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Diet, lifestyle, metabolic markers, and socioeconomic status are associated with cognitive function in school-aged children from a population-based cohort

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BACKGROUND: Cognitive development is associated with diet, activity, sleep, metabolic health, and socioeconomic status. However, evidence remains limited, as most studies have focused on clinical groups or single factors. We examined the combined associations of these variables with cognitive function in school-aged children from the general population.
METHODS: We evaluated 170 school-aged children from a population-based cohort (mean age 6.33 ± 0.03 years; 49% female). Children were evaluated after an overnight fast (>8 h), and anthropometric, metabolic, and socioeconomic variables were evaluated. Diet and physical activity were assessed using validated questionnaires (Vioque FFQ and enKid). Cognitive function was assessed using NEPSY-II and TONI-2 subsets. Correlation and regression analyses were performed.
RESULTS: Cognitive function was positively associated with Mediterranean diet adherence, sleep duration, socioeconomic status, and negatively associated with ultra-processed food intake, TV viewing, and metabolic markers including insulin resistance (HOMA-IR), C-reactive protein, and gamma-glutamyltransferase (all $p < 0.05$). Multivariate analyses showed that Mediterranean diet adherence (OR 2.18, 95%CI 1.08–4.40), economic status (OR 2.50, 95%CI 1.13–5.49), sleep duration (OR 2.90, 95%CI 1.42–5.92), and HOMA-IR (OR 0.47, 95%CI 0.23–0.96) as independently associated with cognitive outcomes, particularly in attention, language, and memory.
CONCLUSIONS: Lifestyle factors and socioeconomic conditions are independently associated with cognitive function in children.

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IMPACT:

- Key message: Diet, sleep, metabolic health, and socioeconomic status are associated with cognitive function in school-aged children.
- Novelty: Simultaneously examines multiple factors associated with cognition in school-aged children from a population-based cohort.
- Impact on cognition: Mediterranean diet adherence, sleep duration, and metabolic health were positively associated with several cognitive domains, including attention, language, and memory.
- Practical use: Highlights the potential relevance of healthy lifestyles and social equity in relation to cognitive development.
- Broader significance: Highlights the multifactorial nature of cognitive development in children.

INTRODUCTION

Cognitive function encompasses a range of higher-order mental processes that enable individuals to learn, adapt to new situations, and make decisions. It is often subdivided into several domains such as attention, language, executive functions, memory, and visuospatial abilities.[1] Such cognitive domains are assessed through the use of age-appropriate standardized neuropsychological tests.[2]

Cognitive function during childhood plays a critical role in academic achievement,[3] and professional success,[4] as well as

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health-related quality of life.[5] Perinatal and postnatal exposures can disrupt the cognitive developmental trajectory, leading to delay or underdevelopment of cognitive skills.[6] Identifying modifiable factors associated with cognitive function may help inform strategies aimed at supporting brain development.

The Mediterranean diet, characterized by high intake of fruits, vegetables, whole grains, and healthy fats, is the dietary pattern with the strongest scientific evidence supporting its health benefits. A recent systematic review reported positive associations between adherence to the Mediterranean diet and cognitive function in children and adolescents.[7] By contrast, the consumption of ultra-processed foods (UPFs), highly refined products resulting from intense industrial processing are characterized by usually being highly energy dense due to having significant amounts of saturated and trans fats, added sugars and salt, and non-nutritional food additives and at the same time, being low in nutrient density, having minimal protein, fiber and micronutrients.[8] UPFs are robustly linked to a wide range of non-communicable diseases, including obesity, type 2 diabetes or cardiovascular disease.[9] Potential adverse associations between ultra-processed foods and brain health have recently been described.[10]

Similarly, physical activity has been associated not only with physical health but also with neuroplasticity and brain function.[11] A recent systematic review showed evidence of beneficial associations between physical activity and cognition, as well as detrimental effects of screen time.[12] Sleep duration has also been linked to cognition, although overall information on this association in children is limited.[13]

In contrast, metabolic disturbances have been linked to impaired cognitive performance, suggesting that metabolic health may be closely related to brain development.[14,15] Obesity, an increasingly prevalent global public health issue, is closely related to metabolic health and is often accompanied by chronic inflammation, insulin resistance, and other metabolic abnormalities. Pediatric obesity, in particular, has been associated with poorer cognitive outcomes, possibly through both direct biological mechanisms and indirect social and environmental factors.[16] While several studies have reported significant associations between poor metabolic indicators, especially elevated fasting glucose and insulin resistance, and poorer cognitive performance in youth, evidence from the general pediatric population remains limited.[17]

Socioeconomic status has also been associated with a wide range of health, cognitive, and socioemotional outcomes in children, with effects beginning before birth and extending into adulthood. Importantly, socioeconomic status may be associated with cognitive development both directly and indirectly through its association with dietary patterns, lifestyle behaviors, and metabolic health, thereby potentially relating to both exposures and outcomes.[18,19]

Despite growing evidence, most studies examining the associations of diet, lifestyle, metabolic parameters, and socioeconomic status with cognition have been conducted in adults or have focused on clinical or high-risk pediatric populations with limited research available in population-based cohorts. In addition, these factors have often been analyzed separately rather than in combination. The primary aim of this study was to examine the independent associations of diet quality, lifestyle behaviors, metabolic health, and socioeconomic status with overall and domain-specific cognitive function in school-aged children from the general population. We hypothesized that higher Mediterranean diet adherence, longer sleep duration, better metabolic health, and higher socioeconomic status would be positively associated with cognitive performance, whereas higher ultra-processed food intake, greater sedentary behavior, and insulin resistance would be negatively associated.

MATERIALS AND METHODS

Study population

The present study is a cross-sectional analysis nested within a population-based birth cohort (Estudi Prenatal Girona, EPG), conducted in 170 school-aged children recruited at Dr. Josep Trueta Hospital of Girona. In this cohort, mothers were recruited during pregnancy, and children were assessed at school age (mean age 6 years).

A total of 432 mothers were initially enrolled in the EPG cohort. Of these, 177 children attended the 6-year follow-up visit. After excluding 7 participants due to missing data or not meeting inclusion criteria, the final sample included 170 children.

