




Associations of dietary carbohydrate and fatty acid intakes with cognition among children

Sehrish Naveed^{1,*} , Taisa Venäläinen^{1,2}, Aino-Maija Eloranta¹, Arja T Erkkilä³, Henna Jalkanen¹, Virpi Lindi¹, Timo A Lakka^{1,4,5} and Eero A Haapala^{1,6}

¹Physiology, Institute of Biomedicine, School of Medicine, University of Eastern Finland, Kuopio Campus, 70211 Kuopio, Finland: ²Clinical Nutrition, Institute of Public Health and Clinical Nutrition, University of Eastern Finland, Kuopio Campus, 70211 Kuopio, Finland: ³Public Health, Institute of Public Health and Clinical Nutrition, University of Eastern Finland, Kuopio Campus, 70211 Kuopio, Finland: ⁴Department of Clinical Physiology and Nuclear Medicine, Kuopio University Hospital and University of Eastern Finland, Kuopio Campus, 70211 Kuopio, Finland: ⁵Kuopio Research Institute of Exercise Medicine, 70100 Kuopio, Finland: ⁶Faculty of Sport and Health Sciences, University of Jyväskylä, 40014 Jyväskylä, Finland

Submitted 18 April 2019; Final revision received 12 August 2019; Accepted 5 September 2019; First published online 21 February 2020

Abstract

Objective: To investigate the cross-sectional associations of dietary carbohydrate and fatty acid intakes with cognition in mid-childhood.

Design: Dietary carbohydrate and fatty acid intakes were assessed using 4-d food records, and cognition was evaluated using the Raven's Coloured Progressive Matrices (RCPM) score. The cross-sectional associations of dietary carbohydrate and fatty acid intakes with cognition were investigated using linear regression analyses adjusted for age, sex, body fat percentage, household income, parental education and daily energy intake.

Setting: The baseline examinations of the Physical Activity and Nutrition in Children study.

Participants: A population-based sample of 487 children (250 boys, 237 girls) aged 6–8 years living in the city of Kuopio, Finland.

Results: A higher dietary intake of fructose (standardised regression coefficient, $\beta = 0.24$, $P < 0.001$), total fibre ($\beta = 0.16$, $P = 0.02$) and soluble fibre ($\beta = 0.15$, $P = 0.02$) was associated with a higher RCPM score in boys. Other dietary carbohydrates and fatty acids, including total carbohydrates, glucose, sucrose, starch, insoluble fibre, total fat, SFAs, MUFAs, PUFAs, palmitic acid (C16), stearic acid (C18), linoleic acid (C18:2), α -linoleic acid (C18:3), arachidonic acid (C20:4), EPA (C20:5n-3) and DHA (C22:6n-6), were not associated with the RCPM score in boys. Dietary carbohydrates or fatty acids were not associated with the RCPM score in girls.

Conclusions: Higher dietary fructose and fibre intakes were associated with better cognition in boys, but not in girls. Dietary fatty acids were not related to cognition in boys or in girls.

Keywords

Diet
Fatty acid
Carbohydrate
Children
Brain
Cognition

Childhood is a period of rapid neural and cognitive development^(1,2) that involves the myelination of various brain areas^(3,4) and the acquisition of higher-order cognitive abilities to regulate goal-directed activity, emotions and decision-making^(5,6). A sufficient quantity and quality of various nutrients, particularly carbohydrates and fatty acids (FAs), are vital for optimal cognitive development in children⁽⁷⁾. The modern era has introduced a poor diet quality, including a low intake of fibre and a high intake of refined sugars and SFAs, among children⁽⁸⁾. A poor diet

quality may impair neural and cognitive development in children^(9,10), but such evidence is limited in general population of school-aged children without nutritional deficiencies or learning disabilities^(11,12).

Glucose is the most studied carbohydrate in association with cognition, as it is the main source of energy for brain cells⁽¹³⁾. The results of previous studies indicate that increased blood glucose after breakfast improves attention, memory and information processing in preadolescent children⁽¹⁴⁾. A higher total dietary fibre intake has been

*Corresponding author: Email sehrishn@uef.fi



associated with better verbal memory⁽¹⁵⁾, and higher dietary intakes of soluble and insoluble fibres have been linked to better selective attention and inhibition⁽¹⁶⁾ in preadolescent children. Furthermore, a recent cross-sectional study found that a lower dietary intake of simple carbohydrates and a higher dietary intake of fibre were associated with better cognition in preadolescent children⁽¹⁷⁾. However, most of the existing studies on the associations of dietary intakes of carbohydrates with cognition have only assessed blood glucose levels after meals^(18,19). Moreover, evidence on the associations of dietary intakes of other carbohydrates with cognition, particularly in children, is limited^(15,16).

