

## The effect of healthy dietary consumption on executive cognitive functioning in children and adolescents: a systematic review

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(Submitted 21 January 2016 – Final revision received 27 June 2016 – Accepted 1 July 2016 – First published online 4 August 2016)

### Abstract

A systematic review was conducted to evaluate whether healthier dietary consumption among children and adolescents impacts executive functioning. PubMed, Education Resources Information Center, PsychINFO and Thomson Reuters' Web of Science databases were searched, and studies of executive functioning among children or adolescents aged 6–18 years, which examined food quality, macronutrients and/or foods, were included. Study quality was also assessed. In all, twenty-one studies met inclusion criteria. Among the twelve studies examining food quality (*n* 9) or macronutrient intakes (*n* 4), studies examining longer-term diet (*n* 6) showed positive associations between healthier overall diet quality and executive functioning, whereas the studies examining the acute impact of diet (*n* 6) were inconsistent but suggestive of improvements in executive functioning with better food quality. Among the ten studies examining foods, overall, there was a positive association between healthier foods (e.g. whole grains, fish, fruits and/or vegetables) and executive function, whereas less-healthy snack foods, sugar-sweetened beverages and red/processed meats were inversely associated with executive functioning. Taken together, evidence suggests a positive association between healthy dietary consumption and executive functioning. Additional studies examining the effects of healthier food consumption, as well as macronutrients, on executive functioning are warranted. These studies should ideally be conducted in controlled environments and use validated cognitive tests.

**Key words:** Executive functioning; Systematic reviews; Child and adolescent diet; Healthy dietary patterns

Cognitive functioning plays a crucial role in both academic achievement<sup>(1,2)</sup> and health-related decision making<sup>(3–5)</sup> in children and adolescents. Executive functioning (EF) is a particularly important domain within cognitive processing and consists of the mental capacity to make goal-directed behaviours, including inhibitory control, working memory, attention and planning. EF skills develop throughout childhood and adolescence and parallel the developmental changes that occur in the brain throughout this period<sup>(6)</sup>.

Diet is likely to play an important role in cognitive functioning and EF, and previous literature reviews have focused on the impact of breakfast consumption and its association with general child cognition and/or academic performance. A review of forty-one publications by Hoyland *et al.*<sup>(7)</sup> concluded that

compared with skipping breakfast, children who consumed breakfast demonstrated improved cognitive performance based on various measures of cognitive functioning and academic achievement. The observed effect was greater among nutritionally at-risk or stunted children compared with those who were well nourished. However, the quality of the breakfast was not assessed given the paucity of publications in that area, and the breakfasts cited within the studies reviewed were typically of poor nutritional quality (e.g. high in refined carbohydrates and sugar). More recently, studies have directly examined food quality and cognitive functioning. A systematic review of this topic will help inform school feeding programmes, wellness policies and paediatric feeding guidelines given the potential importance of diet on academic performance.

**Abbreviations:** CPM, Coloured Progressive Matrixes; EF, executive functioning; GI, glycaemic index; GL, glycaemic load.

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The aim of this systematic review was to document the impact of healthier dietary consumption on EF in children and adolescents. We included studies of overall food quality (including dietary patterns), macronutrients and foods. The research included also extended to studies of other meals beyond breakfast.

## Methods

### Literature search

Electronic databases searched included PubMed (1975–April 2016), Education Resources Information Center (ERIC) database (1966–April 2016), PsycINFO (1967–April 2016) and Thomson Reuters' Web of Science (1900–April 2016). Inclusion criteria included studies and reviews that were related to healthier diets or food consumption compared with less-healthy diets (not fasting) and their association with EF in children or adolescents aged 6–18 years. This age range was selected as this is an important time period of neurogenesis related to EF, and EF skills would have typically developed sufficiently to measure by this time period<sup>(6)</sup>. Publications were not limited by geographical area to enable inclusion of both higher- and lower-income countries, and all summary measures (e.g. risk ratios, difference in means) were included. All types of studies were examined, including cross-sectional, longitudinal and experimental study designs.

The following search terms were used to search all databases (using the filters for human species and the age range 6–18 years in PubMed and PsychInfo): (nutrition OR diet OR meal pattern OR whole grain OR fruit OR vegetable OR fish) AND (executive function OR cognition OR memory OR reasoning OR attention OR learning OR problem solving OR school performance OR academic achievement OR learning/physiology OR educational measurement OR educational status OR neuropsychological tests OR inhibitory control OR impulse control). The reference lists of included manuscripts, related review articles and relevant Medical Subject Heading terms in PubMed were also examined to ensure that all publications and appropriate key words for searches were included. Abstracts were screened for relevancy, and full texts were obtained from the databases or requested from authors if they met inclusion criteria. Study screening, selection and data extraction were completed by two independent researchers in 2015 and again in 2016 (completed in April 2016), with adjudication by a third researcher when necessary. The study protocol was registered at PROSPERO International prospective register of systematic reviews (registration no. CRD42016036950).