The study protocol was approved by the Ethics Review Committee of the Institutional Review Board of Dr Josep Trueta Hospital and was conducted in accordance with their code of ethics, guidelines and regulations. Informed written consent was obtained from the parents before participation.

Eligible participants for the present analysis were school-aged children whose mothers had taken part in the population-based EPG study, who attended the 6-year follow-up visit, and for whom cognitive assessment data were available. Children were considered generally healthy because participants with major congenital anomalies; abnormal blood count, or liver, kidney or thyroid functions; chronic diseases affecting growth, metabolism, or neurodevelopment (including endocrine, neurological, or psychiatric disorders), prolonged medication use; or acute illness or medication exposure that could influence metabolic parameters or cognitive function in the month preceding enrollment were excluded. Children with overweight or obesity were not excluded, provided they did not meet any of the exclusion criteria described above.

Clinical assessments

Clinical examination and fasting venous blood collection were conducted in the morning. Body weight and height were measured using a calibrated scale and a Harpenden stadiometer, respectively. Body mass index (BMI) was calculated as weight (kg) divided by height squared (m^2). Age- and sex-standardized BMI z-scores (SDS) were derived based on regional reference data.[20] Waist and hip were measured in centimeters using a flexible, non-stretchable anthropometric tape. Waist circumference was taken in the supine position at the umbilical level. Hip circumference was measured at the widest part, at the level of the greater trochanters.

Laboratory assessments

All blood samples were obtained between 8:00 and 9:00 AM under fasting conditions. Fasting status (≥8 h) was self-reported by parents at the time of blood collection. Samples were transported to the hospital clinical laboratory and processed following standard clinical protocols. Serum glucose was measured by the hexokinase method and insulin by immunochemiluminiscence (IMMULITE 2000, Diagnostic Products, Los Angeles, CA). Insulin resistance was estimated by the homeostasis model assessment (HOMA-IR = fasting insulin [mU/L] × fasting glucose [mmol/L]/22.5). Alanine aminotransferase (ALT) and gamma-glutamyl transferase (GGT) were measured by kinetic UV assay (IFCC method). Triglycerides (TG) was measured by glycerol-phosphate oxidase method, total cholesterol by enzymatic colorimetric assay and HDL-cholesterol by accelerator selective detergent method (ARCHITECT, Abbott Laboratories, Abbott Park, IL). LDL-cholesterol was estimated by the Friedewald formula. High-sensitivity C-reactive protein (CRP) levels were determined using an ultrasensitive latex immunoassay (CRP Vario, Sentinel Diagnostics, Milan, Italy). Intra- and inter-assay coefficients of variation were less than <10% for all studied parameters. The selected metabolic markers were chosen to capture key aspects of metabolic health, including glucose homeostasis, lipid metabolism, liver function, and low-grade systemic inflammation, all of which have been implicated in neurodevelopment and cognitive function. Biochemical measurements were performed according to standardized laboratory procedures, and assays were conducted in single determinations.

Dietary intake

Dietary intake was assessed using a semi-quantitative food frequency questionnaire adapted from the validated Vioque FFQ for the Spanish population,[21] which collected information on the frequency of consumption (daily and weekly) of a wide range of food groups. The questionnaire was completed by the parents and assessed the child's habitual dietary intake during the previous 9–12 months. Responses were analyzed by the

Nutrition and Epidemiology Group at Miguel Hernández University (EPINUT group) and converted into daily intake amounts using the Spanish food composition tables from CESNID and the Ministry of Health. Nutritional variables were created and organized as follows: daily consumption by food group in grams and daily nutrient intake per individual in grams (Supplemental Table S1).

The NOVA food classification system was used to classify foods and drinks based on their degree of industrial processing into Group 1, Group 2, Group 3, and Group 4.[22] Particularly, we focused on Groups 1 and 4. Group 1 includes unprocessed or minimally processed foods and is generally consumed as they are harvested or with minimal modification, such as washing, refrigeration, or freezing. Examples include fruits, vegetables, whole grains, legumes, fresh meat, fish, and eggs. Group 4 includes ultra-processed foods (UPF) that have undergone more complex industrial processes and contain ingredients that are not typically found in home kitchens, such as additives, colorings, preservatives, sweeteners, and emulsifiers. These products are often designed for high convenience and have a long shelf life. Examples include soft drinks, cookies, breakfast cereals, fast food, and packaged snacks. Results of each NOVA group were expressed as a percentage of the total daily diet [(NOVA group consumption daily grams / total diet daily grams) * 100]. NOVA groups 1 and 4 were selected to represent the extremes of food processing.

Adherence to the Mediterranean diet was assessed by the relative Mediterranean diet (rMED) index proposed by the EPIC-Spain cohort,[23] which includes eight components (vegetables, fruit, olive oil, grains, legumes, fish, meat and processed meat, and dairy products), excluding the ethanol component due to the pediatric population. Results were expressed as a total score ranging from 0 to 16 points. Although related, NOVA classification and the rMED score reflect different but complementary aspects of dietary quality, namely the degree of food processing and adherence to the Mediterranean dietary pattern. To avoid collinearity, NOVA variables and the rMED score were not included simultaneously in multivariable models.

Physical activity

Physical activity was assessed by the enKid questionnaire, a nationally representative cross-sectional survey conducted in Spain among children and adolescents.[24] Information on physical activity was collected through a structured questionnaire that included frequency, duration, and type of physical activity during both school and leisure time, which was answered by the children's parents. Metabolic Equivalent of Task (MET) values were assigned to all reported activities following standardized approaches to characterize the full range of daily activity patterns. Sleep duration was directly reported by parents as hours of sleep per day through the questionnaire and was not derived from MET values.