A higher dietary intake of SFAs and trans-FAs and a lower dietary intake of *n*-3 PUFAs have been related to poorer cognition in some⁽²⁰⁾ but not all⁽²¹⁾ cross-sectional studies among children. A meta-analytic study exhibited that *n*-3 FA supplements improved cognition in infants but not in older children⁽²²⁾. However, recent dietary⁽²³⁾ and supplementary⁽²⁴⁾ intervention studies suggest that increased intakes of *n*-3 and *n*-6 PUFAs, and especially increased intakes of EPA and DHA, are linked to improved cognitive skills in children 8–11 years of age. Nevertheless, there is limited knowledge on the associations of dietary intakes of other FAs than EPA and DHA with cognition.

We investigated the association of dietary intakes of carbohydrates and FAs with cognition in a population sample of school children aged 6–8 years. We hypothesised that higher intakes of fibre and PUFAs and lower intakes of SFAs and refined carbohydrates are related to better cognition in children.

Methods

Study population and design

The present analyses are based on the baseline data from the Physical Activity and Nutrition in Children (PANIC) study, which is a controlled physical activity and dietary intervention study in a population sample of children from the city of Kuopio, Finland. We invited 736 children, 6–9 years of age, who started the first grade in sixteen primary schools of Kuopio in 2007–2009 to participate in the study. Altogether 512 children (248 girls, 264 boys), who accounted for 70% of those invited, participated in the baseline examinations in 2007–2009. The participants did not differ in age, sex or BMI-SD score from all children who started the first grade in the city of Kuopio in 2007–2009 based on the data from standard school health examinations performed for all Finnish children before the first grade. After excluding children with developmental disabilities and attention-deficit hyperactivity disorder, 487 (237 girls, 250 boys) children had complete data used in the analyses.

Assessment of dietary intakes of carbohydrates and fatty acids

We assessed energy and nutrient intakes by food records filled out by the parents on four predefined consecutive days⁽²⁵⁾. Of the food diaries, 99.5% included two weekdays and two weekend days, and 0.5% included three weekdays and one weekend day. A clinical nutritionist instructed the parents to record all food and drinks consumed by their children at home, at school, in afternoon care and elsewhere outside home using household or other measures, such as tablespoons, decilitres and centimetres. She reviewed the food records at return and completed the records with the parents using a picture booklet of portion sizes⁽²⁶⁾, if needed. A clinical nutritionist also asked the catering company about the details of food and drinks, such as menus, cooking fat and spread on bread, served at schools and in afternoon care. Moreover, she disaggregated all prepared foods and mixed dishes into ingredients according to the recipes used. We calculated total energy and nutrient intakes from the collected food record data using the Micro Nutrica® dietary analyses software, version 2.5 (The Social Insurance Institution of Finland), that utilises Finnish and international data on nutrient concentrations of foods⁽²⁷⁾.

The current analyses include the daily intakes of energy (KJ), total carbohydrates, glucose, fructose, sucrose, starch, total fibre, soluble fibre, insoluble fibre, total fat, SFAs, MUFAs, PUFAs, palmitic acid (C16), stearic acid (C18), linoleic acid (C18:2), α -linoleic acid (C18:3), arachidonic acid (C20:4), EPA (C20:5*n*-3) and DHA (C22:6*n*-6).

Assessment of cognition

We assessed nonverbal reasoning using Raven's Coloured Progressive Matrices (RCPM)⁽²⁸⁾ that was administered by one trained researcher. The RCPM includes three sets of twelve items. Each test page includes a large item or a pattern of items and six small items. The children were asked to select the correct small item, which completes the large item or the set of items. The test score was the number of correct answers, ranging from 0 to 36.

Assessment of body size and composition

A research nurse twice measured the body weight of children – first, after fasting for 12 h and, second, after emptying their bladder and standing in light underwear – using a calibrated InBody 720® bioelectrical impedance device (Biospace, Seoul, Korea) to an accuracy of 0.1 kg. We used the mean of these two values in the analyses. A research nurse thrice measured the stature of children in the Frankfurt plane without shoes using a wall-mounted stadiometer to an accuracy of 0.1 cm. We measured body fat percentage and lean body mass using the Lunar® dual-energy X-ray absorptiometry device (GE Medical Systems)^(25,29).

**Other assessments**

The parents were asked to report their annual household income (30 000 €, 30 001–60 000 €, and 60 001 €) and their highest completed or ongoing educational degrees (vocational school or less, polytechnic and university) in a questionnaire. We used the educational degree of the more educated parent in the analyses. The parents were also asked to report the medically diagnosed developmental disorders and attention-deficit hyperactivity disorder of their children.