### Study selection

All study designs were included in the literature review. The definition of healthier foods was based on the recommendations from the Dietary Guidelines for Americans and Harvard's Healthy Eating Plate, which advise diets high in whole grains, fruits and vegetables, as well as lean proteins or proteins high in unsaturated fats (e.g. fish), and low in red/processed meats, SFA, *trans* fats and sugar<sup>(8,9)</sup>. Diets having a low glycaemic

index (GI) or glycaemic load (GL) and that were consistent with these healthier guidelines or diets that were high in MUFA and PUFA were also considered healthy. 'Unhealthy' was used to describe foods or diets high in refined carbohydrates, sugar, SFA or *trans* fats and/or having a high GI or GL. 'Low-fat' diets that did not distinguish between healthier PUFA and MUFA and less-healthy SFA and *trans* fats were also considered unhealthy because these diets typically substituted the fat with highly processed, high-GI/GL foods. The cut-off values for meeting these healthier standards varied by the dietary assessment method. For feeding studies, healthy was defined as a meal with at least one of the healthier foods recommended above (e.g. whole grains, fruit, vegetable, fish, etc.) without the less-healthy items (e.g. refined grains) and/or a low-GI/GL meal. For measures of overall diet, standard scores (e.g. Healthy Eating Index (HEI) scores), nutrient substitutions (e.g. substituting SFA for PUFA) or comparisons of higher *v.* lower levels of macronutrients were used to determine whether a diet was healthy. Authors were contacted when 'healthy' was unclear. Studies were excluded if they included non-human subjects, compared food consumption with fasting only, had an unknown definition of healthy (and there was no clarification from the contacted author), had a definition of healthy greatly different from the review criteria (e.g. defined refined carbohydrates as healthy), had measures of EF combined with additional outcomes outside the scope of the review, which could not be disaggregated, or included malnourished or severely micronutrient-deficient populations (as defined by the publication). Studies that compared fasting with healthier diets were included if they also examined healthy *v.* less-healthy diets in separate analyses (results of fasting *v.* the other diets were not included in this review). Micronutrient supplementation was not examined, as this has been previously systematically evaluated<sup>(10,11)</sup>. In addition, trials of other supplements (e.g. *n*-3 supplementation) were not included in the review; this had minimal impact on the number of studies available, as studies examining cognitive functioning and supplementation have been primarily carried out among pregnant women, infants or adults or have been conducted among malnourished children or children with developmental problems<sup>(12)</sup>.

Publications examining GI or GL were included as both GI and GL measure carbohydrate quality. GI is calculated by measuring the two-hour incremental area under the blood glucose curve after consuming a food portion that contains 50 g of carbohydrates, compared with a control of white bread or glucose<sup>(13)</sup>. Foods such as refined carbohydrates and white potatoes/potato products typically have a high GI value ( $GI \geq 70$ ) because they cause rapid spikes in blood sugar levels<sup>(14)</sup>. Vegetables (excluding potatoes), fruits and legumes typically have a low GI ( $\leq 55$ ), whereas whole grains tend to have a moderate GI (56–69). GL, which accounts for both the impact of the carbohydrate on blood sugar levels and the amount of carbohydrate in a serving of the food, is calculated by multiplying a food's GI by the amount of carbohydrates in the food. Foods with low GL ( $\leq 10$ ) include fruits and vegetables that are high in fibre (excluding potatoes) and many beans/legumes such as chickpeas and black beans. Foods with a high GL ( $\geq 20$ ) include refined carbohydrates, white rice and

white potatoes/potato products. Whole grains such as brown rice or oatmeal typically have medium GL.

Studies that met all these criteria and examined food quality or macronutrients are included in Table 1<sup>(15–26)</sup>, and studies that examined specific foods are included in Table 2<sup>(17,27–35)</sup>. Information extracted from each study included the following: (1) study design and duration, (2) study participant characteristics (age and country of origin), (3) types of measures for the exposures and outcomes (including whether they were validated tools) and (4) study quality (blinding of personnel, risk of attrition bias, etc.).

### Study quality

All publications meeting the criteria were assessed for study quality (Table 3). Relevant components of study quality were based on the *Cochrane Handbook for Systematic Reviews of Effectiveness of Interventions*. Criteria for judging risk of bias in the 'Risk of bias' assessment tool were evaluated by two independent researchers<sup>(36)</sup>. No studies were excluded on the basis of study quality if they met the other inclusion criteria. A summary score was not calculated because of concerns regarding subjectivity and a lack of consensus criteria for creating summary scores.

### Results

Searches in PubMed for studies relevant to healthier diets and EF retrieved 2760 articles, whereas ERIC generated 907 articles, PsycINFO produced 569 articles and Thomson Reuters' Web of Science retrieved 1493 articles.

Of the total 4870 publications, 1650 were duplicates. Of the 3220 publications screened, 3137 were determined not relevant to the review topic based on their titles and abstracts. Among the remaining eighty-three articles, sixty-two were excluded because of a definition of healthy/unhealthy that was unclear or differed greatly from the review criteria, the grouping of EF measures with additional outcomes that were not relevant to EF, the comparison of healthier food consumption with fasting only or the examination of malnourished populations. The remaining twenty-one articles are discussed in this review. The flow chart for the systematic review is presented in Fig. 1.

### Studies examining food quality or macronutrients

**Healthy dietary patterns.** Among all, three studies were of overall dietary patterns and EF. Nyaradi *et al.*<sup>(23)</sup> examined 'Healthy' dietary patterns (i.e. high in fruits, vegetables, whole grains, legumes and fish) *v.* 'Western' dietary patterns (i.e. high in red and processed meat, sugar-sweetened beverages, fried and refined food, and takeout foods) using FFQ, and also assessed working memory among 602 teens aged 14–17 years in Perth, Western Australia. This study found that the 'Healthy' dietary pattern was associated with fewer errors on the Groton Maze Learning Test ( $\beta = -0.023$ ;  $P = 0.035$ ). Haapala *et al.*<sup>(17)</sup> studied the association between non-verbal fluid intelligence/abstract reasoning and overall diet quality among 428 children aged 6–8 years in Finland. This study calculated both Dietary Approaches to Stop Hypertension (DASH) scores and Baltic Sea

Diet Scores (BDS) based on 4-d food records and assessed cognitive performance with the Raven's Coloured Progressive Matrixes (CPM). Overall, this study found that both lower DASH and BDS scores were associated with lower Raven's CPM scores (i.e. poorer cognitive performance). Khan *et al.* examined the association between inhibitory control, fibre intake and overall dietary quality among sixty-five prepubertal children between 7 and 9 years of age by calculating a HEI score for the diets of the participants using 3-d dietary records; HEI scores are a measure of diet quality as determined by US Dietary Guidelines for Americans and are consistent with the DASH diet and Harvard's Healthy Eating Pyramid<sup>(19,37,38)</sup>. Using a modified Flanker task, which assesses cognitive inhibitory control, this study found that higher HEI scores were associated with greater performance accuracy on incongruent task trials and inversely associated with response accuracy interference, suggesting greater cognitive flexibility during increased task demands. Dietary fibre was also positively associated with task accuracy on both congruent and incongruent trials.