Cognitive function

Cognitive domains evaluated in this study included language, attention, memory, and abstract reasoning. These functions were assessed using an adaptation of two standardized instruments: the NEPSY-II (*A Developmental Neuropsychological Assessment*) and the TONI-2 (*Test of Nonverbal Intelligence*).[25] The adapted version included selected subtests specifically targeting each domain: verbal fluency for language, the statue subtest for attention, free recall, cued recall, and recognition tasks for memory, and problem-solving ability for abstract reasoning (Supplemental Table S2). Cognitive scores were based on age-standardized scaled scores provided by the NEPSY-II and TONI-2 instruments. This approach, based on validated subtests, allows an efficient yet comprehensive assessment of key cognitive domains in pediatric populations while minimizing participant burden. Each cognitive domain was analyzed independently to assess specific cognitive abilities. Additionally, a composite cognitive score was calculated by averaging the standardized scores of all individual domains, providing a descriptive index of overall cognitive performance across the evaluated domains. This composite score was used as a summary measure to facilitate the analysis of general cognitive performance in this population-based study. Results were expressed as a score ranging from 1 to 19 points. Internal consistency analyses were not conducted; therefore, the composite score should be interpreted as a descriptive index of overall cognitive performance rather than as a psychometrically validated construct.

Socioeconomic data

Socioeconomic data were collected using standardized questionnaires administered at the time of study enrollment. Parental education was based on the highest level of education attained and categorized into three groups: neither parent had a university degree, one parent had a university degree, or both parents had university degrees. Parental economic status was assessed using a self-reported question on the family's ability to make ends meet. Responses ranged from "with great ease" to "not making ends meet" and were grouped into two categories: higher economic status ("with great ease" or "with ease") and lower economic status ("with difficulty", "with great difficulty", or "not making ends meet").

Statistical analysis

Statistical analyses were performed using SPSS version 22.0 (SPSS Inc.). Results are expressed as mean ± standard error of the mean (SEM) for the continuous variables or percentage (%) for categorical variables. Variables that did not follow a normal distribution were log-transformed.

Pearson bivariate correlations were initially performed to examine simple associations between cognitive function and dietary intake, physical activity, metabolic markers, and socioeconomic data. Subsequently, multiple linear regression analyses were conducted to assess these associations while adjusting for children's age, sex, and BMI.

To investigate which variables were most strongly associated with children's cognition, we performed multivariate linear regression analyses. Cognitive function was included as a dependent variable, and all the variables that showed a significant association in the correlation analyses were included as independent variables. Variables included in the multivariable models were selected based on both biological relevance (theory-driven approach) and significant associations observed in the bivariate analyses (data-driven approach). Multicollinearity among variables was considered and no relevant collinearity was observed. Given the number of statistical tests performed and the interrelatedness of several exposure variables, the analyses were considered exploratory and results were interpreted with caution. No formal correction for multiple comparisons was applied; therefore, the possibility of type I error cannot be excluded.

A logistic regression analysis was performed to evaluate the combined associations of several factors with cognitive performance. For this analysis, the composite cognitive score was dichotomized into higher cognitive performance [mean cognitive score > median (p50)] and lower cognitive performance [mean cognitive score ≤ median (p50)]. Independent variables were also categorized using the median (p50) as the cutoff point to facilitate the interpretation of odds ratios and allow comparison across variables measured on different scales. Dichotomization was applied only in logistic regression models as a secondary analytic approach to facilitate interpretation. Primary analyses were conducted using continuous outcomes, and the results were consistent with those obtained in the logistic regression models. The significance level was set at $p \leq 0.05$. Given the cross-sectional design of the study, the analyses evaluate associations and do not allow causal inferences.

RESULTS

Characteristics of the study population

The study cohort consisted of 170 school-aged children from the general population (49% female; mean age 6 years) (Supplemental Table S3). All anthropometric measurements showed values close to the reference average (50th percentile), and metabolic values were within the normal range.

Dietary questionnaires showed a total energy intake of 1718 ± 37 kcal/day. Among the dairy consumption of foods, there was a predominance of dairy, meat, vegetables, fruits, and cereals. Intake of ultra-processed foods (NOVA Group 4) represented 31% of total grams consumed, while fresh foods (NOVA Group 1) accounted for 62%. Children showed a moderate level of adherence to the Mediterranean diet with an average rMED score of 8 (range 0–16).

Physical activity questionnaires showed an average of 100 METs/day. The most energy was expended during movement-based activities such as climbing stairs, playing in the park or practising sports, and also sedentary activities, including sitting.

The neurocognitive test showed moderate to high cognitive performance, with scores mostly above the mean across all evaluated domains (range 1–19). Children demonstrated the highest performance in language, abstract reasoning, and