Statistical methods

We analysed the data using the statistical software package IBM SPSS Statistics version 21.0 (IBM Corp.). We used the Student's *t* test and the χ^2 test to compare basic characteristics between boys and girls, and multivariate linear regression analyses adjusted for age, sex, body fat percentage, household income, parental education, total physical activity and daily energy intake to investigate the associations of dietary intakes of carbohydrates and FAs with the RCPM score. Because the results of previous studies suggest that the associations of the components of diet quality with cognition are stronger in boys than in girls⁽¹¹⁾, we conducted the analyses separately for boys and girls. However, we performed the analyses also for all children, because sex did not statistically significantly modify the associations of the measures of diet quality with the RCPM score ($P > 0.05$ for interactions).

Results**Basic characteristics**

Boys were taller, had lower body fat percentage and came from families with higher annual household income compared to girls (Table 1). Boys had a higher daily energy intake and higher intakes of total carbohydrates, sucrose, starch, total fibre, insoluble fibre and total fat compared

to girls. Boys also had higher intakes of most FAs, except EPA and DHA, compared to girls (Table 2).

Associations of dietary carbohydrate and fatty acid intakes with cognition

In all children, a higher intake of fructose was associated with a higher RCPM score (adjusted $r^2 = 0.049$) after adjusting for age, sex, body fat percentage, household income, parental education, total physical activity and daily energy intake (Table 3). This association was slightly weakened after further adjusting for the consumption of fruit and berries ($\beta = 0.11$, $P = 0.100$). None of the dietary FAs was associated with the RCPM score in all children.

In boys, higher intakes of fructose (adjusted $r^2 = 0.045$), total fibre (adjusted $r^2 = 0.011$) and soluble fibre (adjusted $r^2 = 0.012$) were related to a higher RCPM score after adjusting for age, body fat percentage, household income, parental education, total physical activity and daily energy intake (Table 3). A further adjustment for the consumption of fruit juices ($\beta = 0.15$, $P = 0.02$; adjusted $r^2 = 0.025$) strengthened the association of soluble fibre with the RCPM score. Similarly, a further adjustment for the consumption of high-fibre bread ($\beta = 0.21$, $P = 0.01$; adjusted $r^2 = 0.015$) or fruit juices ($\beta = 0.16$, $P = 0.02$; adjusted $r^2 = 0.025$) strengthened the association of the intake of total fibre with the RCPM score. However, adjustment for the consumption of fruit and berries ($\beta = 0.19$, $P = 0.040$) or fruit juices ($\beta = 0.23$, $P = 0.006$) slightly attenuated the association of the intake of fructose with the RCPM score. Similarly, further adjustment for the consumption of fruit and berries ($\beta = 0.07$, $P = 0.37$) or vegetables ($\beta = 0.12$, $P = 0.08$) attenuated the association of the intake of total fibre with the RCPM score. Further adjustment for the consumption of fruit and berries ($\beta = 0.03$, $P = 0.72$), vegetables ($\beta = 0.11$, $P = 0.12$) or high-fibre bread ($\beta = 0.16$, $P = 0.03$) attenuated the association of the intake of soluble

Table 1 Characteristics of children*

Variables	All (n 487)				Boys (n 250)				Girls (n 237)				P value for difference
	Mean	n	%	SD	Mean	n	%	SD	Mean	n	%	SD	
Age (years)	7.6			0.37	7.6			0.37	7.6			0.39	0.23
Height (cm)	128.7			5.6	129.6			5.5	127.8			5.6	0.001
Weight (kg)	26.9			5.1	27.2			4.9	26.5			5.1	0.10
Total physical activity (min/d)	15.8			5.9	16.2			6.1	15.5			5.7	0.24
Body fat percentage		18.7	8.2			15.0	8.0			20.5	7.7		0.001
Household income													0.02
<30 000 €	19.6				17.1				22.3				
30 000–60 000 €	41.9				39.0				45.0				
>60 000 €	35.8				40.2				31.1				
Parental education													0.10
Vocational school or less	19.2				19.9				18.5				
Polytechnic	44.0				37.1				51.3				
University degree	35.6				41.4				29.4				
RCPM score	23.9			5.1	23.8			5.2	24.1			4.9	0.57

RCPM, Raven's Coloured Progressive Matrices.

*Data are means (SD's) from the Student's *t* test for continuous variables, and numbers (percentages) from the χ^2 test for categorical variables.