**Glycaemic index/load.** The majority of publications have been school-based feeding studies with a cross-over design. Ingwersen *et al.*<sup>(39)</sup> examined the impact of a high- *v.* low-GI breakfast on attention and memory among 6–11-year-olds ( $n = 64$ ), and found that following consumption of a high-GI breakfast cereal children demonstrated a larger decline in performance on accuracy of attention but had better secondary memory performance, when compared with children consuming a low-GI breakfast cereal, and no association with speed of attention or memory. Benton *et al.*<sup>(15)</sup> examined GL and memory among 5–7-year-olds ( $n = 19$ ) in a cross-over study and found that GL was inversely correlated with verbal memory ( $r = -0.40$ ;  $P < 0.05$ ), but there was no significant association noted between GL and spatial memory, delayed verbal memory or delayed spatial memory. In another study, Micha *et al.* examined both GI and GL among 11–14-year-olds ( $n = 74$ ) using a randomised, cross-over design, and in contrast to previous research they reported that a low-GI meal was associated with significantly improved performance on a word-generation task, which examined declarative verbal memory. The authors also noted that students had better scores on a Stroop task examining response time after consuming high-GI/ high-GL meals and that they performed faster on the Serial sevens test after high-GI meals compared with low-GI meals (for both low- and high-GL meals)<sup>(22)</sup>. It is of note, however, that the authors did not report whether there were significant differences in task accuracy, which is critical for interpreting the results; faster response times on a task of inhibitory control with no measure of accuracy do not necessarily suggest improved performance relative to those with slower response times, but may in fact be suggestive of an impulsive response style. Cooper *et al.*<sup>(16)</sup> examined 12–14-year-olds ( $n = 41$ ) and reported that, although response time on the Stroop test was faster with the high-GI breakfast, improved accuracy on this test was observed following consumption of a low-GI breakfast compared with a high-GI breakfast, and response times and accuracy on the Sternberg Paradigm test and accuracy on the Flanker test improved with a low-GI breakfast.

**Table 1.** Studies of food quality or macronutrients

References	Study design	Participants	Dietary measures	Executive functioning measure(s)	Reported findings	Quality assessment
Benton <i>et al.</i> <sup>(15)</sup>	School-based feeding study with a cross-over design	<i>n</i> 19, 5–7-year-old children in the UK	High- v. medium- v. low-GL breakfast. Each student received a high-, medium- and low-GL school breakfast and had 2 d of testing for each meal type	Tests based on the Recall of Objects test of the British Ability Scale Verbal memory Spatial memory Delayed verbal memory Delayed spatial memory	Verbal memory: better with low-GL breakfast No effects on other tests	SB, CE, AB, BP, V
Cooper <i>et al.</i> <sup>(16)</sup>	School-based feeding study with a cross-over design	<i>n</i> 41, 12–14-year-old adolescents in the UK	High-GI breakfast v. a low-GI breakfast (v. breakfast omission)	Stroop test Sternberg paradigm Flanker task	Stroop test: response times were faster with the high-GI breakfast Overall accuracy was better and was better maintained with a low-GI breakfast Sternberg paradigm: greater improvement in response times and accuracy better maintained with a low-GI breakfast Flanker task: accuracy better maintained with a low-GI breakfast	SB, CE, AB, V
Haapala <i>et al.</i> <sup>(17)</sup>	Cross-sectional study	<i>n</i> 512, 6–8-year-old children in Finland	4-d dietary records were collected to determine DASH diet scores and BSDS	Raven's CPM	Lower DASH and BSDS scores were associated with lower Raven's CPM scores (i.e. poorer cognitive performance)	V, CC
Ingwersen <i>et al.</i> <sup>(39)</sup>	School-based feeding study with a cross-over design	<i>n</i> 64, 6–11-year-old children in the UK	High-GI breakfast (Coco Pops) v. a low-GI breakfast (All-Bran) on 2 consecutive days	CDR Computerized Assessment Battery Speed of Attention Accuracy of Attention Working Memory Secondary Memory Flanker task	Accuracy of attention: High GI had a larger decline in performance over time Secondary memory: better performance after low-GI cereal compared with high-GI cereal at both measured times No effects on other tests	SB, CE, AB, V
Khan <i>et al.</i> <sup>(19)</sup>	Cross-sectional study	<i>n</i> 65, 7–9-year-old children in the USA	3-d food records were used to assess dietary fibre, total fat, SFA, <i>n</i> -3 fatty acids, total PUFA and overall diet quality (based on Healthy Eating Index-2005 scores)	Flanker task	Congruent accuracy was associated with total and insoluble dietary fibre Incongruent accuracy was associated with total and insoluble dietary fibre and diet quality score Response accuracy interference was inversely associated with diet quality and positively associated with greater total fat consumption	V, CC
Khan <i>et al.</i> <sup>(20)</sup>	Cross-sectional study	<i>n</i> 150, 7–10-year-old children in the USA	One 24-h food recall to assess carbohydrate, protein and fat intake	Colour–shape switch task	Greater total fat intake was associated with greater local switch task costs for accuracy Greater SFA and cholesterol intake was associated with greater 'switch' costs for accuracy and reaction time	V, CC
Micha <i>et al.</i> <sup>(21)</sup>	Observational study	<i>n</i> 60, 11–14-year-old children and adolescents in England	Calculated the GI and GL of the participant's breakfast	Serial sevens Stroop task Delayed word recall Immediate word recall	Serials seven: better scores with low-GI meals and high-GL meals Immediate word recall: better scores with high-GI meals No effect on other tests	AB, V, CC
Micha <i>et al.</i> <sup>(22)</sup>	School-based feeding study with students randomised to GL status and a cross-over design for GI	<i>n</i> 74, 11–14-year-old children and adolescents in England	High-GL/high-GI v. high-GL/low-GI v. low-GL/high-GI v. low-GL/low-GI	Serial sevens Stroop task Delayed word recall Immediate word recall word-generation task	Serial sevens: faster performance with high-GI meals (for both low- and high-GL meals) Stroop task: faster performance with high-GI meals (high-GL meals only) Word-generation task: better scores with low-GI meals (for both low- and high-GL meals) No effect on other tests	SB, CE, BP, V, CC

