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Abstract

Background/Objectives: Adequate nutrient intake is crucial for cognitive development and academic performance in schoolchildren. This study assessed the association between dietary nutrient intake and cognition and academic performance in school-aged children from Taabo, Côte d'Ivoire. **Methods:** A total of 251 schoolchildren aged 6-12 years were randomly selected from seven public primary schools. Dietary intake was assessed using repeated 24-hour recalls, cognitive skills with Raven's Progressive Colored Matrices and academic performance using school results in mathematics and literature. **Results:** More than half of the participants had adequate intakes of vitamin A (55.8%) vitamin B6, (61.0%) vitamin B12 (61.0%) and omega-3 fatty acids (70.1%), while most had inadequate intakes of iron (96.8%), zinc (100%) thiamin (99.2%), riboflavin (99.6%) and folate (96.8%). Thiamin, riboflavin, folate, iron, zinc and a nutrient blend (iron, zinc, thiamin, riboflavin and folate) showed significant associations with cognitive scores ($p < 0.05$). Additionally, higher intakes of thiamin (AOR = 6.3; 95% CI: 2.5-16.0, $p < 0.001$) and riboflavin (AOR = 2.2; 95% CI: 1.5-7.8, $p = 0.003$) were linked to increased odds of better cognitive performance compared to lower intakes. No consistent associations were found with academic performance. **Conclusions:** Cognition-related micronutrients are largely inadequate among school-aged children involved in this study. While intakes of thiamin, riboflavin, folate, iron, zinc, and nutrient blend were significantly associated with cognition, no associations were found with academic performance. Further studies exploring such links are needed, especially those involving interventions.

Keywords: micronutrient intake; dietary intake; cognition; academic performance; school-aged children; Côte d'Ivoire

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1. Introduction

The school age (6-12 years) is the period of life between childhood and adolescence, accompanied by a rapid increase in the rate of cognitive development due to social stimulation, including but not limited to school environment [1]. Cognition is the ability to assimilate and process information received from different sources and convert them into knowledge [2]. Cognitive processes include learning, attention, memory, language, reasoning and decision making. For children, especially of school age, cognition is a building block required to obtain adequate academic

performance [3]. Cognitive functions, particularly fluid intelligence, play a crucial role in learning, memory, reasoning, problem solving and adapting to new situations, which are essential for overcoming challenges in the school setting [4]. Cognition is linked to brain structural development [5] and brain structural development can be influenced by nutrition, therefore cognitive functions can indirectly be influenced by nutrition [6]. Brain development undergoes a complex early life development that is modulated by genetics as well as the environment; for the latter, nutrition is one of the factors significantly contributing to it. Nutrients can influence gene expression by providing molecules essential to fulfil their roles in brain growth and development. Nutrients are also critical for neurogenesis, axon and dendrite extension, synaptogenesis, as well as myelination, all of which are fundamental processes for effective brain connectivity. Nutrients therefore operate at the intersection of biological and environmental determinants and play a central role in shaping brain architecture and function [7]. Thus, the quality and composition of children's diet can significantly influence how their learning potential can be realized.

Nutrients such as omega-3 fatty acids, iron, zinc iodine, vitamins A, thiamin, riboflavin, folate and vitamins B6 and B12 have been significantly associated with cognitive performance in school-aged children. Omega-3 fatty acids are the most important for brain and cognitive functions. Dietary intake of polyunsaturated fatty acids, especially omega-3 fatty acids, including DHA and eicosapentaenoic acid (EPA), is often inadequate in school-aged children and adolescents and an adequate intake in these fatty acids are critical for cognitive function growth and better academic performance [8]. Richardson et al. [9]have highlighted that omega-3 fatty acids supplementation increased reading abilities and alertness in school-age children. In addition, Lassek & Gaulin [10] have shown that an increase in n-3 fatty acid intake and a decrease in n-6 fatty acids in the diets is positively associated to cognitive performance in school-aged children.

Iron is also key nutrients for cognitive development and its role in brain has been largely studied. Iron is involved in several enzyme systems. It is involved in the cytochrome c oxidase enzyme system for energy production and in tyrosine hydroxylase for the synthesis of dopamine receptors. Delta-9 desaturase is involved in myelination and fatty acid synthesis, and ribonucleotide reductase regulates brain growth. Studies among school-aged children suggest that adequate iron status is beneficial for cognitive and academic performance [11]. A cross-sectional study in 389 school-aged children in Ghana showed that serum iron was correlated with cognitive performance [4]. Iron supplementation was has also been associated with improved cognitive and academic performance in children with anemia [12]. Thus, iron deficiency can affect brain functions and lead to poor academic performance.

Zinc is also vital nutrient for the brain, with important structural and functional roles. Zinc is a cofactor for over 200 enzymes that regulate various metabolic activities in the body, including protein, DNA and RNA synthesis. Zinc also plays a role in neurogenesis, the maturation and migration of neurons and the formation of synapses. Zinc is involved in the modulation of certain neurotransmitters, particularly glutamate and gamma-aminobutyric acid (GABA) receptors [13]. Zinc is essential for neurodevelopment and cognitive function. While zinc deficiency has been shown to negatively affect these processes, zinc supplementation does not consistently produce beneficial effects. A review of randomized studies involving school-aged children found that zinc deficiency may impair motor activity and neuropsychological functions, particularly reasoning, though evidence regarding its impact on general cognitive development remains inconsistent [14]. Moreover, a study in Brazil reported significant improvements in cognitive performance following zinc supplementation in schoolchildren [15], whereas a randomized controlled trial in Canada found no such effect [16].

Iodine is critical nutrient for metal functions which its deficiency is a major public health concerns in developing countries [17]. The relationship between iodine and cognitive development has been investigated in several studies. It is well established that iodine is crucial for thyroid hormones production which are involved many neurological processes. Iodine deficiency is associated with mental retardation, speech and hearing impairment [18]. Thus, an adequate iodine status is essential for optimal cognitive development in children. An iodine supplementation in 310

children aged 10 to 12 in Albania showed a significant improvement in cognitive and motor skills in iodine-deficient children [19].

B vitamins, especially, thiamin (vitamin B1), riboflavin (vitamin B2), folate (vitamin B9), vitamin B6 and vitamin B12, are also known as key nutrients associated with cognitive development. Thiamin acts as a coenzyme in glucose metabolism and neurotransmitter production (e.g., acetylcholine), making it vital for cognitive function, particularly in growing brains [20]. Riboflavin is involved in metabolism of carbohydrates, fats, proteins, energy production and the metabolism of other B vitamins, such as pyridoxine (vitamin B6), folate and niacin (vitamin B3) [21]. Folate is plays a crucial role in neurocognitive development, influencing key processes such as DNA synthesis, gene expression regulation, and neurotransmitter synthesis [22]. Folate, along with choline, acts as a methyl-donor nutrient, affecting brain development through DNA methylation mechanisms [23]. Vitamin B6 plays a critical role in neurotransmitter metabolism by facilitating the conversion of glutamate to γ-aminobutyric acid (GABA) and supporting the synthesis of serotonin and dopamine. Vitamin B6, together with folate and vitamin B12, contributes to the reduction of homocysteine, a neurotoxic amino acid associated with cognitive impairment and neurodegenerative risk [24,25]. Vitamin B12 is an important micronutrient found only in animal foods and is necessary for full brain development and cognition [26]. Research in developing countries has reported high rates of vitamin B12 deficiency in children, largely due to inadequate dietary intake. This deficiency can be associated with impaired cognitive development and stunted growth [27,28].

Vitamin A is also important for regulating neurodevelopmental pathways that can affect cognition [29]. Vitamin A deficiency in children can lead to serious consequences, including vision impairment, anaemia and poor immune system. However, in school-aged children, the evidence on the relationship between vitamin A and cognition is inconsistent across studies. In Ethiopia, vitamin A supplementation was associated with improved cognitive test scores [30], while in Nepal, vitamin A supplementation had no beneficial effect on cognition in school-aged children [31].

In Côte d'Ivoire, separate studies conducted in school-age children reported high prevalence of stunting (5.8-40%), vitamin A deficiency (31%) and iron deficiency (20-39%) [32–34]. Other studies have shown a significant influence of malnutrition and socio-demographic status on school performance [35,36], suggesting that the performance of these children could be linked to their dietary intake of the aforementioned nutrients or other not investigated yet. However, little is known especially regarding nutrient intake and cognitive function and academic performance in Ivorian schoolchildren, despite the high prevalence of malnutrition and micronutrient deficiencies reported. Therefore, the current study was conducted to assess the association between dietary nutrient intake and cognition and school performance in school-aged children in the Health and Demographic Surveillance System of Taabo, Côte d'Ivoire.

