthesis of the literature, as well as a better understanding of the effect of time and other potential moderating factors (e.g., the difference in GL between meals). Future work may also benefit from providing more detailed information about, for example, the method of randomisation or the number of participant dropouts. This would ensure that a study is correctly classified as high or low quality.

4.4. Limitations

The findings are limited by a very low to low certainty of evidence. Studies were highly heterogeneous in terms of participant characteristics, the type of statistical methods employed, pre-test conditions, the composition of breakfast, sample size, and the type of cognitive test administered. The risk of bias assessment indicated that, overall, no study showed a high risk of bias, however 24 out of 33 studies showed some concerns of bias which were mainly related to the randomisation process, blinding of participants and researchers, and study protocol pre-registration.

There was some degree of overlap between the 'younger' and 'older' subgroups (below or above 35 years of age). For example, Sanchez-Aguadero et al. (2020) sample had a mean age of 28.1 years but an age range of 20–40 years. This should be considered when interpreting the results. Subgroup analyses according to GT status were performed by categorising participants as having 'poorer' GT if fasting glucose levels were above 6.1 mmol/L and/or two-hour glucose levels were above 7 mmol/L. This definition was chosen because it is clinically relevant (Petersen and McGuire, 2005) and did not markedly increase the number of studies excluded from the subgroup analyses. However, these measures reflect different aspects of metabolism (Meyer et al., 2006), therefore it is questionable whether they should have been combined. As the area evolves, subsequent meta-analysis should consider the moderating effect of postprandial glucose and fasting glucose separately. Lastly, we analysed measures of selective attention and sustained attention together. However, attention is not a unitary construct, therefore as the number of studies increase, future research might consider these aspects of attention separately.

4.5. Recommendations for future studies

To date, the considerable difference in experimental design between studies has limited the drawing of conclusions. It is suggested that

factors listed above are all taken into account when designing studies. There are several other avenues for research. For example, few studies have investigated the cognitive effects of manipulating the GL of a lunchtime or evening meal, or the second meal cognitive effect. Future work could also place a greater emphasis on understanding the neurobiological mechanisms underlying the effect of breakfast GL on acute cognition. This could be achieved by using neuroimaging methods, which have not yet been applied to this area of research. Similarly, various biomarkers that are related to acute cognitive performance and/or postprandial glycaemia could be measured, such as heart rate variability, insulin, glucagon, glucagon-like peptide-1, free fatty acids, or cortisol (Dybjer et al., 2020; Nilsson et al., 2008; Saito et al., 2018). Lastly, several studies have reported that the gut microbiome plays a key role in postprandial glycaemia (Berry et al., 2020; Mendes-Soares et al., 2019; Zeevi et al., 2015), and as such may influence the cognitive response to variations in breakfast GL. This could be investigated by administering different dietary fibres.

5. Conclusions

In conclusion, the meta-analysis revealed that the consumption of a LGL breakfast, rather than a HGL breakfast, was associated with better episodic memory during the late postprandial period in adults. Furthermore, the relationship between breakfast GL and episodic memory was influenced by individual differences in GT and age. A review of studies involving children and adolescents also suggested that a LGL breakfast may benefit episodic memory and attention during the late postprandial period.

Although there are many reports of a significant influence of the glycaemic nature of breakfast, these are not consistent. As such, it would be premature to suggest that public health guidelines recommend consuming a LGL breakfast to improve acute cognitive performance. Using the guiding principles discussed above, more comparable studies are needed in order to establish the critical variables that lead to a beneficial response. Such findings would have far reaching implications for public health policy and school breakfast programmes. The present review found that the nature of the task used, the timing of testing, population age, and individual differences in GT are relevant. No doubt there are other factors that should be considered, which will emerge as the field progresses.

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Data availability

the datasets generated and/or analysed during the present review are available from the corresponding author on reasonable request.

Declaration of interest

none.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.neubiorev.2022.104824.

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