Table 2 Energy and nutrient intakes in children*

Variables	All (n 487)		Boys (n 250)		Girls (n 237)		P value for difference
	Mean	SD	Mean	SD	Mean	SD	
Energy intake (KJ/d)	6802.4	1297.2	7152.5	1299.7	6433.2	1190.1	<0.001
Carbohydrate intake (g/d)							
Total carbohydrate	210.2	45.7	219.6	47.6	200.3	41.4	<0.001
Sucrose	51.2	19.8	53.5	21.3	48.7	17.7	<0.001
Glucose	11.3	5.0	11.7	5.3	11.0	4.6	0.12
Fructose	9.6	4.8	9.7	5.2	9.5	4.4	0.75
Starch	96.2	23.8	101.0	25.2	91.1	21.0	<0.001
Fibre intake (g/d)							
Total fibre	14.2	4.1	14.6	4.3	13.8	3.8	0.04
Soluble fibre	3.3	1.0	3.4	1.0	3.2	0.9	0.20
Insoluble fibre	6.3	2.0	6.5	2.1	6.0	1.8	0.006
Fat intake (g/d)							
Total fat	54.6	14.9	57.8	14.5	51.1	14.5	<0.001
SFAs	22.1	7.1	23.4	6.9	20.7	7.1	<0.001
MUFAs	18.1	5.1	19.2	5.0	16.9	5.0	<0.001
PUFAs	8.9	2.8	9.5	3.0	8.3	2.6	<0.001
Palmitic acid (C16)	9.0	3.1	9.6	3.1	8.4	3.1	<0.001
Stearic acid (C18)	4.1	1.6	4.4	1.6	3.7	1.5	<0.001
Linoleic acid (C18:2)	6.6	2.4	7.0	2.5	6.1	2.3	<0.001
α -Linoleic acid (C18:3)	1.4	0.5	1.5	0.5	1.3	0.4	<0.001
Arachidonic acid (C20:4)	0.09	0.1	0.1	0.1	0.08	0.1	<0.001
EPA (C20:5n-3)	0.04	0.1	0.04	0.1	0.03	0.1	0.14
DHA (C22:6n-6)	0.1	0.1	0.1	0.1	0.1	0.1	0.11

*Data are means (SD's) from the Student's *t* test.

Table 3 Association of dietary intakes with the RCPM score

Variables	All children		Boys		Girls	
	β	<i>P</i>	β	<i>P</i>	β	<i>P</i>
Daily carbohydrate intake (g/d)						
Total carbohydrate	0.15	0.09	0.21	0.10	0.07	0.55
Glucose	0.06	0.23	0.11	0.13	0.002	0.97
Sucrose	0.04	0.50	-0.002	0.98	0.08	0.33
Fructose	0.14	0.002	0.24	0.000	0.03	0.57
Starch	-0.02	0.72	-0.02	0.81	0.02	0.79
Daily fibre intake (g/d)						
Total fibre	0.08	0.08	0.16	0.02	-0.004	0.95
Soluble fibre	0.07	0.13	0.15	0.02	-0.02	0.77
Insoluble fibre	0.02	0.58	0.08	0.21	-0.05	0.40
Daily fat intake (g/d)						
Total fat	-0.104	0.14	-0.18	0.05	-0.006	0.96
SFAs	-0.12	0.07	-0.09	0.16	0.04	0.68
MUFAs	-0.06	0.35	-0.11	0.19	-0.005	0.96
PUFAs	-0.02	0.61	-0.01	0.88	0.04	0.55
Palmitic acid (C16)	-0.08	0.19	-0.16	0.06	0.003	0.97
Stearic acid (C18)	-0.07	0.19	-0.11	0.14	-0.04	0.52
Linoleic acid (C18:2)	-0.02	0.72	-0.01	0.86	0.01	0.85
α -Linoleic acid (C18:3)	0.02	0.68	0.05	0.46	-0.02	0.72
Arachidonic acid (C20:4)	-0.07	0.13	-0.04	0.55	-0.10	0.12
EPA (C20:5n-3)	0.02	0.61	0.07	0.28	-0.02	0.73
DHA (C22:6n-6)	0.02	0.66	0.08	0.20	-0.04	0.51

The values are from linear regression models after adjustment for age, sex, body fat percentage, household income, parental education, total physical activity and daily energy intake. *P*-values <0.05, indicating statistically significant associations, are bolded.

fibre with the RCPM score. None of the dietary FAs was related to the RCPM score in boys.

In girls, the intakes of carbohydrates or FAs were not associated with the RCPM score after adjusting for age, body fat percentage, household income, parental education, total physical activity and daily energy intake (Table 3).

Discussion

We found that higher dietary intakes of fructose, total fibre and soluble fibre were associated with better cognition in boys but not in girls. However, dietary FAs were not related to cognition in boys or in girls.