2. Materials and Methods

2.1. Study Design and Area

This study adopted a cross-sectional observational design. It was conducted between January and May 2023 in a sample of school-aged children aged 6 to12 years from the Health and Demographic Surveillance System (HDSS) of Taabo, Côte d'Ivoire.

The HDSS is located in the south-central region of Côte d'Ivoire approximately 150 km of Abidjan and 60 km of Yamoussoukro, the economic and political capitals of Cote d'Ivoire respectively [37]. The HDSS covers an area of 980 km² between 6°0' and 6°20' north latitude and 4°55' and 5°15' west longitude. The region has a tropical climate characterized by two rainy seasons (March to July and October to November) and two dry seasons (December to February and August to September). However, climate change has increasingly blurred the distinction between these seasons [38]. The average annual rainfall is about 284 mm, while the average temperature ranges between 27.6°C and 28.3°C. Relative humidity varies between 76.6% and 79.6%. The Taabo HDSS is predominantly rural and comprises 13 main villages, over 100 small hamlets and a small town called Taabo-Citée with a

population of 7,514. The total population of the HDSS is estimated at 57,189 [39]. Agriculture is the dominant economic activity, with staple crops including yams, bananas, maize and cassava, while cocoa and coffee are the main cash crops. Livestock (cattle, small ruminants, pigs and poultry) and fishing also contribute to the local economy. This study was conducted in in the small urban area of Taabo-cité or Barrage and in six villages which are Tokohiri, Ndenou, Ahouati, Leleblé, Ahouakro, Adikouassikro **(Figure 1)**.

2.2. Sample Size and Sampling Procedure

A total of 252 children aged 6 to12 years were recruited from seven public primary schools (PPS) in the HDSS area. The HDSS is administratively divided into three academic zones: zone A, zone B, and zone C. Seven government-owned schools namely Ahouakro, Tokohiri, N'Denou, Ahouati, Leleble, and Taabo-Barrage PPS were randomly selected within these zones, with proportional consideration given to the number of schools in each zone. In each selected school, 36 children from grades one to six were recruited, with six children per grade. A systematic random sampling method was used to select pupils within each grade using updated school enrolment lists, restricted to children in the required age range, provided by the teachers or headteachers.

2.3. Eligibility Criteria

Children aged 6 to 12 years who attended school in one of the seven selected PPSs within the Taabo HDSS were eligible to participate in the study. Children were excluded if parental or guardian consent was not obtained, if they were outside the age range, had any apparent disease or were enrolled in similar or nutrition intervention studies.

2.4. Sociodemographics and Anthropometrics

The sociodemographic information collected included the age, sex, school grade of the participants. Education level and occupation of parents or guardians were also collected. The age of each child was determined based on their birth date provided in the school records.
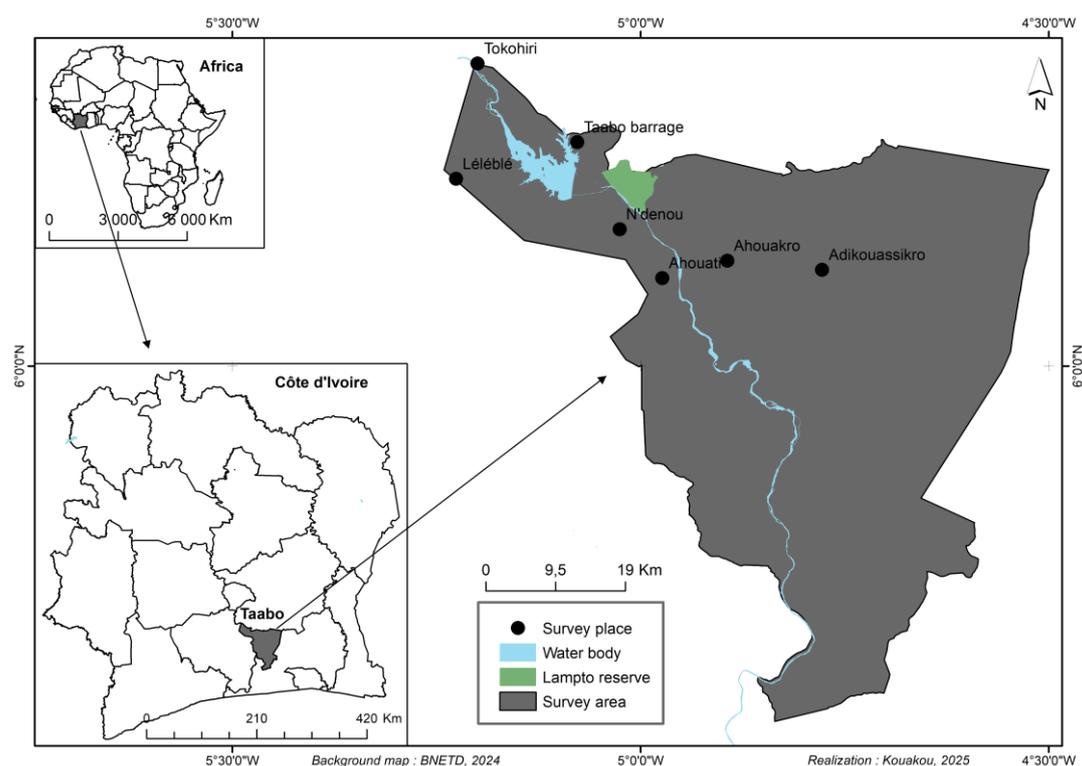
Figure 1. Map showing the study area located in the south-central region of Côte d'Ivoire.

For anthropometric data, height and weight of each child were measured according to the World Health Organization recommendations for children and adolescents (WHO 2011). Z-scores for each of the nutritional indicators, including BMI for age, weight for age and height for age, and the prevalence of wasting, stunting and thinness were calculated using the AnthroPlus software available on the WHO website [41]. All children below negative two standard deviations (SD) were considered to be underweight, stunted or wasted. Children between -2SD and +2 SD were considered to have normal status, while those above positive two standard deviations were considered to be overweight, overgrown and obese (Onis et al., 2007).

2.5. Dietary Intake Assessment

Dietary intake data were collected from participants on two non-consecutive weekdays. All foods and beverages consumed at home (including breakfast, lunch, dinner, and snacks) and outside the home were recorded. A pre-tested 24-hour dietary recall questionnaire was used, following the methodology described by Gibson & Ferguson [44] in the WHO Dietary Assessment Manual. According to this method, two non-consecutive 24-hour recalls were obtained from each child, with a minimum of two days between interviews. The first recall was conducted with all participants (n =

252), while 245 participants (97%) completed the second recall. Visual portion estimation tools, such as commonly used household measures and photographic food atlas, were used during data collection to help participants recall portion sizes consumed. Dietary intakes of iron, zinc, iodine, vitamin B6, folate, vitamin B12, vitamin A, eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) were estimated for each child using NutriSurvey software (Anderegg, 2008), which had been adapted to include local Ivorian foods. The dietary patterns of the children studied included both animal- and plant-based sources [45]. Therefore, nutrient bioavailability for iron and zinc was assumed to be moderate, in accordance with WHO/FAO guidelines [46]. Nutrient adequacy was assessed using the Recommended Dietary Allowances (RDAs) provided by WHO/FAO in 2004 for micronutrients [46] and by the European Food Safety Authority for omega-3 fatty acids [47]. Due to substantial variability, nutrient intake was categorized into tertiles based on the distribution of each nutrient: lower ($\leq$ 33.3rd percentile), medium (33.4th-66.7th percentile) and higher tertiles (> 66.7th percentile).

2.6. Cognitive Skills Assessment

Cognitive assessment was carried out using the Raven's Coloured Progressive Matrices (RCPM). The RCPM, a widely used test of non-verbal intelligence, was chosen for its cultural fairness and its ability to assess fluid cognitive abilities, which are crucial for academic performance [4]. To ensure that all children understood the tasks, test instructions were first given in French and then translated into the local language. Individual test sessions were conducted without a time limit, following the standard procedure outlined in the test manual [48]. The test consisted of presenting participants with a matrix of symbols and asking them to identify the missing symbol from a set of six options. Each correct answer was worth one point, and the total score was calculated by summing the correct answers, with a maximum possible score of 36 points. As there is no local norm of the RCPM for Ivorian children, cognitive performance was defined as low if less than the 50th percentile, medium if between the 50th and 75th percentiles, and high if equal to or greater than the 75th percentile [49]. The corresponding threshold scores were (low < 14, medium 14-18, high $\geq$ 18).