Table 1. Continued

References	Study design	Participants	Dietary measures	Executive functioning measure(s)	Reported findings	Quality assessment
Nyaradi <i>et al.</i> <sup>(23)</sup>	Longitudinal study	<i>n</i> 602, 14 and 17-year-old adolescents in Australia	Semi-quantitative FFQ was used to assess 'Healthy' (high in fruits, vegetables, whole grains, legumes and fish) and 'Western' (high in red and processed meats, sugar-sweetened beverages, fried and refined food, and take-away foods) dietary patterns	GML	GML: 'Healthy' dietary pattern was associated with fewer errors	V, CC
Sheppard & Cheatham <sup>(24)</sup>	Cross-sectional study	<i>n</i> 70, 7–9-year-old children in the USA	Three 24-h dietary recalls were used to assess <i>n</i> -3 and <i>n</i> -6 PUFA and the ratio of <i>n</i> -6: <i>n</i> -3	CANTAB Spatial working memory Spatial span Stockings of Cambridge	SWM: lower <i>n</i> -6: <i>n</i> -3 ratio was associated with greater working memory SSP: no effect SOC: lower <i>n</i> -6: <i>n</i> -3 ratio was associated with better performance on planning tasks (faster times)	V, CC
Smith & Foster <sup>(25)</sup>	Randomised trial	<i>n</i> 36, 14–17-year-old adolescents in Australia	Low-GI breakfast (All-Bran cereal and milk) <i>v.</i> high-GI breakfast (corn flakes)	CVLT Immediate free recall List A Immediate free recall List B Short-delay free recall Short-delay cued recall	No effect on recall tests	SB, CE, AB
Zhang <i>et al.</i> <sup>(26)</sup>	Cross-sectional study	<i>n</i> 3666, 6–16-year-old children and adolescents in the USA	24-h recalls were used to assess total fat, SFA, PUFA, MUFA and cholesterol	WISC-R DST Block-design test	Using nutrient density models, substituting PUFA for SFA or carbohydrates was associated better DST scores Using nutrient residual models, there was a positive association between PUFA and better DST scores and an inverse association between DST scores and cholesterol. No effect on block design, or other nutrient density or nutrient residual models	SB, BP, V, CC

GL, glycaemic load; SB, low risk of selection bias; CE, compliance with exposure; AB, low risk of attrition bias; BP, blinding of personnel; V, valid and reliable outcomes; GI, glycaemic index; DASH, Dietary Approaches to Stop Hypertension; BSDS, Baltic Sea Diet Scores; Raven's CPM, Coloured Progressive Matrixes; CC, control for confounding variables; CDR, Cognitive Drug Research; GML, Groton Maze Learning Test; SWM, Spatial Working Memory; SSP, Spatial Span; CANTAB, Cambridge Neuropsychological Test Assessment Battery; SOC, Stockings of Cambridge; CVLT, California Verbal Learning Test; WISC-R, Wechsler Intelligence Scale for Children, Revised; DST, digit span test.

**Table 2.** Studies of foods

References	Study design	Participants	Dietary measures	EF measure(s)	Reported findings	Quality assessment
Ames <i>et al.</i> <sup>(27)</sup>	Cross-sectional study	<i>n</i> 198, 14–17-year-old adolescents in the USA	Semi-quantitative FFQ was used to assess sugar-sweetened beverage, sweet snack and salty/fatty snack intake	IGT Generic Go/No-Go Food-cued Go/No-Go	IGT: poorer decision making associated with sugar-sweetened beverage consumption among males Generic Go/No-Go: inhibitory problems associated with sugar-sweetened beverage, sweet snack and salty/fatty snack consumption among males Food-cued Go/No-Go: inhibitory problems with sweet-snack consumption among males	SB, V
Chung <i>et al.</i> <sup>(28)</sup>	9 week single-blind, randomised, controlled, parallel experiment	<i>n</i> 26, 15–17-year-old adolescents in Korea	Participants were given white rice or a mixture of brown rice, beans and walnuts	A-CPT DST Stroop test Trail making test A Trail making test B Wisconsin card sorting test Verbal learning test AX-CPT Raven's CPM	Verbal Learning Test (delayed recall at 20 min): better among the white rice group at the end of 9 weeks AX-CPT: white rice group had a significant decrease in correct responses and increase in omission errors at the end of 9 weeks No effects on other tests	SB, CE, AB, BP, V, CC
Haapala <i>et al.</i> <sup>(17)</sup>	Cross-sectional study	<i>n</i> 428, 6–8-year-old children in Finland	4-d dietary records were collected to determine fruit, vegetable, fish, high-fibre grains, low-fat milk, sugar-sweetened beverage and red/processed meat consumption		Lower fruit and greater red/processed meat consumption were associated with lower Raven's CPM scores (i.e. poorer cognitive performance). Lower vegetable consumption was associated with lower Raven's CPM scores among males only Males in the lowest quartile of intake of fruits, vegetables, high-fibre grains, and fish, and with the highest intakes of red/processed meats had the lowest Raven's CPM scores compared with males in the highest quartile	V, CC
Mahoney <i>et al.</i> <sup>(29)</sup>	School-based feeding study with a cross-over design	<i>n</i> 60, 6–11-year-old children in the USA	Participants were given instant oatmeal or ready-to-eat, refined cereal (or no breakfast). One day of testing for each meal type	A-CPT CPT Rey Complex Figure Copy and Recall Test DST Backward Forward Map Task Verbal Task	DST: females performed better in the backward DST with oatmeal (both 6–8-year olds and 9–11-year olds). No differences for males or for Forward DST (females or males) Map Task: better correct and blank item scores with oatmeal among 9–11-year olds A-CPT test: performance better after oatmeal among 6–8 year olds No effects on other tests	SB, CE, AB, BP, V
Riggs <i>et al.</i> <sup>(30)</sup>	Cross-sectional study	<i>n</i> 107, 9–10-year-old children in the USA	Self-reported fruit, vegetable and snack intakes (adapted from validated FFQ)	Subscales of the BRIEF-SR Inhibitory control Working memory	Inverse association between EF and snack food intake No association between EF and fruit or vegetable intake	V, CC
Riggs <i>et al.</i> <sup>(31)</sup>	After-school-based study with students randomised to intervention or control group	<i>n</i> 184, 9–10-year-old children in the USA	Self-reported fruit, vegetable, and snack intakes before and after intervention (adapted from validated FFQ)	Subscales of the BRIEF-SR Inhibitory control Working memory	Inverse association between executive function and snack food intake at baseline Positive association between executive function and fruit/vegetable intake at baseline and at 4 months post-intervention	SB, V