Our finding on the association between a higher dietary intake of fructose and better cognition in boys is in contrast to previous observations on an inverse association between dietary fructose and cognition in adults⁽³⁰⁾. One reason for these contrasting findings may be that a higher intake of fructose from refined sugars may impair cognitive performance, whereas a higher intake of fructose from natural sources, such as fruits, vegetables and grain products, may be neuroprotective and support cognitive functions^(31–33). We previously observed in the present study population that carbohydrates were mainly obtained from low-fibre grain products, and the main sources of fibre were high-fibre bread and vegetables⁽²⁵⁾ and that fruit and fruit juice consumption was directly related to cognition⁽¹¹⁾. Natural sources of fructose, such as fruits, include also other neuroprotective nutrients, such as B vitamins and antioxidants, which may partly explain these observations^(32,33). Accordingly, we found that the consumption of fruit and berries partly explains the positive association between dietary fructose and the RCPM score.

Our observation on the positive associations of dietary total and soluble fibres with cognition in boys is in accordance with few previous findings in children⁽¹⁶⁾ and in older adults⁽³⁴⁾. We previously found that a higher consumption of high-fibre grain products is related to better cognition in children⁽¹¹⁾. A higher intake of fibre may support normal cognitive development, because it was found to amplify the effect of neuroprotective brain-derived neurotrophic factor⁽³⁵⁾. A higher dietary fibre intake has also been associated with a decreased concentration of neuroinflammatory markers, such as IL-1 β and TNF- α , in the brain⁽³⁶⁾.

We found positive associations of dietary fructose and fibre with cognition in boys but not in girls. The results of some previous studies suggest that dietary factors have a stronger effect on brain development in boys than in girls^(7,37). Isaacs and co-workers observed that a higher use of protein-enriched formula during infancy is associated with a larger volume of caudate nucleus and intelligence quotient in adolescence among boys but not among girls⁽⁷⁾. The explanation of these sexually dimorphic findings is not known, but they may relate to differences in the stage and rate of neural maturation between boys and girls⁽⁷⁾. However, few studies have reported their data in boys and girls separately. Therefore, further studies on sex differences in the associations of dietary factors with cognition are warranted.

We observed no associations of dietary glucose, sucrose, starch or insoluble fibres with cognition in children. One explanation may be that different carbohydrates have varying effects on diverse types of cognition. Papanikolaou and co-workers found that a carbohydrate-rich meal with a high glycaemic index is associated with deterioration in verbal memory but not working memory, measured by a digit span test, among adults⁽³⁸⁾. Another study in children showed that working memory was poorer after consuming a meal with a

high glycaemic index than after a meal with a low glycaemic index⁽¹⁸⁾. However, neither of these meals had effects on sustained attention⁽¹⁸⁾.

We found no statistically significant associations of dietary FAs with cognition in children. Our observations are in line with those of some previous studies that dietary intake or supplementation of FAs had a weak, if any, association with cognitive performance in well-nourished children with no psychological or reading disabilities^(12,24,39,40). It is possible that the intake of FAs⁽²⁵⁾ and the proportion of plasma FAs⁽⁴¹⁾ among children in our study was adequate to support normal development of cognition^(6,42).

The other reason for no associations of dietary FAs with cognition in the present study may be that dietary FAs have different impacts on various cognitive domains. The dietary intake of *n*-3 FAs has been directly associated with relational memory, but not with item memory in children⁽²⁰⁾. Furthermore, the dietary intake of SFA has been inversely associated with relational and item memory in children aged 7–9 years^(20,43). The reason for these observations may be that PUFAs, such as *n*-3 FAs, have a pronounced positive effect on cognitive functions that are regulated in the hippocampus, such as relational memory, whereas SFAs have more global negative effects on memory⁽⁴³⁾.

The strengths of the present study include a relatively large population sample of children and valid methods used to assess dietary factors and cognition. The parents were asked to record all food and drinks consumed by their children at home, at school, in afternoon care and elsewhere outside home on four predefined and consecutive days, including two weekdays and two weekend days, which provides a better view on overall nutrition than using weekdays only. Moreover, a clinical nutritionist reviewed the food records at return and completed the records with the parents using a picture booklet of portion sizes⁽²⁶⁾, if needed. Our analyses are based on cross-sectional data, and we, therefore, cannot provide evidence for a causal link between dietary factors and cognition. We neither had dietary data from infancy or early childhood, which are important phases of cognitive development⁽⁶⁾ and could, therefore, have an effect on our results. Furthermore, it would have been optimal to use multiple cognitive tests to study the associations of dietary factors with different aspects of cognition.

In conclusion, higher dietary intakes of fructose, total fibre and soluble fibre were associated with better cognition in boys 6–8 years of age. However, dietary fats were not associated with cognition in children. These findings suggest that increasing the consumption of fruit and fruit juices, which are natural sources of fructose, and high-fibre food products, such as grain products, may support normal cognition in boys. Longitudinal studies and optimal dietary intervention studies are needed to provide further evidence for the role of dietary carbohydrates and fats in cognition to investigate whether gender modifies the associations of dietary factors with cognition.