2.7. Academic Performance Assessment

Academic performance was assessed based on participants' average scores in mathematics and literature at the end of the 2023-2024 school year. Using a method adapted from Ateillah et al.[50] to fit the local context, three performance levels were defined: low performance for average scores below 5 out of 10, medium performance for scores between 5 and 7 (out of 10), and high performance for scores above 7 out of10. Noteworthy, in Côte d'Ivoire, the minimum required average score for primary school is 5 out of 10.

2.8. Statistical Analysis

Data were analyzed using the Statistical Package for the Social Sciences version 20.0 (SPSS IBM Inc). Categorical variables were summarized using frequencies and percentages, while continuous variables were expressed as means ± standard deviations (SD). Principal component analysis (PCA) was applied to identify nutrients associated with cognitive or school performance. Mean scores in the cognitive test and academic outcomes (mathematics and literature) were compared across sociodemographic, anthropometric and dietary intake groups (lower and higher tertiles) using the Kruskal-Wallis test, with the Mann-Whitney U test used for two-group comparisons. Chi-squared tests (χ^2) were conducted to assess associations between categorical variables. Spearman's rank correlation coefficients were computed to examine the relationships between nutrient intake, cognitive scores and academic performance. Nutrients that showed significant correlations with cognitive test scores or academic performance were combined into a composite variable: "nutrient blend". A multivariable logistic regression was further conducted to identify factors associated to cognitive and school performance among the study participants. Variables which were significantly

(p < 0.05) associated with cognition or school performance in the bivariable analyses were selected for the logistic regression models. All models were adjusted for maternal education level and father's occupation. No correction for multiple comparisons was applied; instead, unadjusted p-values were considered, with significance set at p < 0.05.

3. Results

3.1. Sociodemographic and Anthropometric Characteristics

As shown in **Table 1**, 16.7% of school-aged children were enrolled in each school grade. Among the children recruited, 116 (46.2%) were female and 135 (53.8%) were male. The mean age was 9.3 ± 1.9 years (range: 6-12 years). Age distribution was as follows: 35.1% were aged 6-8 years, 30.3% were aged 9-10 years, and 34.7% were aged 11-12 years. The majority of participants (80.5%) came from large households (more than five members), and most (97.2%) lived with their parents. Regarding paternal characteristics, 79.3% of fathers worked in the primary sector (e.g., agriculture), and most had completed only primary education. In contrast, 60.6% of mothers were housewives with no formal education. Approximately 72.5% of the children reported eating lunch at the school cafeteria. Additionally, 90% revised their coursework for 30-60 minutes after school (classified as moderate study duration). More than half of the children (56.7%) had never repeated a school grade.

For anthropometrics, the mean z-scores were -0.49 (SD ± 1.15) for BMI-for-age, -0.32 (SD ± 1.19) for weight-for-age and -0.08 (SD ± 1.78) for height-for-age as compared to WHO reference mean **(Table A1)**. The BMI-for age of the children was slightly lower (around 2% deviation) when compared with WHO growth standard whereas the height for age and weight for age was largely lower (more 5 % deviation) compared to WHO growth standard **(Figures A1, A2 and A3)**. The prevalence of stunting, underweight and wasting were 11.6 %, 10. 1 % and 9.2% respectively. The percentage of participants having any kind of under nutrition (stunting, wasting and underweight) was 30.9%.

Table 1. Comparison of mean scores in cognitive and school performance across sociodemographic and anthropometric groups.

Variable	N	%	Cognition			Mathematics			Literature		
			Mean ± SD		p-value	Mean ± SD		p-value	Mean ± SD		p-value
Gender											
Female	116	46.2	14.9 ± 4.5 [a]		0.046[*]	5.9 ± 2.3		0.807[*]	5.5 ± 1.8		0.624[*]
Male	135	53.8	15.8 ± 4.3 [b]			6.0 ± 2.4			5.4 ± 1.8		
Age											
6-8 years	88	35.1	13.1 ± 2.7 [b]		< .001	6.8 ± 2.8[a]		< .001	5.9 ± 1.9[a]		0.002
9-10 years	76	30.3	15.9 ± 4.9 [a]			5.4 ± 2.1[b]			5.4 ± 1.8[ab]		
11-12 years	87	34.7	17.1 ± 4.4 [a]			5.6 ± 1.9[b]			5.0 ± 1.6[b]		
Absence in class											
Never	70	27.9	15.5 ± 4.9		0.807	6.0 ± 2.6		0.516	5.5 ± 2.0		0.874
1-3 days	157	62.5	15.3 ± 4.2			6.0 ± 2.2			5.4 ± 1.7		
More than 3 days	24	9.6	15.6 ± 3.8			5.4 ± 2.4			5.3 ± 1.8		
Grade repetition											
Never	141	56.2	15.3 ± 4.3		0.753	6.0 ± 2.5		0.114	5.7 ± 1.9[a]		0.04
Once	87	34.7	15.2 ± 3.9			6.1 ± 2.1			5.2 ± 1.6[a]		
More than once	23	9.2	16.5 ± 6.1			5.1 ± 2.2			4.9 ± 1.6[a]		
Household size											
Small (≤5)	49	19.5	15.7 ± 5.0		0.953[*]	6.1 ± 2.3		0.682[*]	5.6 ± 1.9		0.692[*]
Large (> 5)	202	80.	15.3 ± 4.2			5.9 ± 2.4			5.4 ± 1.8		
Duration (min)											
Short (≤ 30 min)	7	2.8	13.9 ± 2.3		0.284	6.6 ± 2.9		0.720	5.0 ± 1.6		0.284
Medium (30-60 min)	226	90.0	15.3 ± 4.3			5.9 ± 2.4			5.4 ± 1.8		
Long (≥ 60 min)	18	7.2	17.1 ± 5.4			6.2 ± 1.5			5.8 ± 1.6		
School canteen											
No	69	27.5	14.8 ± 4.4		0.085[*]	5.8 ± 2.6		0.962	5.5 ± 2.1		0.966

	N	%	Mean ± SD	p	Mean ± SD	p	Mean ± SD	p
Yes	182	72.5	15.6 ± 4.4		6.0 ± 2.3		5.4 ± 1.7	
Live with parents								
No	7	2.8	15.3 ± 4.6	0.930[*]	4.8 ± 1.9	0.194[*]	4.9 ± 1.1	0.534[*]
Yes	244	97.2	15.4 ± 4.4		6.0 ± 2.4		5.4 ± 1.8	
Mother's occupation								
Tertiary sector	24	9.6	15.9 ± 4.8	0.566[*]	6.2 ± 2.3	0.680[*]	5.4 ± 1.8	0.664[*]
Housewife	227	90.4	15.3 ± 4.3		5.9 ± 2.4		5.4 ± 1.9	
Mother's education								
Higher	5	2.0	17.8 ± 7. 1[a]	0.018	5.7 ± 1.2	0.419	5.8 ± 1.6	0.619
Illiterate	114	45.4	14.6 ± 4.2[a]		6.1 ± 2.4		5.4 ± 1.8	
Primary	88	35.1	15.8 ± 4.3 [a]		5.7 ± 2.4		5.3 ± 1.8	
Secondary	44	17.5	16.3 ± 4.3 [a]		6.1 ± 2.2		5.8 ± 1.9	
Father's occupation								
Primary sector	200	79.7	15.2 ± 4.5	0.272	6.0 ± 2.4	0.322	5.4 ± 1.8[a]	0.023
Secondary sector	10	4.0	16.2 ± 5.2		4.9 ± 2.4		4.3 ± 1.2[a]	
Tertiary sector	41	16.3	15.8 ± 3.5		6.2 ± 2.3		5.9 ± 1.7[b]	
Father's education								
Higher	21	8.4	16.2 ± 4.5	0.575	6.3 ± 2.3	0.688	5.9 ± 1.7	0.094
Illiterate	65	25.9	15.0 ± 4.5		6.1 ± 2.5		5.4 ± 1.7	
Primary	102	40.6	15.2 ± 4.4		5.8 ± 2.4		5.1 ± 1.8	
Secondary	63	25.1	15.8 ± 4.3		6.0 ± 2.3		5.8 ± 1.8	
School grade								
Grade 1	42	16.7	13.0 ± 2.0 [b]	< .001	6.8 ± 3.2[a]	< .001	5.9 ± 2.0[ab]	0.004
Grade 2	42	16.7	12.6 ± 2.4 [b]		6.8 ± 2.4[ab]		5.9 ± 1.2[a]	
Grade 3	42	16.7	14.5 ± 3.3 [b]		5.0 ± 2.1[c]		4.9 ± 1.9[b]	
Grade 4	41	16.3	16.1 ± 4.2 [a]		5.2 ± 2.1[b]		5.0 ± 1.6[b]	
Grade 5	42	16.7	18.1 ± 5.5 [a]		5.8 ± 1.7[ab]		5.3 ± 2.0[ab]	