Table 2. Continued

References	Study design	Participants	Dietary measures	EF measure(s)	Reported findings	Quality assessment
Riggs <i>et al.</i> <sup>(32)</sup>	Cross-sectional study	<i>n</i> 1587, 9–10-year-olds in the USA	Self-reported fruit, vegetable and snack intakes (adapted from validated FFQ)	Subscales of the BRIEF-SR Inhibitory control Working memory	Inverse association between executive function and snack food intake Positive association between executive function and fruit/vegetable intake	V, CC
Sorensen <i>et al.</i> <sup>(33)</sup>	School-based feeding study with a cross-over design	<i>n</i> 726, 8–11-year-old children in Denmark	Fish consumption was assessed using biomarkers for <i>n</i> -3 PUFA (EPA and DHA)	D2 test of attention	Baseline PUFA levels positively associated with concentration performance and processing speed Impulsivity and inattention were inversely correlated with EPA/DHA level in males, whereas inattention errors were positively correlated with EPA/DHA levels in females Increases in EPA/DHA from the intervention were associated with improved performance on measures of EF	SB, AB, V, CC
van der Wurff <i>et al.</i> <sup>(34)</sup>	Cross-sectional study	<i>n</i> 266, 13–15-year-old adolescents in the Netherlands	Fish consumption measured by an omega-3 index (EPA and DHA in blood in erythrocytes as a per cent of total fatty acids)	CST D2 test of attention DST Backward Forward LDST Stroop	There was a positive association between omega-3 index and performance on the LDST and D2 test of attention No effect on other tests	BP, V, CC
Wesnes <i>et al.</i> <sup>(35)</sup>	Randomised, cross-over study	<i>n</i> 29, 9–16-year-old children and adolescents in the UK	Participants were given Cheerios cereal, Shreddies cereals or glucose drink (or no breakfast)	CDR Computerised Assessment Battery Attention Working memory Episodic secondary memory	The glucose drink was associated with greater declines in attention and episodic secondary memory compared with the two cereal conditions No effect on working memory	SB, CE, AB

EF, executive functioning; IGT, Iowa Gambling Task; SB, low risk of selection bias; V, valid and reliable outcomes; A-CPT, Auditory Continuous-Performance Test; DST, digit span test; CPT, Continuous-Performance Test; AX-CPT, AX version of the Continuous-Performance Test; CE, compliance with exposure; AB, low risk of attrition bias; BP, blinding of personnel; CC, control for confounding variables; Raven's CPM, Coloured Progressive Matrixes; BRIEF-SR, Behavioral Rating Inventory of Executive Function – Self-Report; CST, Concept Shifting Task; LDST, Letter Digit Substitution Task; CDR, Cognitive Drug Research.