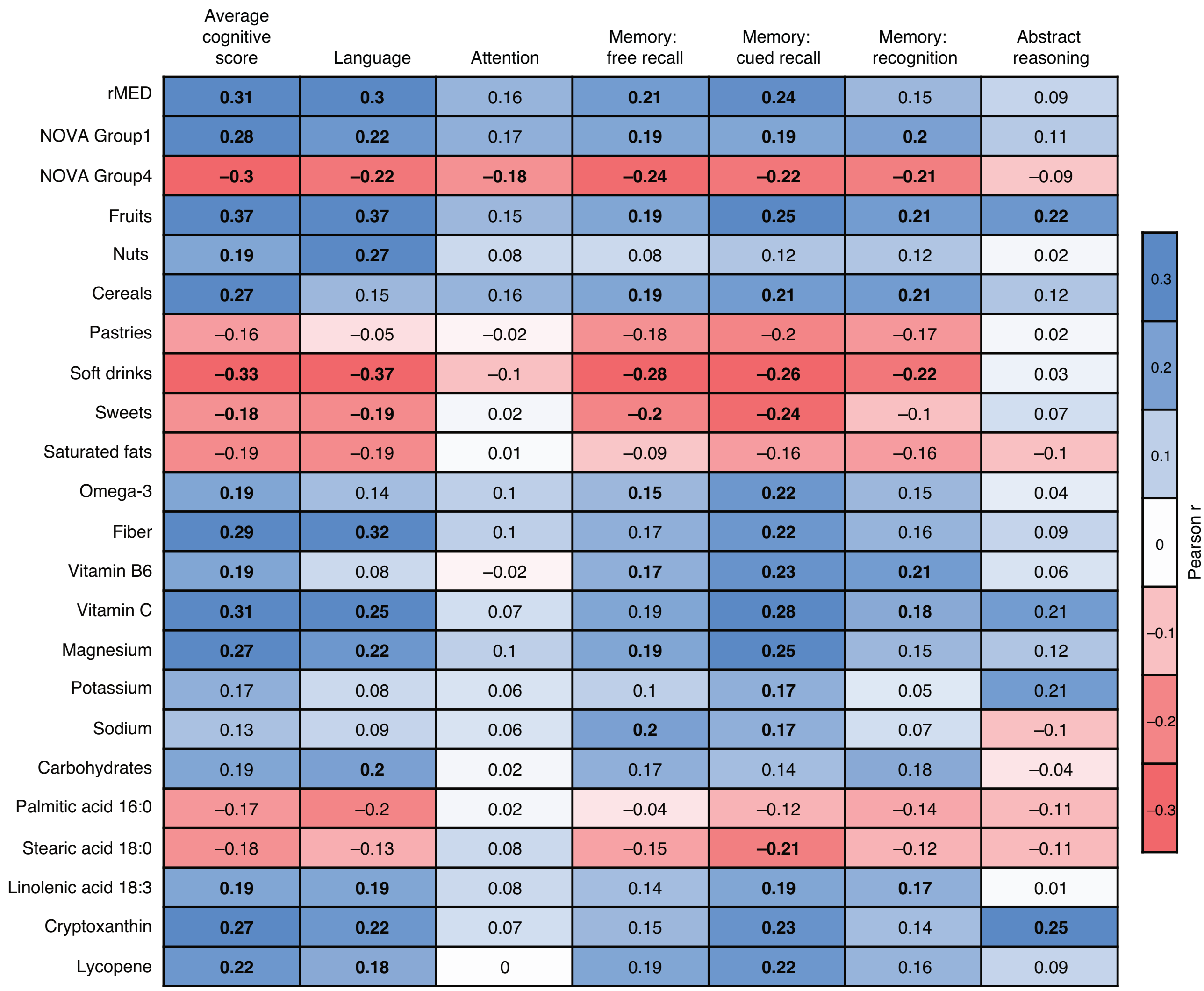

Fig. 1 Associations between cognitive function and dietary intake. Heatmap showing unadjusted Pearson correlation coefficients between cognitive function and dietary intake variables. Positive correlations are shown in blue and negative correlations in red. The color intensity reflects the strength of the correlation. Values in bold indicate associations that remained statistically significant after adjustment for age, sex, and BMI at 6 years. NOVA Group 1: fresh foods; NOVA Group 4: ultra-processed foods; rMED: relative Mediterranean diet score.

attention. Memory-related domains showed slightly lower but still average scores. These results indicate that the cognitive performance in the study population was generally within the expected range for age, without evidence of major impairments or developmental delays.

The socioeconomic indicators suggest a relatively high socioeconomic status within the study cohort, with about 50% of parents holding a university degree and 70% of families classified as having high economic status.

Associations of dietary intake with cognitive function

Unadjusted Pearson correlation analyses revealed several significant associations of dietary indices, food groups, and nutrients with various cognitive domains in the study population (Fig. 1).

Higher adherence to the Mediterranean diet (rMED score) was positively associated with average cognitive score ($r = 0.309$, $p < 0.001$) and with several cognitive domains, including language ($r = 0.296$, $p < 0.001$), free recall memory ($r = 0.208$, $p < 0.05$), and cued recall memory ($r = 0.242$, $p < 0.001$). Similarly, greater consumption of fresh foods (NOVA Group 1) was positively associated with average cognitive score ($r = 0.282$, $p < 0.001$) and multiple cognitive domains. Conversely, higher intake of ultra-processed foods (NOVA Group 4) showed significant negative associations with average cognitive score ($r = -0.302$, $p < 0.001$) and most cognitive domains [language, attention, memory (all $p < 0.05$)] except for abstract reasoning.

Intake of fruits showed positive associations across several cognitive domains, including average cognitive score ($r = 0.373$, $p < 0.001$), language, memory, and abstract reasoning (all $p < 0.05$). Nuts and cereals also demonstrated positive associations with average cognitive score and some domains (all $p < 0.05$). In contrast, consumption of soft drinks and sweets was negatively associated with average cognitive score and specific domains such as language and memory (all $p < 0.05$).

Positive correlations were observed between average cognitive score and nutrients such as omega-3 fatty acids, fiber, vitamin B6, vitamin C, magnesium, linolenic acid, and carotenoids (including cryptoxanthin and lycopene) (all $p < 0.05$). These associations were also evident across different cognitive domains, particularly in language and memory (most notably in free recall and cued recall tasks). Negative associations were observed with saturated fats, specifically palmitic and stearic acids.

Most of these associations remained statistically significant after adjustment for age, sex, and BMI (Fig. 1, bold values), while

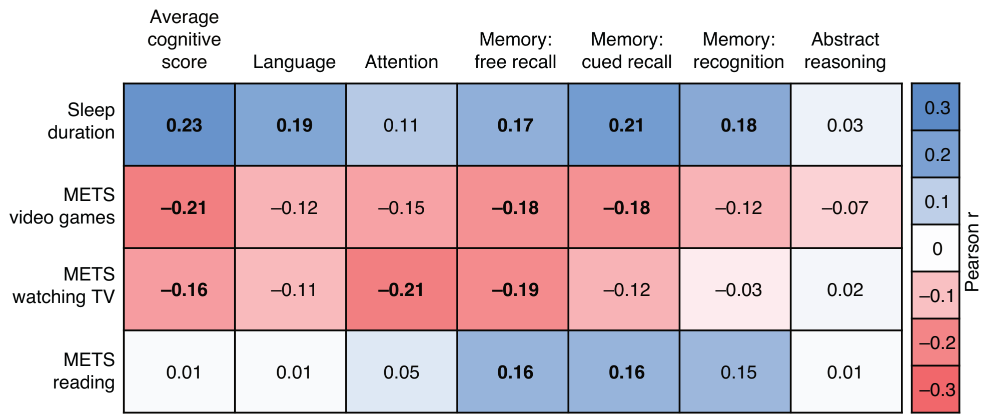

Fig. 2 Associations between cognitive function and physical activity. Heatmap showing unadjusted Pearson correlation coefficients between cognitive function and physical activity variables. Positive correlations are shown in blue and negative correlations in red. The color intensity reflects the strength of the correlation. Values in bold indicate associations that remained statistically significant after adjustment for age, sex, and BMI at 6 years. METS: metabolic equivalent of tasks; TV: television.