Acknowledgements

Acknowledgements: The first author acknowledges the work of all co-authors especially Dr. Haapala and Prof. Timo Lakka for their support throughout. **Financial support:** The current study was financially supported by grants from the Jenny and Antti Wihuri Foundation, the Sinikka and Sakari Sohlberg Foundation, the Ministry of Social Affairs and Health of Finland, the Ministry of Education and Culture of Finland, the Finnish Innovation Fund Sitra, the Social Insurance Institution of Finland, the Finnish Cultural Foundation, the Juho Vainio Foundation, the Yrjö Jahnsson Foundation, the Foundation for Pediatric Research, the Paavo Nurmi Foundation, the Paulo Foundation, the Diabetes Research Foundation Kuopio, the Kuopio University Hospital (EVO funding number 5031343) and the Research Committee of the Kuopio University Hospital Catchment Area (the State Research Funding), Yrjö Jahnsson Foundation. **Conflict of interest:** The manuscript has been approved by all authors, and there are no conflicts of interest regarding it. **Authorship:** N.S., L.T.A. and H.E.A. were responsible for study design; S.N. drafted the manuscript and analysed the data. V.T., E.A.M., A.T., J.H., L.V. and L.T.A. collected the data and contributed the intellectual content and interpretation of results. L.T.A. is the principal investigator of the PANIC study. **Ethics of human subject participation:** The current study was conducted according to the guidelines laid down in the Declaration of Helsinki, and all procedures involving study participants were approved by the Research Ethics Committee of the Hospital District of Northern Savo, Kuopio. Written informed consent was obtained from the parents of all subjects.

References

- Bourre JM (2006) Effects of nutrients (in food) on the structure and function of the nervous system: update on dietary requirements for brain. Part 1: Micronutrients. *J Nutr Health Aging France* **10**, 377–385.
- Lenroot R & Giedd J (2009) Brain development in children and adolescents: Insights from anatomical magnetic resonance imaging. *Neurosci Biobehav Rev* **30**, 718–729.
- Thatcher RW (1991) Maturation of the human frontal lobes: Physiological evidence for staging. *Dev Neuropsychol* **7**, 397–419. doi: 10.1080/87565649109540500
- Bryan J, Osendarp S, Hughes D *et al.* (2004) Nutrients for cognitive development in school-aged children. *Nutr Rev* **62**, 295–306. United States.
- Atallah HE, Frank MJ & O'Reilly RC (2004) Hippocampus, cortex, and basal ganglia: Insights from computational models of complementary learning systems. *Neurobiol Learn Mem* **82**, 253–267. Available from: <http://www.sciencedirect.com/science/article/pii/S1074742704000693>
- Diamond A (2013) Executive Functions. *Annu Rev Psychol* **64**, 135–168. doi: 10.1146/annurev-psych-113011-143750
- Isaacs E & Oates J (2008) Nutrition and cognition: Assessing cognitive abilities in children and young people. *Eur J Nutr* **47**, S3, 4–24. Available from: <http://www.ncbi.nlm.nih.gov/pubmed/18683026>
- Danaei G, Finucane MM, Lu Y *et al.* (2011) National, regional, and global trends in fasting plasma glucose and diabetes prevalence since 1980: Systematic analysis of health examination surveys and epidemiological studies with 370 country-years and 2.7 million participants. *Lancet* **378**, 31–40. Available from: <http://www.ncbi.nlm.nih.gov/pubmed/21705069>