	N	%									
Grade 6	42	16.7	18.0 ± 4.4 [a]		6.3 ± 1.8[ab]		5.5 ± 1.7[ab]	
Weight for age								
Underweight	11	8.8	13.1 ± 1.7	0.226	4.7 ± 3.0[a]	0.035	5.3 ± 1.8	0.562
Normal	235	90.8	15.5 ± 4.4		6.0 ± 2.3[ab]		5.4 ± 1.8	
Overweight	5	0.4	15.7 ± 5.0		7.8 ± 1.4[b]		5.8 ± 1.7	
Height for age								
Stunting	19	8.8	17.5 ± 6.0	0.172	5.6 ± 2.6	0.774	11.2 ± 3.4	0.188
Normal	214	84.9	15.2 ± 4.2		6.0 ± 2.3		5.5 ± 1.8	
Overgrowth	18	0.4	15.8 ± 4.2		5.6 ± 2.4		4.9 ± 1.5	
BMI for age								
Thinness	23	9.2	15.9 ± 4.3	0.816	5.9 ± 2.5	0.976	5.8 ± 2.0	0.570
Normal	224	90	15.3 ± 4.4		6.0 ± 2.3		5.4 ± 1.7	
Overweight/Obesity	2	0.8	17.5 ± 7.8		6.3 ± 2.4		6.4 ± 1.9	

Note. Values are presented as frequency (N) and percentage (%) for categorical variables, as unadjusted means ± standard deviation (SD) and standard error (SE) for cognitive scores, and scores in mathematics and literature, stratified by sociodemographic and anthropometric categories. Group differences were assessed using the Kruskal-Wallis test. For comparisons involving two groups, the Mann-Whitney U test was applied. Statistical significance was set at $p < 0.05$. Values sharing the same letter within a column do not differ significantly based on Dunn's post hoc test p-values ($p < 0.05$). *p-value from Mann-Whitney U test.

3.2. Cognitive and School Performance

The average score obtained by the children on the cognitive test was 15.37 ± 4.38 (out of a maximum of 36) with the majority (43.4%) having low performance (score below the 50th percentile). For school performance, the mean scores were 5.96 ± 2.36 for mathematics and 5.43 ± 1.79 for literature (out of a maximum of 10 for both). The majority of the children in mathematics (44.2%) and literature (47.8%) had medium performance (Score between 5 and 7 out of 10). The threshold scores for both mathematics and literature were low < 5, medium 5-7, high > 7 respectively **(Table A1)**.

3.3. Cognitive and Academic Performance by Sociodemographic and Anthropometric Characteristics

Cognition test scores and school performance across the different sociodemographic and anthropometric groups are presented in Table 1. Comparisons of cognitive scores revealed statistically significant differences by sex, age group, and school grade. Using the Mann-Whitney U test, boys and girls differed in their cognition scores (p = 0.046). Kruskal-Wallis tests indicated highly significant differences across age groups (p < 0.001) and school grade levels (p < 0.001). After adjusting for covariate such as maternal education and father's occupation, girls had significantly lower odds of achieving high cognitive scores compared to boys (AOR = 0.6, 95% CI 0.3-0.9, p = 0.048) indicating that girls were 40% less likely than boys to attain higher cognitive performance. In addition, cognitive performance improved with age. Children aged 11-12 years were more than twice as likely to score above the 50th percentile on the cognitive test compared to those aged 9-10 years, while younger children (6-8 years) were significantly less likely to do so (AOR = 0.4; 95% CI: 0.2-0.8; p = 0.010). School grades were also significantly associated with cognitive performance. Compared to children in grade six, those in lower grades demonstrated reduced odds of cognitive performance. Specifically, children in grades one (AOR = 0.1, 95% CI: 0.05-0.4, p < 0.001), two (AOR = 0.1, 95% CI: 0.0-0.3, p < 0.001), and three (AOR = 0.2, 95% CI: 0.1-0.5, p < 0.001) showed significantly lower adjusted odds.

Regarding academic performance, significant differences in mean scores were observed across age groups, grade levels and schools in mathematics and literature or in both. Children aged 6-8 years recorded significantly higher mean scores in mathematics (p < 0.001) and literature (p = 0.002) compared to their older peers aged 9-10 and 11-12 years. At the school level, children from Ahouati and Adikouassikro primary schools demonstrated the highest performance in literature. For school grade, the logistic regression analysis revealed negative associations for children in grade three (AOR = 0.2; 95% CI: 0.1–0.6; p = 0.004) and grade four (AOR = 0.3; 95% CI: 0.1-0.9; p = 0.029), indicating reduced odds of performing above the 50th percentile in mathematics relative to grade six. In literature performance, children in grade two demonstrated significantly higher odds of achievement compared to those in Grade Six (AOR = 4.1; 95% CI: 1.3-12.7; p = 0.014). No statistically significant differences were observed among the other grades.

Anthropometric characteristics analysis showed a significant difference (p < 0.035) between weight-for-age groups (underweight, normal weight and overweight) in mathematics. However, in the adjusted analysis, no association was observed between weight-for-age status and mathematics either with cognitive score or literature performance among the participants.

3.4. Associations Between Nutrient Intake and Cognitive or Academic Performance

Daily nutrient intakes, the proportion of participants with adequate and inadequate intakes, and the distribution across the lower, medium and higher tertiles are provided in **Table 2**. The majority of participants had an inadequate intake of most nutrients assessed, with 99.2% for vitamin B1, 99.6% for vitamin B2, 96.8% for folate and 96,8% for iron. While zinc intake was inadequate in all children (100%), iodine intake was adequate in all the participants. Moreover, more than half of the children had adequate intake of vitamin A (55.8%), vitamin B12 (61.0%) and omega-3 fatty acids (70.1%)

The principal component analysis (PCA) showed that all assessed nutrients were found along one component with cognitive test scores, but not along the other component which contained the two outcomes from school performance **(Figure A5)**. Comparison of median cognitive test scores using the Mann-Whitney U test revealed significant differences ($p < 0.05$) between children in the lowest and highest tertiles for thiamin, riboflavin, folate, iron, zinc and nutrient blend. In addition, significant associations between intake of these micronutrient and cognitive test scores were observed using Chi-square test and Spearman's rank correlation (rho), as presented in **Tables 3** and **Table A3**. Children in the highest tertile of thiamin ($\chi^2 = 20.8$, $p < 0.001$), riboflavin ($\chi^2 = 12.6$, $p = 0.002$), folate ($\chi^2 = 10.4$, $p = 0.006$), iron ($\chi^2 = 7.1$, $p = 0.029$), zinc ($\chi^2 = 6.8$, $p = 0.033$), and the nutrient blend ($\chi^2 = 7.5$, $p = 0.024$) exhibited significantly better cognitive performance, with a higher proportion scoring above the 75th percentile compared to those in the lowest tertile. In the multivariable logistic regression analysis adjusted for maternal education and paternal occupation, children in the highest tertile of thiamin intake (AOR = 6.3; 95% CI: 2.5-16.0; $p < 0.001$) and riboflavin intake (AOR = 2.2; 95% CI: 1.5-7.8; $p = 0.003$) had significantly higher odds of achieving better cognitive performance compared to those in the lowest tertile.

Concerning academic performance, thiamin ($\chi^2 = 7.9$, $p = 0.019$) and zinc ($\chi^2 = 9.7$, $p = 0.008$) intakes were significantly associated with literature performance. Among children in the lowest tertile of thiamin and zinc intake, the majority (52.0 % for thiamin and 60.0% for zinc) scored between 5 and 7 out of 10 (medium performance). Un expectedly, in the adjusted analysis, children with higher intakes of thiamin (AOR = 0.30; 95% CI: 0.10-0.60; $p = 0.002$) and zinc (AOR = 0.40; 95% CI: 0.20-0.70; $p = 0.005$) showed decreased odds of better literature performance compared to those in the lowest tertile. No significant associations were observed for vitamin A, riboflavin, folate, iron, iodine, omega-3 fatty acids, or the nutrient blend **(Table 4)**.

Table 2. Mean of daily nutrient intake, percentage of adequate and inadequate intakes and distribution across tertiles.