**Table 3.** Quality assessment of studies

References	Low risk of selection bias	Compliance with exposure	Low risk of attrition bias	Blinding of personnel	Valid and reliable outcomes, for example appropriateness of cognitive test	Control for confounding variables
Ames <i>et al.</i> <sup>(27)</sup>	+	N/A	N/A	Not enough information given	+	Examined sex separately
Benton <i>et al.</i> <sup>(15)</sup>	+	+	+	+	+	Sex (not included in models as there were no differences by sex)
Chung <i>et al.</i> <sup>(28)</sup>	+	+	+	+	+	Randomised by age, education, height, weight and BMI
Cooper <i>et al.</i> <sup>(16)</sup>	+	+	+	Not enough information given	+	
Haapala <i>et al.</i> <sup>(17)</sup>		N/A	N/A	Not enough information given	+	Age, sex, parental education, and household income, total physical activity, total screen-based sedentary behaviour, cardiovascular performance, motor performance, body fat percentage, clinical puberty, current height as a percentage of the predicted adult height, developmental disorders, skipping meals, eating behaviours, and total energy
Ingwersen <i>et al.</i> <sup>(39)</sup>	+	+	+	Not enough information given	+	Examined sex separately
Khan <i>et al.</i> <sup>(19)</sup>		N/A	N/A	Not enough information given	+	Age, pubertal stage, intelligence quotient, VO <sub>2max</sub> , and per cent fat mass (sex and SES were not significant confounders)
Khan <i>et al.</i> <sup>(20)</sup>		N/A	N/A	Not enough information given	+	Age, sex, SES, Kaufman Brief Intelligence Test, VO <sub>2max</sub> , BMI, and total energy intake
Mahoney <i>et al.</i> <sup>(29)</sup>	+	+	+	+	+	
Micha <i>et al.</i> <sup>(21)</sup>	+	N/A	+	Not enough information given	+	Sex, SES, age, height, weight, BMI, Hb levels, blood glucose levels, 'happy' mood score before the cognitive function tests, and time between breakfast and the first cognitive function test
Micha <i>et al.</i> <sup>(22)</sup>	+	+		+	+	Order of administration of breakfast meals, sex, age, height, weight, BMI, and glucose, and cortisol levels at baseline
Nyaradi <i>et al.</i> <sup>(23)</sup>				Not enough information given	+	Maternal education, family income, the presence of biological father in the family, family functioning and sex
Riggs <i>et al.</i> <sup>(30)</sup>		N/A	N/A	N/A	+	Sex, ethnicity, SES and academic achievement
Riggs <i>et al.</i> <sup>(31)</sup>	+	Not enough information given		Not enough information given	+	
Riggs <i>et al.</i> <sup>(32)</sup>	Not enough information given	N/A	N/A	N/A	+	Age, sex, ethnicity, SES (student free lunch status) and school grades
Sheppard & Cheatham <sup>(24)</sup>		N/A	N/A	Not enough information given	+	Maternal education, physical activity, total energy content, data collection time period (paternal education, sex and breast-fed status as an infant were not significant confounders)
Smith & Foster <sup>(25)</sup>	+	+	+	Not enough information given	+	
Sorensen <i>et al.</i> <sup>(33)</sup>	+		+		+	Individual (as a random effect to account for repeated measures), baseline value of the cognitive test, intervention order, sex, household intervention, year group, baseline age, and month of baseline test
van der Wurff <i>et al.</i> <sup>(34)</sup>		N/A	N/A	+	+	BMI, sex, age, alcohol consumption, smoking status, parental education
Wesnes <i>et al.</i> <sup>(35)</sup>	+	+	+	Not enough information given	+	
Zhang <i>et al.</i> <sup>(26)</sup>	+	N/A	N/A	+	+	Ethnicity, maternal education, rural/urban classification of residence area, maternal marital status, poverty status, food insufficient, stature-for-age Z-score, BMI-for-age, Fe deficiency, health status, substance abuse, physical activity

SES, socio-economic status.

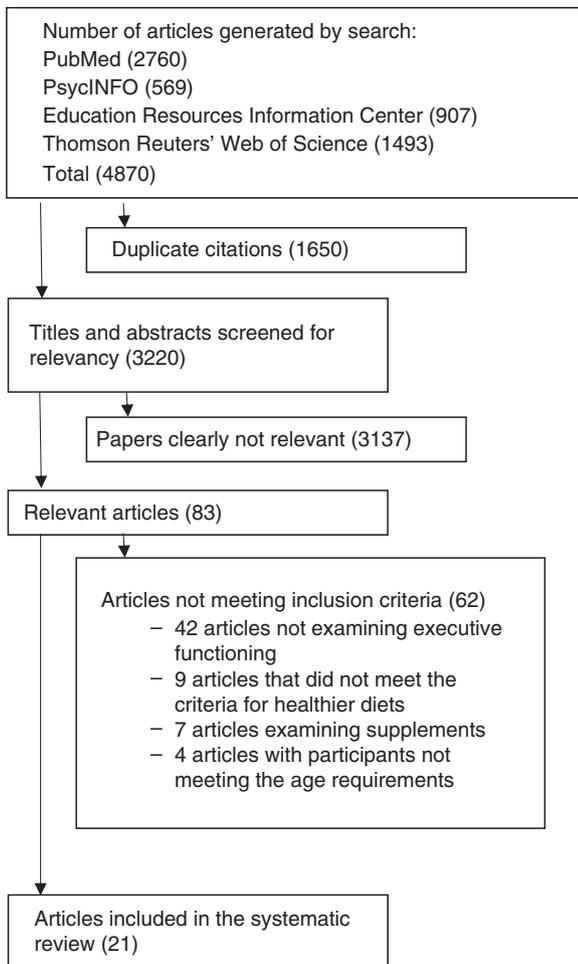


Fig. 1. Flow chart showing the number of articles at each stage of the search.

Among the studies that did not use a cross-over design, one study conducted a randomised trial among Australian 14–17-year-olds ( $n$  36) using the Modified California Verbal Learning Test and found no association between GI and immediate or short-delay free recall<sup>(25)</sup>. An observational study among 11–14-year-olds ( $n$  60) found that students had better immediate word recall task scores with high-GI meals compared with low-GI meals (for both high- and low-GI meals), but no effect of GI on delayed word recall<sup>(21)</sup>.