Fig. 3 Associations between cognitive function and metabolic parameters. Heatmap showing unadjusted Pearson correlation coefficients between cognitive function and metabolic parameters. Positive correlations are shown in blue and negative correlations in red. The color intensity reflects the strength of the correlation. Values in bold indicate associations that remained statistically significant after adjustment for age, sex, and BMI at 6 years. HOMA-IR: homeostatic model assessment for insulin resistance; GGT: gamma-glutamyltransferase; CRP: C-reactive protein.

associations with saturated fatty acids were attenuated; only stearic acid remained negatively associated with cued recall memory ($p < 0.05$).

Associations of physical activity and sleep with cognitive function

Unadjusted Pearson correlation analyses revealed no significant association between movement-based activities and cognitive function but identified significant relationships between sedentary behaviors and cognition (Fig. 2).

Sleep duration and reading were positively associated with cognitive outcomes. Sleep duration was associated with average cognitive score ($r = 0.230$, $p < 0.01$), language ($r = 0.187$, $p < 0.05$), memory domains (free recall: $r = 0.174$, $p < 0.05$; cued recall: $r = 0.212$, $p < 0.01$ and recognition ($r = 0.180$, $p < 0.05$). Reading showed weaker but significant associations with memory performance, particularly free recall ($r = 0.162$, $p < 0.05$) and cued recall ($r = 0.158$, $p < 0.05$).

In contrast, playing video games and watching TV were negatively associated with cognitive outcomes. Playing video games was negatively associated with average cognitive score ($r = -0.205$, $p < 0.01$), as well as with memory tasks, including free recall ($r = -0.175$, $p < 0.05$) and cued recall ($r = -0.178$, $p < 0.05$). Watching TV was inversely associated with average cognitive score ($r = -0.162$, $p < 0.05$) and showed significant negative associations with attention ($r = -0.205$, $p < 0.05$) and free recall memory ($r = -0.194$, $p < 0.05$).

All these associations remained statistically significant after adjustment for age, sex, and BMI (Fig. 2, bold values).

Associations of metabolic markers with cognitive function

Unadjusted Pearson correlation analyses revealed negative associations between metabolic parameters and cognitive function (Fig. 3).

Elevated HOMA-IR values were significantly associated with lower scores in overall cognitive performance ($r = -0.187$, $p < 0.05$), language ($r = -0.201$, $p < 0.01$) and all memory domains (free recall, cued recall, and recognition; all $p < 0.05$). Higher levels of GGT were negatively associated with average cognitive score ($r = -0.208$, $p < 0.01$), as well as free ($r = -0.244$, $p < 0.01$) and cued recall ($r = -0.226$, $p < 0.01$) memory. CRP was inversely associated with average cognitive score ($r = -0.152$, $p < 0.05$) and recognition memory ($r = -0.199$, $p < 0.05$). Additionally, triglycerides were negatively associated with memory recognition ($r = -0.215$, $p < 0.01$).

All these associations remained statistically significant after adjustment for age, sex, and BMI (Fig. 3, bold values).

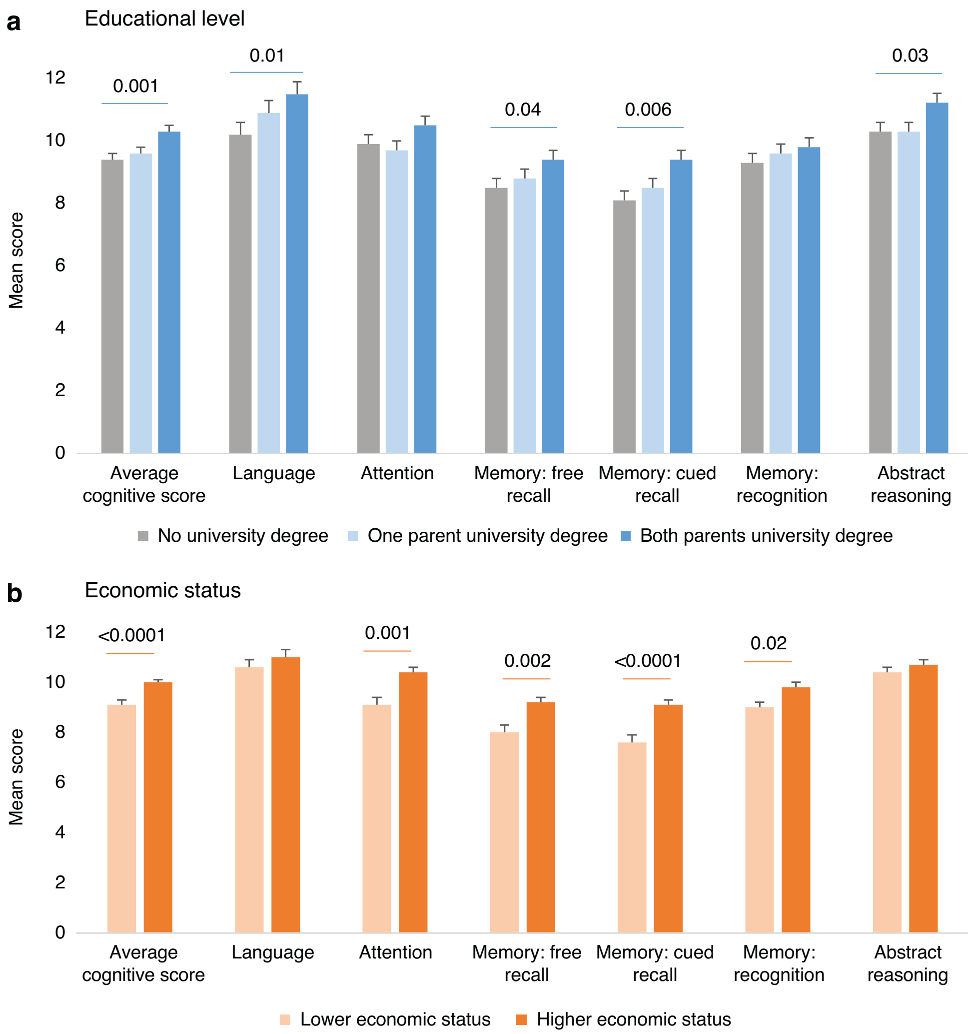

Fig. 4 Associations between cognitive function and socioeconomic status. Error bars showing mean cognitive scores across the evaluated cognitive domains, grouped by (**a**) parental education level: no university degree, one parent with university degree, and both parents with university degree, and (**b**) parental economic status: lower and higher. Differences between groups were tested using one-way ANOVA. P-values for trend is shown.