Nutrient intake	Mean	±	SD	Adequate		Inadequate		1st tertile		2nd tertile		3rd tertile	
				N	%	N	%	N	%	N	%	N	%
Vitamin A (μg)	1170.7	±	1278.1	140	55.8	111	44.2	84	33.5	84	33.5	83	33.1
Vitamin B1 (mg)	0.4	±	0.2	2	0.8	249	99.2	98	39.0	113	45	40	15. 9
Vitamin B2 (mg)	0.3	±	0.2	1	0.4	250	99.6	94	37.5	112	44.6	45	17. 9
Folic acid (μg)	116.1	±	67.3	1	0.4	250	99.6	84	33.5	85	33.9	82	32.7
Vitamin B12 (μg)	2.6	±	1.8	153	61.0	98	39. 0	92	36.7	77	30.7	82	32.7
Vitamin B6 (mg)	3.6	±	4.6	160	63.7	91	36.3	98	39.0	72	28.7	81	32.3
Iron (mg)	2.0	±	1.7	8	3.2	242	96.8	83	33.1	85	33.9	83	33.1
Zinc (mg)	2.3	±	1.0	0	0	251	100	85	33.3	86	34.3	80	31.9
Iodine (μg)	691.1	±	416.9	251	100	0	0	83	33.1	85	33.9	83	33.1
Omega-3 fatty acids (g)	0.4	±	0.4	176	70.1	75	29.9	128	51.0	61	24.3	62	24.7
Nutrient blend	123.0	±	69.3	NA	NA	NA	NA	84	33.5	84	33.5	83	33.1

Note: Values are presented as mean ± standard deviation for daily nutrient intake, and as frequency (N) and percentage (%) for adequacy and tertile distribution. Nutrient adequacy was determined using WHO/FAO Dietary Reference Intakes (2004), except for iron and omega-3 fatty acids, for which reference values from the Institute of Medicine (IOM, 2005) and the European Food Safety Authority (EFSA, 2010) were used respectively.

Table 3. Distribution of cognitive and academic performance across among the lower and higher tertiles of nutrient intakes.

Nutrient intake tertile	Cognition					Mathematics					Literature				
	Above75th	50th75th	Below 50th	χ2	*p*	Above 7/10	5/10-7/10	Below 5/10	χ2	*p*	Above 7/10	5/10-7/10	Below 5/10	χ2	*p*
Vitamin A (μg)															

Higher tertile	27(32.5)	30(36.1)	26(31.3)	3.4	0.181	18(21.7)	40(48.2)	25(30.1)	3.6	0.166	14(16.9)	33(39.7)	36(43.4)	3.0	0.228
Lower tertile	22(26.2)	24(28.6)	38(45.2)			29(34.5)	36(42.9)	19(22.6)			15(51.7)	43(56.6)	26(41.9)		
Vitamin B1 (mg)															
Higher tertile	20(50.0)	13(32.5)	7(17.5)	20.8	<.001	8(20.0)	20(50.0)	12(30.0)	2.5	0.274	5(12.5)	13(32.5)	22(55.0)	7.9	0.019
Lower tertile	18(18.4)	24(24.5)	56(57.4)			33(33.7)	42(42.9)	23(23.5)			18(18.4)	51(52.0)	29(29.6)		
Vitamin B2 (mg)															
Higher tertile	19(42.2)	13(28.9)	13(28.9)	12.6	0.002	10(22.2)	23(51.1)	12(26.7)	1.3	0.522	6(13.3)	18(40.0)	21(46.7)	2.9	0.238
Lower tertile	16(17.0)	25(26.6)	53(56.4)			29(30.9)	40(42.6)	25(26.6)			15(16.0)	49(52.1)	31(31.9)		
Folate (µg)															
Higher tertile	32(39.0)	21(25.6)	29(35.4)	10.4	0.006	22(26.8)	36(43.9)	24(29.3)	0.4	0.833	14(17.1)	34(41.5)	34(41.5)	2.1	0.350
Lower tertile	14(16.7)	28(33.3)	42(50.0)			26(31.0)	34(40.5)	24(28.6)			13(15.5)	44(52.4)	27(32.1)		
Vitamin B12 (µg)															
Higher tertile	23(28.0)	23(28.0)	36(43.9)	0.2	0.886	22(26.8)	37(45.1)	23(28.0)	0.1	0.977	13(15.9)	38(46.3)	31(37.8)	0.1	0.964
Lower tertile	23(25.0)	41(44.6)	28(30.4)			26(28.3)	41(44.6)	25(28.3)			16(17.4)	42(45.7)	34(37.0)		

Vitamin B6 (mg)															
Higher tertile	18(22.2)	21(25.9)	42(51.9)	1.5	0.482	18(22.2)	41(50.6)	22(27.2)	3.2	0.207	12(14.8)	38(46.9)	31(38.3)	0.77	0.719
Lower tertile	25(25.1)	31(31.6)	42(42.9)			30(30.6)	37(37.8)	31(31.6)			17(17.4)	49(50.0)	32(32.6)		
Iron (mg)															
Higher tertile	45(30.0)	49(32.7)	56(37.3)	7.1	0.029	38(25.3)	66(44.0)	46(30.7)	0.3	0.856	26(17.3)	67(42.1)	56(37.3)	2.2	0.337
Lower tertile	12(14.5)	25(30.1)	46(55.4)			22(26.5)	46(47.0)	22(26.5)			11(13.3)	43(51.8)	29(34.9)		
Zinc (mg)															
Higher tertile	30(37.5)	25(31.3)	25(41.5)	6.8	0.033	20(25.0)	38(47.5)	22(27.5)	1.2	0.548	12(15.0)	29(36.3)	39(48.8)	9.7	0.008
Lower tertile	17(20.0)	29(34.1)	39(45.9)			27(31.8)	34(40.0)	24(28.2)			10(11.8)	51(60.0)	24(28.2)		
Iodine (µg)															
Higher tertile	26(31.3)	24(28.9)	33(39.8)	1.0	0.605	20(24.1)	38(45.8)	25(30.1)	2.0	0.366	10(12.0)	45(54.2)	28(33.7)	2.9	0.236
Lower tertile	21(25.3)	29(34.9)	33(39.8)			28(33.7)	35(42.2)	20(24.1)			17(20.5)	36(43.4)	30(36.1)		
Omega-3 fatty acids (g)															
Higher tertile	20(32.3)	13(21.0)	64(46.8)	4.0	0.133	16(25.8)	26(41.9)	20(32.3)	0.4	0.816	7(11.3)	31(50.0)	24(38.7)	1.1	0.567
Lower tertile	45(23.8)	64(33.9)	80(42.3)			51(27.0)	85(44.9)	53(28.0)			32(16.9)	89(47.1)	68(36.0)		

Nutrient Blend															
Higher tertile	31(37.3)	22(26.5)	30(36.1)	10.3	0.006	23(27.7)	36(43.4)	24(28.9)	0.33	0.849	15(18.1)	34(41.0)	34(41.0)	2.22	0.329
Lower tertile	13(15.5)	29(34.5)	42(50.0)			26(30.9)	33(39.3)	25(29.8)			13(15.5)	44(52.4)	27(32.1)		

Note. Data are presented as frequency (N) and percentage (%). Associations nutrients intakes with cognition and school performance were assessed using the chi-squared (χ^2) test. Statistical significance was defined as $p < 0.05$. χ^2 = chi-squared test statistic. p= chi-squared (χ^2) test p-value.

Table 4. Binary logistic regression of sociodemographic and nutritional factors associated with cognitive test scores and school performance above 50th percentile and 5 out 10 respectively.