- Nyaradi A, Li J, Hickling S *et al.* (2013) The role of nutrition in children's neurocognitive development, from pregnancy through childhood. *Front Hum Neurosci* **7**, 97. Available from: <http://www.ncbi.nlm.nih.gov/pubmed/23532379>
- Haapala E, Lintu N, Vaisto J *et al.* (2015) Associations of physical performance and adiposity with cognition in children. *Med Sci Sport Exerc* **47**, 2166–2174. Available from: https://www.researchgate.net/profile/Leah_Robinson3/publication/273439198_Associations_of_Physical_Performance_and_Adiposity_with_Cognition_in_Children/links/574f6bfd08aebb988044f4de/Associations-of-Physical-Performance-and-Adiposity-with-Cognition-in-Chi
- Haapala EA, Viitasalo A, Venäläinen T *et al.* (2015) Associations of diet quality with cognition in children – The physical activity and nutrition in children study. *Br J Nutr* **114**, 1080–1087.
- Osendarp SJM, Baghurst KI, Bryan J *et al.* (2007) Effect of a 12-mo micronutrient intervention on learning and memory in well-nourished and marginally nourished school-aged children: 2 parallel, randomized, placebo-controlled studies in Australia and Indonesia. *Am J Clin Nutr* **86**, 1082–1093. Available from: <http://www.ncbi.nlm.nih.gov/pubmed/17921387>
- Stephen A, Alles M, de Graaf C *et al.* (2012) The role and requirements of digestible dietary carbohydrates in infants and toddlers. *Eur J Clin Nutr* **66**, 765–779. Nature Publishing Group. Available from: <http://www.ncbi.nlm.nih.gov/pubmed/22473042>
- Márquez Acosta M, Sutil de Naranjo R, Rivas de Yopez C *et al.* Influencia del desayuno sobre la función cognoscitiva de escolares de una zona urbana de Valencia, Venezuela. *Arch Latinoam Nutr* **200**, 57–63. Available from: http://www.scielo.org/ve/scielo.php?pid=S0004-06222001000100008&script=sci_arttext&tlng=pt
- Micha R, Rogers PJ & Nelson M (2011) Glycaemic index and glycaemic load of breakfast predict cognitive function and mood in school children: A randomised controlled trial. *Br J Nutr* **106**, 1552–1561. Available from: http://www.journals.cambridge.org/abstract_S0007114511002303
- Khan NA, Raine LB, Drollette ES *et al.* (2015) Dietary fiber is positively associated with cognitive control among prepubertal children. *J Nutr* **145**, 143–149. American Society for Nutrition. Available from: <http://www.ncbi.nlm.nih.gov/pubmed/25527669>
- Hassevoort KM, Lin AS, Khan NA *et al.* (2018) Added sugar and dietary fiber consumption are associated with creativity in preadolescent children. *Nutr Neurosci* 1–12. Taylor & Francis. doi: 10.1080/1028415X.2018.1558003
- Benton D, Maconie A & Williams C (2007) The influence of the glycaemic load of breakfast on the behaviour of children in school. *Physiol Behav* **92**, 717–724.
- Cooper SB, Bandelow S, Nute ML *et al.* (2012) Breakfast glycaemic index and cognitive function in adolescent school children. *Br J Nutr* **107**, 1823–1832. Available from: http://www.journals.cambridge.org/abstract_S0007114511005022
- Baym CL, Khan NA, Monti JM *et al.* (2014) Dietary lipids are differentially associated with hippocampal-dependent relational memory in prepubescent children. *Am J Clin Nutr* **99**, 1026–1032. American Society for Nutrition. Available from: <http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3985209/>
- Zhang J, Hebert JR & Muldoon MF (2005) Dietary fat intake is associated with psychosocial and cognitive functioning of school-aged children in the United States. *J Nutr*