**Macronutrients.** Four cross-sectional studies included in the present systematic review examined differences in macronutrients. In a study that used data from 3666 children and adolescents participating in the Third National Health and Nutrition Examination Survey to examine macronutrient distributions, each 5% increase in energy from PUFA was associated with a decreased odds of poor performance in the digit span test (working memory) when replacing SFA (OR 0.58; CI 0.37, 0.91) or carbohydrates (OR 0.61; CI 0.43, 0.88)<sup>(26)</sup>. In nutrient residual models, greater consumption of PUFA was associated with decreased odds of poor digit span scores (OR 0.74; CI 0.58, 0.94), and high cholesterol intake was

associated with increased odds of poor digit span scores (OR 1.25; CI 1.11, 1.42). No significant associations were seen between macronutrients and a measure of spatial ability, the Block design test. In addition, a study conducted by Khan *et al.*<sup>(19)</sup> examining 7–9-year-olds ( $n$  65) found that greater overall fat consumption was associated with higher task interference, suggesting poorer maintenance of cognitive control, but reported no association between SFA,  $n$ -3 fatty acids or PUFA and EF. A second study by Khan *et al.*<sup>(20)</sup> that used a task-switching paradigm to measure cognitive flexibility examined carbohydrate, protein and fat intake among 7–10-year-olds ( $n$  150). This study also found that higher total fat intake was associated with longer reaction times during the task condition, which required greater cognitive flexibility. Further, the authors reported a correlation between greater SFA and cholesterol intakes and higher ‘switch’ costs, which represent difficulty in maintaining multiple cognitive sets in working memory and are indicative of less-efficient executive control processes. Finally, a cross-sectional study among 7–9-year-old children ( $n$  70), conducted by Sheppard & Cheatham<sup>(24)</sup>, assessed EF using measures of planning (Stockings of Cambridge (SOC)) and working memory (Spatial Working Memory and Spatial Span) from the Cambridge Neuropsychological Test Assessment Battery and assessed diet using three 24-h recalls to determine  $n$ -3 and  $n$ -6 fatty acid levels and the ratio of  $n$ -6: $n$ -3. This study found that children with lower  $n$ -6: $n$ -3 ratios (i.e. consumed relatively higher levels of  $n$ -3 fatty acids) showed greater performance on EF tasks. In particular, they had shorter initial processing times during the spatial working memory task and had reduced average times during the planning task (SOC). In addition, a significant interaction between the overall fatty acid intake levels and their ratio was observed, with higher average  $n$ -3 fatty acid levels associated with greater mean planning times (i.e. poorer EF performance), in the presence of higher  $n$ -6 fatty acid intake (i.e. overall high quantities of the fatty acids, but a low  $n$ -6: $n$ -3 ratio).

### Studies examining foods

**Whole grains.** Several studies have examined whole grains because of their healthier nutrient profile and generally lower GI/GL values. The first was a small, randomised, cross-over study among twenty-nine children and adolescents aged 9–16 years, which found that a glucose drink was associated with significantly larger declines in attention and working memory compared with wholegrain cereal<sup>(35)</sup>. Mahoney *et al.*<sup>(29)</sup> conducted a school-based, cross-over feeding study, and found that after consuming oatmeal, females performed better on the backwards digit span test, 9–11-year-old girls and boys had better scores on the Map Task, and 6–8-year olds performed better on the Auditory Continuous-Performance Test (A-CPT) compared with their performance after consuming refined breakfast cereal. The study by Haapala *et al.*<sup>(17)</sup> also found that males who were in the lowest quartile of high-fibre grain consumption had the lowest scores on the Raven’s CPM (non-verbal reasoning) compared with those in the highest quartile. Finally, Chung *et al.*<sup>(28)</sup> implemented a randomised, controlled feeding study among 15–17-year-olds ( $n$  26), and

found that those who had been assigned to consume white rice had significantly greater improvements in scores on a verbal learning test after a delayed recall at 20 min compared with those consuming the healthier diet composed of whole grains, kidney beans and walnuts ( $P < 0.05$ ), but not on the AX version of the Continuous-Performance Test (AX-CPT) – a measure of attention, vigilance and response impulsivity. Those consuming white rice had a significant decrease in correct responses on the AX-CPT as well as an increase in omission errors at the end of the study compared with those consuming the healthier diet<sup>(28)</sup>. There were no significant differences between the groups on the other tests administered, which included the A-CPT, digit span test, Stroop test, Trail making test A and B and the Wisconsin Card Sorting Test.

#### *Sweet and salty snacks and sugar-sweetened beverages.*

Four studies examined salty and sugary snacks and beverages and found consistent associations between 'junk' foods and poorer EF. Ames *et al.*<sup>(27)</sup> found that among male adolescents, greater sugar-sweetened beverage consumption was associated with poorer decision making on the Iowa Gambling Task and reduced ability to inhibit inappropriate responses on the standard Go/No-Go task. In addition, sweet and salty/fatty snacks were associated with inhibitory problems on the standard Go/No-Go task, and sweet-snack consumption was associated with inhibitory problems on the food-based Go/No-Go task among males. Multiple studies by Riggs *et al.*<sup>(30–32)</sup> that examined snack food consumption among children also found an inverse association with self-reported measures of EF.

*Fruits and vegetables.* Four studies examined fruits, vegetables and EF, with three finding higher fruit and vegetable intakes associated with greater EF. In the small, cross-sectional study among 9–10-year-olds conducted by Riggs *et al.*<sup>(30)</sup>, no association between fruit or vegetable consumption and EF was observed, which the authors noted may have been due to the small sample size. However, in the two larger studies conducted by Riggs *et al.*<sup>(31,32)</sup>, fruit and vegetable intakes were positively associated with EF. Finally, Haapala *et al.* found a positive association between fruit consumption and abstract reasoning measured using Raven's CPM. This study also found that males who were in the lowest quartile of vegetable consumption also had the lowest Raven's CPM scores compared with those in the highest quartile<sup>(17)</sup>.