Variable	Cognition			Mathematics			Literature		
	AOR	95% C. I	p-value	AOR	95% C. I	p-value	AOR	95% C. I	p-value
Gender									
Girls	0.6	(0.3-0.9)	0.048	1.2	(0.7-2.1)	0.584	1.2	(0.7-2.0)	0.541
Boys		Reference							
Age groups									
6-8 years	0.4	(0.2-08)	0.010	1.9	(0.9-3.3)	0.073	1.8	(0.9-3.5)	0.103
11-12 years	2.2	(1.1-4.2)	0.024	1.1	(0.6-2.1)	0.784	0.5	(3.0-1.0)	0.054
9-10 years		Reference							
School grade									
Grade one	0.1	(0.5-0.4)	<.001	0.8	(0.3-2.2)	0.59	1.2	(0.7-4.6)	0.235
Grade two	0.1	(0.-0.3)	<.001	1.7	(0.5-5.8)	0.369	4.1	(1.3-12.7)	0.014
Grade three	0.2	(0.1-0.5)	<.001	0.2	(0.1-0.6)	0.004	0.7	(0.3-1.6)	0.375
Grade four	0.4	(0.1-1.1)	0.072	0.3	(0.1-0.9)	0.029	0.4	(0.2-1.1)	0.064
Grade five	0.6	(0.2-1.6)	0.291	0.6	(0.2-1.6)	0.308	0.6	(0.3-1.5)	0.270
Grade six		Reference							
Weight-for-age									

Under/overweight	Reference						
Normal	0.4	(0.1-1.1)	0.066	1.7 (0.6-5.0)	0.342	1.7 (0.6-5.1)	0.332
Vitamin B1 intake							
Lower	Reference						
Higher	6.3	(2.5-16.0)	<.001	0.7 (0.3-1.6)	0.676	0.3 (0.1-0.6)	0.02
Vitamin B2 intake							
Lower	Reference						
Higher	2.2	(1.5-7.8)	0.003	1.0 (0.4-2.2)	0.961	0.5 (0.3-1.1)	0.099
Folate intake							
Lower	Reference						
Higher	1.8	(0.9-3.3)	0.086	1.0 (0.5-2.0)	0.935	0.7 (0.3-1.2)	0.196
Iron intake							
Lower	Reference						
Higher	1.9	(1.0-3.6)	0.056	0.9 (0.4-1.8)	0.727	0.9 (0.5-1.7)	0.750
Zinc intake							
Lower	Reference						
Higher	1.7	(0.8-3.3)	0.130	1.1 (0.5-2.2)	0.820	0.4 (0.2-0.7)	0.005
Nutrient blend intake							
Lower	Reference						
Higher	1.7	(0.9-3.3)	0.101	1.0 (0.5-2.1)	0.918	0.6 (0.3-1.2)	0.136

AOR: Adjusted Odds Ratio; CI: Confidence Interval. Micronutrient intake levels were categorized into lower and higher tertiles, with the lower tertile used as reference. All models were adjusted for maternal education level and paternal occupation. Statistical significance was set at $p < 0.05$.

4. Discussion

This study reported the association of dietary nutrient intakes with both cognition and school performance in school-aged children from the HDSS of Taboo, Côte d'Ivoire. Almost half (46.2%) the participants were female indicating that the sample of children recruited in the study was balanced in terms of gender. We observed that cognitive performance improved with age and school grade-levels. This may underline a cumulative impact of both developmental maturation and sustained educational exposure. This trend is consistent with findings from a recent study in school-aged children (4- 7years), which show that age-related gains in cognitive control and reasoning abilities emerge progressively throughout childhood, supported by enriched learning environments and structured curricula [51]. For academic performance, the results showed that younger children outperformed older peers in both mathematics and literature, indicating a potential early academic advantage. This observation is consistent with previous findings by Correa-Burrows et al.[52] , who reported higher academic performance among younger age groups. However, when accounting for school grade levels, mathematical performance declined in middle grades (three and four) relative to grade six, suggesting a dip during transitional academic phases, a pattern similarly observed in previous studies among schoolchildren [53,54]. On the other hand, literature performance peaked in grade two, highlighting a potential early literacy development window, which aligns with the findings of Bleiweiss-Sande et al.[55], who observed enhanced language performance in early primary grades. These findings underscore the need to explore age-grade mismatches and possible curriculum or cognitive load challenges in intermediate grades.

Analysis of nutritional indicators showed that participants had lower BMI-for-age (Δ −0.49) and weight-for-age (Δ = -0.32) compared with WHO standards. The overall prevalence of undernutrition was relatively high among the children in this study. Co-occurrence of stunting and underweight was present in 21.7%, contributing to an overall undernutrition prevalence of 30.9%. Similar findings have been reported in previous studies conducted among school-aged children in Côte d'Ivoire [56,57]. Children malnutrition remains a major challenge for many developing countries. According to the WHO report, 22.5% malnourished children live in Sub-Saharan Africa [58]. It is extensively documented that malnutrition can negatively affect cognitive development in school-aged children resulting in poor academic performance. A review conducted by Grantham-McGregor showed that malnourished children exhibit poorer cognitive abilities and academic achievement compared to well-nourished peers [59]. A study involving 436 primary school children from Northern Ethiopia also reported a significant association between undernutrition and lower academic performance [60]. Specific cognitive function have been even demonstrated to be affected by a chronic malnutrition: attention, memory and executive function, which are all crucial for performance in academic setting [61]. In the current study, although obese children had higher performance in mathematics compared to their underweight peers, no consistently significant associations were found between nutritional status and academic performance or cognition in the children studied. Further research is needed to clarify the relationships nutritional status and school performance or cognition in these children as well as the underlying mechanisms.

This study found a high percentage of inadequate intakes of thiamin, riboflavin, folate, and iron, which may suggest a widespread burden of micronutrient inadequacy among the school-aged children studied. Nutrient intakes were principally assessed based on Dietary Reference Intake provided by WHO/FAO [46]. Similar findings have been reported among children aged 7-11 years in Côte d'Ivoire, where the adequate intake of none of the assessed nutrients, including iron and zinc, was met. In that study, zinc intake reached 72% of the Recommended daily intake (RDI), while iron intake covered only 31% to 45.4% [45]. Additional evidence from studies assessing biochemical markers in Ivorian school-aged children has shown high prevalence of anemia (30-50%), iron deficiency (47%) and vitamin A deficiency (17%) [32–34]. Such deficiencies are commonly associated with inadequate dietary intake, poor bioavailability from predominantly plant-based diets, and frequent exposure to parasitic infections (e.g., helminths and malaria) [62,63]. Micronutrient

deficiencies are recognized contributors to impaired immune function and cognitive development in children. It has been estimated that approximately 200 million school-aged children in low- and middle-income countries failed to reach their full cognitive potential due to inadequate nutrition [64]. The prevalence of inadequate nutrient intake observed among the children involved in this study is worrying, and therefore there is a need for evidence-based nutritional strategies to improve their micronutrient status. In contrast to most other micronutrients, where at least a significant proportion of children were deficient, all children had adequate iodine intake. This finding highlights the effectiveness of iodine fortification strategies, (e.g., iodized salt), in ensuring sufficient dietary iodine intake in Côte d'Ivoire [65].

This study revealed that dietary intakes of thiamin, riboflavin and folate were significantly associated with cognitive performance assessed using the Raven's Coloured Progressive Matrices (RCPM). Children in the highest tertile of thiamin and riboflavin intake were significantly more likely to exhibit better cognitive performance compared to those in the lowest tertile, even after adjusting for potential confounders such as the mother's level of education and the father's occupation. These findings align with those obtained from a prior study involving the same sample of school-aged children, where blood concentration of folate showed a significant correlation (p = 0.03) with numeracy skills [66]. Other studies in Kenyan and Korean school-aged children found significant associations between thiamin, riboflavin, folate and improved cognitive performance [67,68]. However, this study found no significant association between vitamin B6, vitamin B12 and cognitive scores or school performance. Similar findings emerged from the analysis of biomarker data, where no association was observed between pyridoxal 5′-phosphate (active form of vitamin B6) and cognition ($p = 0.46$) nor between vitamin B12 levels and cognition ($p = 0.10$) [66]. These results are also consistent with those reported by Annan et al. (2019), who found no association between the dietary intake of vitamin B6 and vitamin B12 and cognitive performance among Ghanaian school-aged children (9-13 years). In contrast, studies conducted by Gewa et al. and Kim & Kang reported significant positive associations between dietary intakes of vitamin B6 and B12 and cognitive test scores in school-aged populations [67,68]. This divergence highlights the ambiguity surrounding the relationship between vitamins B6 and B12 and cognitive function, which further investigation might help to elucidate. B vitamins are involved in several biological processes. They serve as key coenzymes in the metabolism of carbohydrates, fats and proteins, facilitating energy production crucial for brain function and cognitive development [21], particularly during primary school years. The brain's daily energy consumption is estimated at 20-25% of the total body energy expenditure [70]. B vitamins are also involved in DNA synthesis, gene expression regulation, and neurotransmitter synthesis [22]. Deficiencies in B vitamins can significantly affect cognitive development and school performance.

Significant associations were also observed between iron intake and cognitive test scores. Children in the higher tertile of iron intake showed better cognitive performance, with a higher proportion scoring in the upper percentile (above 50th) of the cognitive performance. This finding aligns with results obtained from iron biomarkers in the same participants, where transferrin (Iron-binding protein considered the primary iron transport protein), showed a strong correlation with cognitive test scores (p = 0.0004) and ferritin (Iron storage protein) demonstrated a similar trend (p = 0.06). This finding is consistent with results from a randomized controlled trial conducted among school-aged children in Kenya (mean age ~7.4 years), in which higher dietary iron intake was significantly associated with improved Raven's Coloured Progressive Matrices (RCPM) scores, reflecting better problem-solving and abstract reasoning abilities. At the biological level, iron is involved in several essential processes. It serves as a cofactor in numerous enzyme systems critical for energy metabolism and neurological function. Iron also plays a key role in neurotransmitter synthesis and the myelination of nerve fibers, both of which are vital for cognitive development [71]. Iron deficiency can considerably affect health status and cognitive functions.