Associations of socioeconomic status with cognitive function

Cognitive function varied according to parental education level. Children whose parents had a university degree showed significantly higher cognitive function compared to those with parents without a university degree (Fig. 4a). A significant positive trend was observed across levels of parental education for the average cognitive score ($p = 0.001$), language ($p = 0.01$), memory (free recall: $p = 0.05$; cued recall: $p = 0.006$), and abstract reasoning ($p = 0.03$). Differences in attention and recognition memory were not statistically significant across groups.

Similarly, children from families with higher economic status demonstrated significantly better cognitive function compared to those from lower economic status households (Fig. 4b). Significant differences were observed for average cognitive score ($p < 0.0001$) and in specific cognitive domains, including attention ($p = 0.001$), memory free recall ($p = 0.002$), memory cued recall ($p < 0.0001$), and memory recognition ($p = 0.02$). No significant differences were found in language or abstract reasoning scores between economic groups.

Independent factors associated with cognitive function

Multivariate linear regression analyses were conducted to identify factors independently associated with cognitive function in average and across the different studied domains (Table 1). The analysis revealed that higher adherence to the Mediterranean diet (rMED; $\beta = 0.160$, $p = 0.05$), higher economic status ($\beta = 0.180$, $p = 0.04$), greater sleep duration ($\beta = 0.177$, $p = 0.03$) and reading (METS reading; $\beta = 0.197$, $p = 0.01$), and lower insulin resistance (HOMA-IR; $\beta = -0.185$, $p = 0.02$) were independently associated with better average cognitive score. The model explained approximately 30% of the variance in average cognitive score (adjusted $R^2 = 0.293$).

For specific cognitive domains, language was mainly explained by higher adherence to the Mediterranean diet (rMED; $\beta = 0.301$, $p < 0.0001$) and lower levels of HOMA-IR ($\beta = -0.194$, $p = 0.01$). Attention was explained by higher economic status ($\beta = 0.246$, $p = 0.004$) and less time watching TV ($\beta = -0.193$, $p = 0.02$). Free recall and cued recall showed similar patterns as were positively explained by economic status ($\beta = 0.213$, $p = 0.008$ and $\beta = 0.231$, $p = 0.004$), sleep duration ($\beta = 0.218$, $p = 0.009$ and $\beta = 0.170$, $p = 0.04$), and reading ($\beta = 0.269$, $p = 0.001$ and $\beta = 0.267$, $p = 0.001$), and negatively explained by GGT ($\beta = -0.205$, $p = 0.01$ and $\beta = -0.169$, $p = 0.03$) and HOMA-IR ($\beta = -0.158$, $p = 0.04$ and $\beta = -0.167$, $p = 0.05$). Recognition memory was positively explained by reading ($\beta = 0.226$, $p = 0.01$), and negatively explained by CRP ($\beta = -0.201$, $p = 0.02$) and HOMA-IR

Table 1. Multivariate linear regression analysis of factors associated with cognitive function.

	Average cognitive score		Language		Attention		Memory: Free recall		Memory: Cued recall		Memory: Recognition	
	Beta	***P-value***	***Beta***	***P-value***	***Beta***	***P-value***	***Beta***	***P-value***	***Beta***	***P-value***	***Beta***	***P-value***
rMED	0.160	0.04	0.301	<0.0001	--	--	--	--	--	--	--	--
Economic status	0.180	0.03	--	--	0.246	0.004	0.213	0.008	0.231	0.004	0.184	0.01
Sleep duration	0.177	0.03	--	--	--	--	0.218	0.009	0.170	0.04	--	--
METS reading	0.197	0.01	--	--	--	--	0.269	0.001	0.267	0.001	0.226	0.01
METS video games	--	--	--	--	--	--	--	--	--	--	--	--
METS TV	--	--	--	--	-0.193	0.02	--	--	--	--	--	--
GGT	--	--	--	--	--	--	-0.205	0.01	-0.169	0.03	--	--
CRP	--	--	--	--	--	--	--	--	--	--	-0.201	0.02
HOMA-IR	-0.185	0.02	-0.194	0.01	--	--	-0.158	0.04	-0.167	0.05	-0.186	0.03
Age	--	--	0.216	0.006	--	--	--	--	--	--	--	--
Sex	--	--	--	--	--	--	--	--	--	--	--	--
BMI	--	--	--	--	--	--	--	--	--	--	--	--
Adjusted R^2	0.293		0.209		0.165		0.275		0.290		0.213	

The table shows standardized beta coefficients (Beta) and corresponding *p*-values for variables significantly associated with the outcomes. R²: coefficient of determination indicating proportion of variance explained by the model. Only variables with statistically significant associations ($p < 0.05$) are presented. *rMED* relative Mediterranean Diet score, *METS* metabolic equivalent of tasks, *TV* television, *GGT* gamma-glutamyl transferase *CRP* C-reactive protein, *HOMA-IR* homeostatic model assessment of insulin resistance.

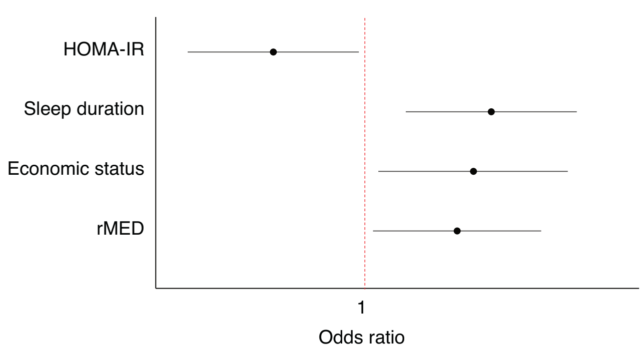

Fig. 5 Logistic regression model assessing factors associated with cognitive function. Forest plot showing odds ratios (OR) and 95% confidence intervals for the association between selected factors and average cognitive performance. The dashed red line indicates the null value (OR = 1). Values greater than 1 indicate a positive association with higher cognitive performance; values below 1 indicate a negative association. Variables included in the model: HOMA-IR (homeostasis model assessment of insulin resistance), sleep duration, economic status, and rMED (relative Mediterranean diet adherence).