*Proteins.* Three studies examined the consumption of animal-based sources of protein (i.e. fish or red/processed meat) and EF. Haapala *et al.*<sup>(17)</sup> found that males who were in the lowest quartile of fish consumption had the lowest abstract reasoning scores. In addition, this study found that, among both males and females, greater red and processed meat consumption was associated with lower scores on the Raven's CPM. A study conducted by Sorensen *et al.*<sup>(33)</sup> assessed 726 children aged 8–11 years using a school-based feeding intervention that provided students with fish twice per week. Diet was assessed using *n-3* fatty acid biomarkers, whereas EF was measured with the D2 test of attention. The authors noted that at baseline EPA

and DHA status was positively correlated with concentration performance and processing speed; in addition, impulsivity and inattention were inversely correlated with EPA/DHA level (i.e. higher EPA/DHA was associated with lower impulsivity/inattention errors) in boys, whereas inattention errors were positively correlated with EPA/DHA levels in girls. Following the 3-month school meal intervention, EPA/DHA levels increased and were associated with improved performance on measures of EF. Finally, a study by van der Wurff *et al.*<sup>(34)</sup> examined multiple domains of EF and their association with fish consumption, measured using *n-3* fatty acid biomarkers to calculate an omega-3 index (calculated as EPA and DHA in blood erythrocytes as a per cent of total fatty acids). Among the 266 adolescents participating in the study, there was a positive association between the omega-3 index and performance on the Letter Digit Substitution Task and fewer errors of omission on the D2 test of attention, indicating better information processing speed and less impulsivity with greater fish consumption.

## Discussion

Overall, studies examining the longer-term effect of a healthier diet found consistently positive associations with EF, whereas studies examining the acute association between GI and GL and EF found mixed results, although the majority was suggestive of improved EF with lower GI/GL foods. Similarly, studies examining macronutrients were inconsistent, and the limited number of studies in this area made it difficult to draw conclusions. Studies examining specific foods primarily found that healthier foods (e.g. whole grains, fruits and/or vegetables) were positively associated with EF, whereas snack foods – which are typically high in sugar, refined grains and SFA – sugar-sweetened beverages and red/processed meats were inversely associated with EF. Studies examining fish intake were also suggestive of a positive association with EF.

Studies examining healthier diets and EF have used varying tests of cognition, which may in part help explain the inconsistent findings among those examining GI and GL. It is important to note that different versions of a cognitive task (i.e. the Stroop Color Word Task) are likely to yield different results, making comparisons and interpretation of data across studies difficult. In addition, because EF covers multiple processes (e.g. planning, working memory, inhibitory control), there is heterogeneity among the areas assessed by each of the validated tests available. Although there are a number of 'gold standard' measures of EF (i.e. the Wisconsin Card Sorting Test), measures must be tailored to fit specific population requirements, including age, education, intelligent quotient, time requirements to administer the tests and the cognitive domain of interest, which may also impact the interpretation of the results. A recent review of GI and more general cognition in both children and adults also found that the findings were inconclusive, and noted that this may also be due to the use of cognitive tests that may not be sensitive enough to detect small but meaningful variations in cognition<sup>(40)</sup>. Given the number of well-validated tests, it is therefore essential to select both appropriately sensitive tests and to assess a sufficient number of participants to ensure the power to detect changes in EF.

It is possible that healthier foods improved EF through multiple mechanisms. Certain vitamins (e.g. B vitamins and vitamin C) and minerals (e.g. Zn) are cofactors for enzymes that synthesise neurotransmitters, thus impacting cognition throughout childhood and adolescence<sup>(41–43)</sup>. In addition, micronutrients (e.g. folate) and healthy fats, particularly PUFA, impact myelin sheath integrity and nerve cell membranes, which affect neuron function<sup>(42)</sup>. Brain glucose levels may also impact EF<sup>(42)</sup>. A healthier diet may lead to changes in the brain structure and function, particularly in the frontal cortical regions involved, through synapse formation, in neurogenesis, myelination and glucose control.

Improvements in EF resulting from healthier diets can have important academic, public health and policy implications, as EF is associated with both academic performance and health-related decision making. As the majority of youth in the USA fail to meet dietary recommendations, policies that improve diet, and thus EF, may have important implications<sup>(44)</sup>. Schools may consider policies that further improve the school food environment, including both school meals and competitive foods, to potentially impact the academic performance and health of students. Similarly, policies that improve the content of the foods available through the Supplemental Nutrition Assistance Program (SNAP) may have important implications for children, as roughly half of SNAP participants are children aged 18 years or younger<sup>(45)</sup>.

This review is subject to a number of limitations. Publication bias is a possibility, as studies of diet and EF with null findings may have been less likely to be published. Further, substantial differences emerged in the types of foods and diets examined as well as the metrics used to assess both diet and EF. This may have impacted the interpretation of the relationship between a healthier diet and EF. Finally, in many studies, it was not possible to determine the causal nature of the relationship due to the cross-sectional study designs; it is possible that, given better EF, children are able to make healthier food choices. Future, longitudinal studies examining the impact of a healthier diet on EF are warranted.

In summary, although the association between GI/GL and EF remains unclear, there appears to be a positive association between EF and healthier overall diets and foods. In addition, studies suggest that consumption of less-healthy snack foods, sugar-sweetened beverages and red/processed meats is associated with poorer EF. Overall, future short- and long-term studies should examine healthier food consumption, including whole grains, fruits, vegetables and fish in a controlled environment, such as a cross-over feeding study. Studies examining macronutrients are also warranted, and additional studies examining sugar-sweetened beverages or red/processed meats and their potential impact on EF are also indicated. The use of sensitive, validated cognitive measures is essential to determine potential associations between food and EF.

### Acknowledgements

The authors thank Sara Rimm-Kaufman for her thoughtful assistance with the interpretation of the studies reviewed.

This research received no specific grant from any funding agency or from commercial or not-for-profit sectors.

The authors' contributions were as follows: J. F. W. C., E. B. R. and S. A. G. defined the scope of the project. J. F. W. C. and M. T. G. performed the literature search, reviewed identified publications and assessed study quality. J. F. W. C. wrote the manuscript with significant contributions from E. B. R., L. B. F. K., M. T. G. and S. A. G. All the authors contributed to the interpretation of the data, approved the final manuscript and took full responsibility for the final content.

None of the authors has any conflicts of interest to declare.

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