A significant association was also observed between zinc intake cognitive test scores. Children in the highest tertile of zinc intake demonstrated a higher proportion scoring above the 75th

percentile on cognitive assessments compared to those in the lowest tertile. This implies that adequate dietary zinc intake may contribute to enhanced cognitive performance among school-aged children. This result is also consistent with findings from Ghanaian school-aged children (9–13 years), where a weak but statistically significant positive association (p = 0.050) was reported between zinc intake and cognitive test scores [69]. However, an inverse relationship has been observed between zinc intake and school performance. In our previous study [66], no significant association was found between serum zinc and school performance (r = -0.08, p = 0.19). The present findings are consistent with those from a study conducted among Ghanaian school-aged children (6-11 years), where zinc status was negatively correlated with reasoning and problem-solving skills, critical for school performance. These results underscore the ambiguity in the relationship between zinc status and cognitive or academic performance, as reported in previous literature [14]. Further investigation is warranted to clarify this association.

This study found a positive association between the composite blend of micronutrients (vitamin A, thiamin, riboflavin, folate, zinc and iron) and cognitive test performance, suggesting a potential synergistic effect on cognitive development in school-age children. During school-age ages (6-12), executive functions (EF), including working memory, attention control, planning and inhibition, undergo rapid refinement, primarily governed by prefrontal cortex (PFC) maturation. This neurodevelopmental trajectory relies on: Neurotransmitter modulation (e.g., dopamine, acetylcholine), Synaptic pruning and plasticity, Myelination, Neuronal energy metabolism. Each nutrient in the blend contributes to EF development: Vitamin A regulates retinoic acid signaling critical for dopaminergic plasticity and synaptic function [72]. Thiamin facilitates glucose metabolism and supports neurotransmitter synthesis [73]. Riboflavin enhances mitochondrial energy production in high-demand PFC circuits [74]. Folate drives DNA methylation, neurogenesis and monoamine synthesis [75]. Zinc modulates Brain-Derived Neurotrophic Factor (BDNF) expression and synaptic plasticity and iron is essential for dopamine production, myelin formation, and oxygen delivery [76]. Evidence from randomized controlled trials has shown positive effects of these micronutrients on EF in school-aged children. A study in Ethiopian schoolchildren demonstrated that high-dose vitamin A supplementation significantly improved working memory and the combination with iron showed enhanced benefit in vulnerable subgroups [77]. Similarly, Román et al. emphasized the neurocognitive significance of folate, iron, and vitamin A in childhood EF development [78]. Noteworthy, the nutrient included in the blend were selected based on observed significant correlations in the dataset (except for vitamin A) and prior literature linking these nutrients to EF development. Future research should further explore causal mechanisms and validate this combination in controlled intervention settings.

This study found no association between vitamin A, vitamin B6, vitamin B12, iodine or omega-3 fatty acids intakes and cognitive test scores or school performance. Similar results were reported in Ghanaian school-aged children (9-13 years), where vitamin A, vitamin B6, vitamin and vitamin B12 intakes showed no association with cognition [69]. In addition, a study in South African schoolchildren (6-11 years) reported no association between omega-3 fatty acids intake and cognition [79]. In contrast, studies among school-aged children in Korea and Kenya revealed significant correlations between vitamin A, vitamin B6 and vitamin B12 intakes and cognition [67,68]. Other studies have reported significant associations between iodine or omega-3 fatty acids intake and cognition in school-aged children [10,80]. This clearly shows that evidence from studies on the association between these nutrients intake and cognition remains equivocal. The specificity of the population might impact, both in term of genetic background and background insufficiencies (nutritional). A recent review on the importance of lipids for neurodevelopment in low and middle-income countries underlined that the metabolism of fatty acids in humans is affected by gene variants of Fatty Acid Desaturases (FADS), which is responsible for encoding the key enzymes (D5D and D6D) needed for fatty acid synthesis. Noteworthy, conversion of ALA into DHA and EPA and of LA into ARA is done by FADS but with low efficiency. Specifically, only 8%–20% of a dose of ingested ALA is converted into EPA and 0.5%-9% into DHA [81]. Further studies might elucidate the relationship

between these nutrients and cognitive functions. Noteworthy, the majority of the nutrients assessed in the present study were not associated with school performance, despite a large body of literature reporting an association between improved cognition and better school performance among sub-Saharan schoolchildren [82–84]. This discrepancy could be attributed to the multifactorial nature of academic achievement, which is influenced not only by cognition, but also by environmental factors such as teaching quality or socio-economic background. These factors may explain the variation observed in the academic performance between the schools included in this study.

This study has some limitations. School-aged children were interviewed directly about their dietary intake from the previous day using a 24-hour dietary recall questionnaire. Visual portion estimation tools, such as commonly used household measures and photographic food atlas, were employed during data collection to help participants recall portion sizes and reduce reporting bias. However, the authors recognize that the 24-hour recall method may not be the most reliable for this age group and that overestimation or underestimation of food portions is therefore possible. Additionally, the study did not assess total energy intake or consider the impact of dietary inhibitors, such as phytates, on iron absorption, both of which could have affected the interpretation of micronutrient adequacy. Furthermore, as this was a cross-sectional study, it cannot infer causality.

5. Conclusions

This study found that cognition-related micronutrients, particularly B-vitamins and minerals are largely inadequate among school-aged children in the Taabo HDSS, Côte d'Ivoire, except for vitamin A and iodine, which were assumed adequate in most participants. While intakes of thiamin, riboflavin, folate, iron, zinc and nutrient blend were significantly associated with cognitive test scores, no consistent associations were observed between nutrient intakes and academic performance, in contrast to previous studies. Future studies using controlled trials are needed to evaluate the causal relationship between these nutrients and cognition or school performance in this population.