(β = −0.186, $p = 0.03$) levels. Abstract reasoning was not significantly explained by any of the variables in the model. The proportion of explained variance for the domain-specific models ranged from 16.5% to 29.0% (Table 1).

Finally, we employed a logistic regression model to quantify their joint relationship with cognitive performance (Fig. 5). Adherence to the Mediterranean diet (rMED) was significantly associated with higher cognitive performance (OR = 2.18, 95% CI = 1.08–4.40, $p = 0.02$). Higher economic status was also independently associated with higher cognitive performance (OR = 2.50, 95% CI = 1.13–5.49, $p = 0.02$). Sleep duration was significantly associated with higher cognitive performance (OR = 2.90, 95% CI = 1.42–5.92, $p = 0.003$). In contrast, HOMA-IR was inversely associated with cognitive performance (OR = 0.47, 95% CI = 0.23–0.96, $p = 0.04$).

DISCUSSION

Our study provides comprehensive evidence that diet quality, lifestyle factors, metabolic health, and socioeconomic status were associated with cognitive function in school-aged children from the general population. Multivariate analyses identified that Mediterranean diet adherence, economic status, sleep duration, and insulin resistance (HOMA-IR) were the main factors independently associated with cognitive outcomes. These associations appeared domain-specific, being particularly associated with attention, language, and memory, while abstract reasoning showed no clear association.

Cognition and diet quality

Our findings suggest that higher adherence to the Mediterranean diet is positively associated with cognitive function in children. This aligns with previous research showing that the consumption of healthy fatty acids, vitamins, essential minerals, fiber, and carotenes has been associated with better cognitive outcomes in adults.[26] Moreover, the high intake of omega-3 fatty acids, abundant in oily fish and nuts, has been associated with increased cerebral blood flow and neuronal membrane function, which may be related to memory processes.[27] From an anatomical point of view, adherence to the Mediterranean diet has been linked to a healthier brain structure, especially increased gray and white matter volumes and improved connectivity.[28] The Mediterranean diet provides nutrients that have been associated with neurodevelopment, lower inflammation, and better vascular health, which may partly relate to cognitive outcomes.[29] In children, available evidence remains limited and inconclusive. While some studies have reported positive associations between adherence to the Mediterranean diet and cognitive performance in several domains, including memory, attention, language, creativity, and executive function, others have found no significant relationship.[7] This variability may reflect differences in study design, sample characteristics, or the methods used to assess diet and cognition.

UPF consumption has been consistently linked to adverse health outcomes across the lifespan, including cardiovascular, metabolic, and mental disorders.[30] In older adults, higher UPF consumption was linked to faster global cognitive decline.[31] In children, high consumption of UPF is associated with poorer cognitive development, particularly in areas such as attention, memory, and academic performance.[32,33] This evidence supports our findings, where higher consumption of unprocessed foods (NOVA 1) was associated with better cognitive function, while greater intake of UPF foods (NOVA 4) was associated with lower cognitive performance across most evaluated domains, including attention, memory, and language. Several mechanisms have been proposed that may explain the potential adverse effects of UPF on neurocognitive health. On one side, these products are typically deficient in essential nutrients critical for optimal brain development and functioning, while being rich in added sugars, refined carbs, unhealthy fats, and artificial ingredients, which have been associated with poorer cognitive outcomes.[34] For example, added sugars in UPFs may contribute to fluctuations in blood glucose levels, which could impair vascular function and oxygen delivery to the brain, potentially affecting memory and cognitive processing speed.[35] On the other side, various food additives commonly found in UPF, such as emulsifiers, artificial colors, and flavor enhancers, have been hypothesized to be associated with neurocognitive health through potential effects on neural signaling and brain regions involved in cognitive functions.[36]

Taken together, our findings suggest that dietary patterns and food processing may be associated with cognitive function through complementary pathways. While adherence to the Mediterranean diet reflects overall nutritional quality and was the main independent dietary determinant in multivariable analyses, ultra-processed food consumption showed consistent adverse associations in bivariate analyses, potentially reflecting associations with additional factors related to food processing, such as altered food matrix, additives, and metabolic dysregulation. As these measures capture related but distinct aspects of diet, they were not included simultaneously in multivariable models to avoid collinearity. This highlights the importance of considering both diet quality and degree of processing when evaluating nutritional factors associated with cognitive outcomes.

Cognition and lifestyle factors

Systematic reviews increasingly highlight that adequate sleep, elevated levels of physical activity, and reduced sedentary behavior have been associated with better cognitive development in children.[37–39] Sleep has been suggested to play a role in enhancing neuroplasticity and supporting the consolidation of memory through its effects on key physiological systems.[40] Similarly, physical activity has been associated with neurobiological processes such as angiogenesis, synaptogenesis, neurogenesis, and the upregulation of neurotrophic factors, mechanisms critical for brain development and function.[41] In contrast, excessive sedentary behavior may impair neurogenesis and synaptic plasticity.[42] Notably, recent research suggests that the cognitive associations of sedentary behaviors may differ depending on the activity. For instance, screen-based behaviors such as TV viewing have been associated with reduced white matter integrity in the brain,[43] whereas activities like reading may exert protective or even beneficial effects on cognitive functioning by enhancing neural connectivity and promoting brain plasticity, particularly in regions involved in language and memory.[44]

Our findings further support this evidence and show that sleep duration and reading were both positively associated with cognitive performance, particularly in memory-related tasks. In contrast, video gaming and television viewing were negatively associated with several cognitive domains, including attention and memory. Importantly, our multivariate models identified that sleep duration was independently associated with cognitive functioning, reinforcing the relevance of sleep in supporting brain health during development.

Unlike some previous studies, we did not find significant associations between cognitive outcomes and movement-based activities. A plausible explanation is the age of the children (6 years), as at this developmental stage, they are unlikely to engage in structured or intensive physical activity. Most children at this age tend to have similar levels of general movement or play, which may reduce variability and limit the ability to detect associations.