- 135, 1967–1973. Oxford University Press. Available from: <https://academic.oup.com/jn/article/135/8/1967/4663924>
22. Jiao J, Li Q, Chu J *et al.* (2014) Effect of n-3 PUFA supplementation on cognitive function throughout the life span from infancy to old age: A systematic review and meta-analysis of randomized controlled trials. *Am J Clin Nutr* **100**, 1422–1436. Available from: <http://www.ncbi.nlm.nih.gov/pubmed/25411277>
 23. Sørensen LB, Damsgaard CT, Dalskov S-M *et al.* (2015) Diet-induced changes in iron and n-3 fatty acid status and associations with cognitive performance in 8–11-year-old Danish children: secondary analyses of the Optimal Well-Being, Development and Health for Danish Children through a Healthy New Nordic Diet School Meal Study. *Br J Nutr* **114**, 1623–1637. Available from: <http://www.ncbi.nlm.nih.gov/pubmed/26359192>
 24. Johnson M, Fransson G, Östlund S *et al.* (2017) Omega 3/6 fatty acids for reading in children: a randomized, double-blind, placebo-controlled trial in 9-year-old mainstream schoolchildren in Sweden. *J Child Psychol Psychiatry* **58**, 83–93. Available from: <http://www.ncbi.nlm.nih.gov/pubmed/27545509>
 25. Eloranta A-M, Lindi V, Schwab U *et al.* (2012) Dietary factors associated with overweight and body adiposity in Finnish children aged 6–8 years: The PANIC Study. *Int J Obes* **36**, 950–955. Available from: <http://www.ncbi.nlm.nih.gov/pubmed/22665136>
 26. Paturi M, Nieminen R, Reinivuo H *et al.* (2006) *Picture Book of Food Portion Sizes*. Helsinki, Finland: Publications of the National Public Health Institute.
 27. Rastas M, Seppänen R, Knuts L *et al.* (1997) *Nutrient Composition of Foods*. Helsinki, Finland: Publications of the Social Insurance Institution.
 28. Raven J, Raven J & Court J (1998) *Coloured Progressive Matrices. Manual for Raven's Progressive Matrices and Vocabulary Scales*. London: Oxford Psychologist Press Ltd.
 29. Tompuri TT, Lakka TA, Hakulinen M *et al.* (2015) Assessment of body composition by dual-energy X-ray absorptiometry, bioimpedance analysis and anthropometrics in children: The Physical Activity and Nutrition in Children study. *Clin Physiol Funct Imaging* **35**, 21–33. Available from: <http://www.ncbi.nlm.nih.gov/pubmed/24325400>
 30. Ye X, Gao X, Scott T *et al.* (2011) Habitual sugar intake and cognitive function among middle-aged and older Puerto Ricans without diabetes. *Br J Nutr* **106**, 1423–1432. Available from: http://www.journals.cambridge.org/abstract_S0007114511001760
 31. Ye X, Gao X, Scott T *et al.* (2011) Habitual sugar intake and cognitive function among middle-aged and older Puerto Ricans without diabetes. *Br J Nutr* **106**, 1423–1432. Available from: <http://www.ncbi.nlm.nih.gov/pubmed/21736803>
 32. Tucker KL, Qiao N, Scott T *et al.* (2005) High homocysteine and low B vitamins predict cognitive decline in aging men: The veterans affairs normative aging study. *Am J Clin Nutr* **82**, 627–635. Available from: <http://www.ncbi.nlm.nih.gov/pubmed/16155277>
 33. Akbaraly NT, Faure H, Gourlet V *et al.* (2007) Plasma carotenoid levels and cognitive performance in an elderly population: Results of the EVA Study. *J Gerontol A Biol Sci Med Sci* **62**, 308–316. United States. Available from: <https://www.ncbi.nlm.nih.gov/pubmed/17389729>
 34. Ortega RM, Requejo AM, Andrés P *et al.* (1997) Dietary intake and cognitive function in a group of elderly people. *Am J Clin Nutr* **66**, 803–809. Available from: <http://www.ncbi.nlm.nih.gov/pubmed/9322553>
 35. Schroeder FA, Lin CL, Crusio WE *et al.* (2007) Antidepressant-like effects of the histone deacetylase inhibitor, sodium butyrate, in the mouse. *Biol Psychiatry* **62**, 55–64. Available from: <http://www.ncbi.nlm.nih.gov/pubmed/16945350>
 36. Sherry CL, Kim SS, Dilger RN *et al.* (2010) Sickness behavior induced by endotoxin can be mitigated by the dietary soluble fiber, pectin, through up-regulation of IL-4 and Th2 polarization. *Brain Behav Immun* **24**, 631–640. Available from: <http://www.ncbi.nlm.nih.gov/pubmed/20138982>
 37. Craft S, Murphy C & Wemstrom J (1994) Glucose effects on complex memory and nonmemory tasks: The influence of age, sex, and glucoregulatory response. *Psychobiology* **22**, 95–105. doi: 10.3758/BF03327086
 38. Papanikolaou Y, Palmer H, Binns MA *et al.* (2006) Better cognitive performance following a low-glycaemic-index compared with a high-glycaemic-index carbohydrate meal in adults with type 2 diabetes. *Diabetologia* **49**, 855–862. Available from: <http://www.ncbi.nlm.nih.gov/pubmed/16508776>
 39. Ryan AS, Astwood JD, Gautier S *et al.* (2010) Effects of long-chain polyunsaturated fatty acid supplementation on neurodevelopment in childhood: A review of human studies. *Prostaglandins Leukot Essent Fatty Acids* **82**, 305–314. Elsevier. Available from: <http://www.ncbi.nlm.nih.gov/pubmed/20188533>
 40. Muthayya S, Eilander A, Transler C *et al.* (2009) Effect of fortification with multiple micronutrients and n-3 fatty acids on growth and cognitive performance in Indian schoolchildren: the CHAMPION (Children's Health and Mental Performance Influenced by Optimal Nutrition) Study. *Am J Clin Nutr* **89**, 1766–1775. Available from: <http://www.ncbi.nlm.nih.gov/pubmed/19369376>
 41. Venäläinen T, Schwab U, Ågren J *et al.* (2014) Cross-sectional associations of food consumption with plasma fatty acid composition and estimated desaturase activities in Finnish children. *Lipids* **49**, 467–479. Available from: <http://www.ncbi.nlm.nih.gov/pubmed/24659110>
 42. Rask-Nissilä L, Jokinen E, Terho P *et al.* (2000) Neurological development of 5-year-old children receiving a low-saturated fat, low-cholesterol diet since infancy: A randomized controlled trial. *JAMA* **284**, 993–1000. Available from: <http://www.ncbi.nlm.nih.gov/pubmed/10944645>
 43. Kanoski SE & Davidson TL (2011) Western diet consumption and cognitive impairment: Links to hippocampal dysfunction and obesity. *Physiol Behav* **103**, 59–68. Available from: <http://www.ncbi.nlm.nih.gov/pubmed/21167850>