Beyond its independent association, socioeconomic status may also act as a broader contextual factor that shapes multiple health-related exposures, including dietary habits, lifestyle behaviors, and access to educational and environmental resources that support cognitive development. This interconnected role suggests that SES may partially underlie the observed associations between modifiable factors and cognitive outcomes.[18]

Cognition and metabolic health

Findings on the association between metabolic health and cognitive function in children and adolescents remain inconsistent. While metabolic syndrome has generally been associated with impairments across a range of cognitive domains,[45] individual studies report mixed results for specific components, with the most consistent evidence of negative effects seen for obesity and insulin resistance.[16] We found that higher blood biomarkers of poor metabolic health, including GGT, CRP, triglycerides, and mainly HOMA-IR, were associated with lower cognitive function in young children. These results contribute to the literature in children with type 1 and type 2 diabetes that demonstrates consistent and negative effects of poor metabolic health on cognition.[46,47] Furthermore, these results are consistent with studies in the general population in which elevated blood biomarkers, suggestive of poor metabolic health, were found to be associated with lower cognitive function on attention, memory, and language tests. For example, insulin resistance has been associated with poorer performance on cognitive tasks in obese children,[48] and healthy preschoolers,[17]. Elevated CRP has been associated with poorer cognitive function in adolescents,[49] and in adults, increased levels of CRP,[50] and GGT,[51] have been associated with cognitive decline. Even though associations between childhood obesity and cognitive function have been previously described,[1,52] in our population-based cohort, obesity parameters were not associated with cognitive functions. Other studies also failed to find significant associations of child BMI or waist circumference with cognitive functions.[17,53] The observed associations may reflect underlying biological mechanisms such as low-grade systemic inflammation, oxidative stress, and impaired energy metabolism in the brain. These data suggest that metabolic health, mainly insulin resistance, may represent an understudied factor associated with child cognitive development, and bring peripheral metabolism into focus as an early life course issue for developmental morbidity.

Cognition and socioeconomic status

In our study, we found that socioeconomic status, measured by parental education and family income, was significantly associated with cognitive function in children. This aligns with previous research indicating that socioeconomic factors are closely linked to cognitive, emotional, and health outcomes across the lifespan, with these associations beginning in early development and persisting into adulthood. Several mechanisms have been identified to explain this relationship. For instance, parents with higher levels of education are more likely to foster intellectually stimulating home environments, offer academic support, and provide greater exposure to language-rich interactions and learning opportunities.[54] On the other hand, higher family income has been associated with cognitive development by facilitating access to educational materials, extracurricular enrichment, nutritious food, and secure, resource-rich living environments.[55] Additionally, both parental education and family income have been related to brain structural development, particularly in areas involved in language acquisition, memory processing, and executive function.[56] Beyond its independent association with cognitive outcomes, socioeconomic status may also act as a broader contextual factor shaping dietary habits, lifestyle behaviors, and access to health-promoting resources, which may partially explain the interconnected associations observed in our study.

Domain-specific associations

In our study, diet, lifestyle, metabolic markers, and socioeconomic status were significantly associated with attention, language, and memory (including free recall, cued recall, and recognition), but abstract reasoning was not significantly explained by any of the variables in the model. This discrepancy may reflect differences in the neural substrates underlying these cognitive domains. Attention, language, and memory are domain-specific functions that rely on metabolically sensitive brain regions such as the prefrontal cortex, parietal cortex, and hippocampus, which may be more sensitive to the effects of nutritional status, inflammation, and metabolic dysregulation.[41,57] In contrast, abstract reasoning, a core component of fluid intelligence, is supported primarily by frontoparietal networks, particularly the dorsolateral prefrontal cortex and inferior parietal lobule, and tends to be more stable and less sensitive to short-term environmental factors.[58] This neurobiological distinction may explain why metabolic and lifestyle factors selectively impact certain cognitive functions but not others.

Strengths and limitations

This study offers several important strengths, including a comprehensive evaluation of diet quality, lifestyle factors, metabolic health, socioeconomic status, and multiple cognitive domains, which provides a multidimensional perspective on cognitive development in children. The use of validated assessment tools and biomarkers enhances the reliability of our findings, while the relatively large and well-characterized sample size increases statistical power. Additionally, multivariate modeling provides valuable insights into the relative associations of different factors with cognitive function, which may help inform future research and intervention strategies.

However, some limitations should be acknowledged. The cross-sectional design restricts causal inferences, highlighting the need for longitudinal research to clarify temporal relationships. Dietary and lifestyle data were self-reported, which may introduce recall bias or inaccuracies. Potential confounding variables such as home environment and parental cognitive abilities were not fully controlled. Moreover, the relatively high socioeconomic profile of the cohort and the geographically localized sample may limit the generalizability of the findings to more socioeconomically diverse pediatric populations. Lastly, although multiple cognitive domains were assessed, some areas, like executive function or processing speed, were not included and warrant further investigation. Furthermore, the composite cognitive score combined several distinct neurocognitive domains and should therefore be interpreted as a descriptive index of overall cognitive performance rather than as a psychometrically validated global cognition construct. In addition, given the exploratory nature of the study, the relatively modest sample size, and the large number of statistical comparisons performed, the possibility of type I error cannot be excluded and findings should therefore be interpreted with caution.

CONCLUSIONS

Our study provides evidence that diet quality, lifestyle factors, metabolic health, and socioeconomic status are associated with cognitive function in school-aged children from the general population. Specifically, adherence to the Mediterranean diet, sleep duration, insulin resistance, and socioeconomic status were key factors independently associated with cognitive function, particularly in attention, language, and memory domains. These findings highlight the potential relevance of nutritional, behavioral, and metabolic factors early in life in relation to brain development. Future longitudinal studies are needed to establish causal relationships and to further evaluate the potential relevance of these modifiable factors in relation to cognitive outcomes in children. In this context, our findings should be considered hypothesis-generating and may help inform the design of future longitudinal and interventional studies.

DATA AVAILABILITY

The datasets generated and/or analyzed during the current study are not publicly available due to privacy and ethical restrictions involving pediatric participants but are available from the corresponding author on reasonable request.

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COMPETING INTERESTS

The authors declare no competing interests.

PATIENT CONSENT

Written informed consent was obtained from the parents or legal guardians of all participating children prior to enrolment in the study.

ADDITIONAL INFORMATION

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