Appendix A

Table A1. Mean and standard deviation of nutritional indicators: weight-for-age z-score, height-for-age z-score, and BMI-for-age z-score.
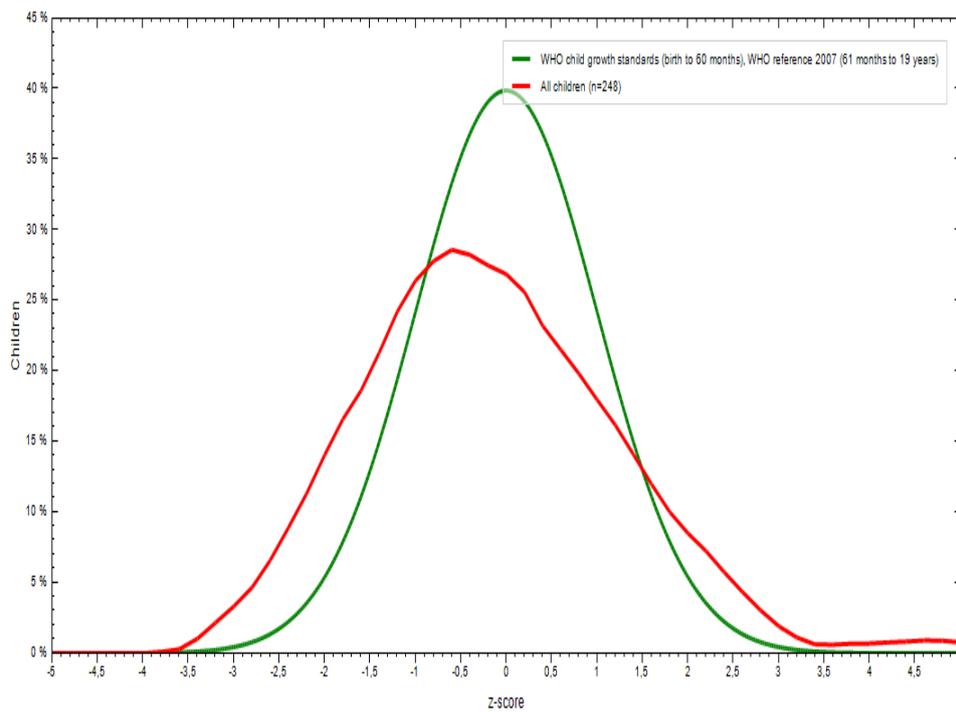
Variable	Mean	Std. Deviation	95% CI Mean Upper	95% CI Mean Lower	Minimum	Maximum
Weight for age	-0.32	1.04	-0.17	-0.46	-2.87	2.77
Height for age	-0.20	1.64	0.01	-0.40	-13.43	5.37
BMI for age	-0.44	2.78	-0.09	-0.78	-3.89	39.61
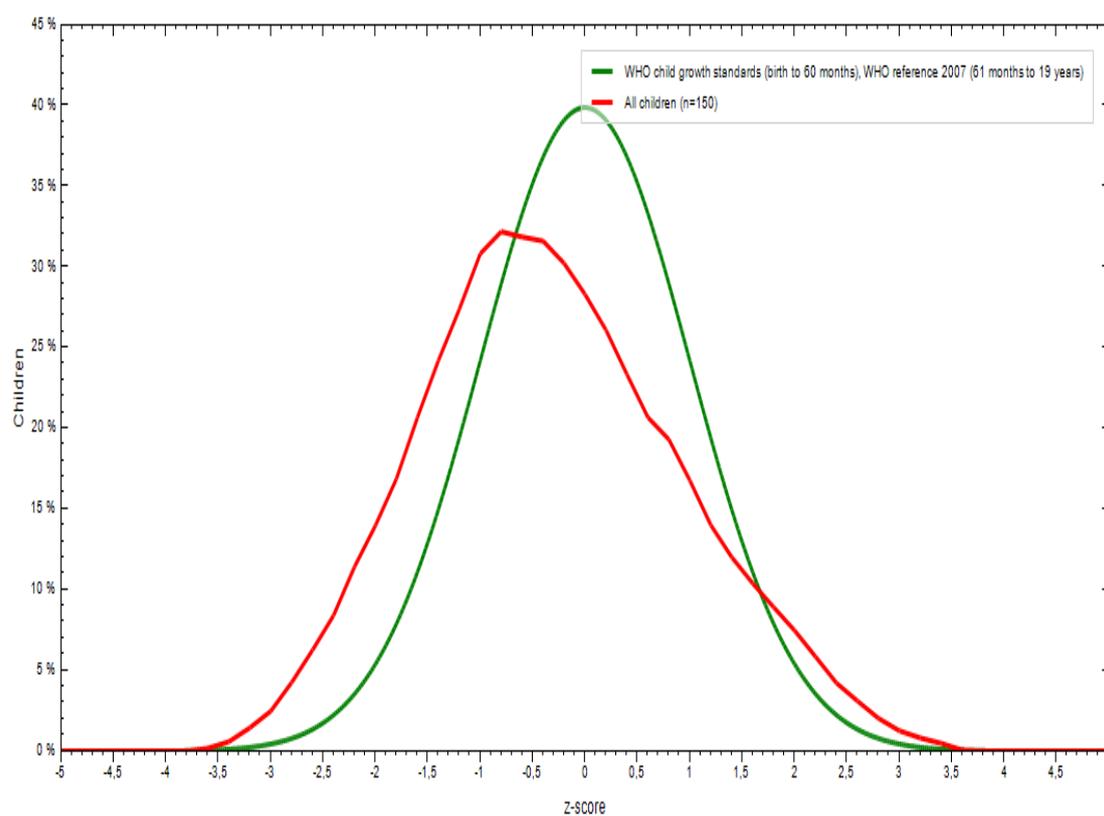
**Figure A1.** Comparison of participants BMI-for-age values with WHO growth standards.
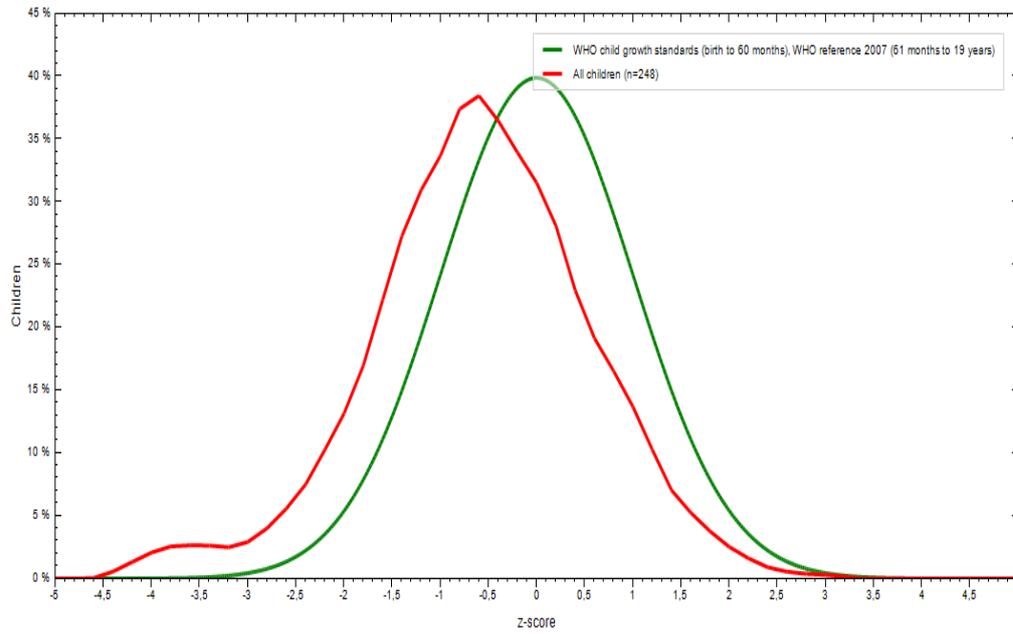
Figure A2. Comparison of participants height-for-age values with WHO growth standards.

Figure A3. Comparison of participants' weight -for-age values with WHO growth standards**.**

Table A2. Mean scores and standard deviation (SD) in cognitive tests, mathematics, and literature and distribution of scores across performance categories: low (below the 50th percentile), medium (50th-75th percentile) and high (above the 75th percentile) performance for cognition test and low below 5/10, medium (5/10-7/10), and high (above 7/10) performance for mathematics and literature.

Variable	Mean	±	SD	Frequency *N* (%)		
				High	Medium	Low
Cognition	15.4	±	4.4	65 (25.9)	77 (30.7)	109 (43.4)
Mathematics	6.0	±	2.4	67 (26.7)	111 (44.2)	73 (29.1)
Literature	5.4	±	1.8	39 (15.5)	120 (47.8)	92 (36.7)
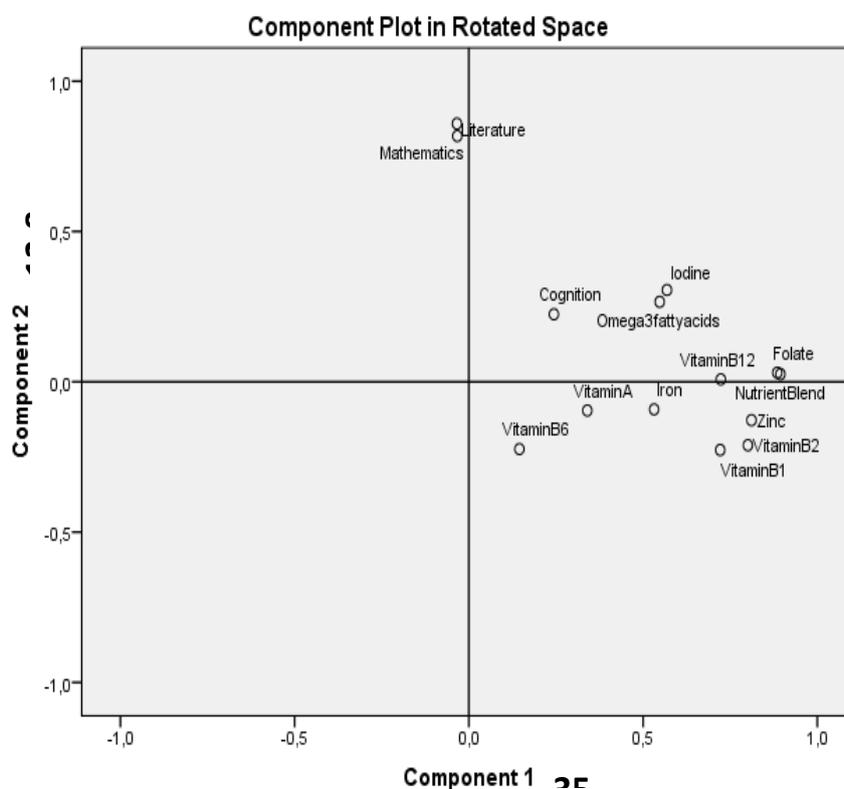
Figure A4. Identification of nutrients associated with cognition and school outcomes using principal component analysis.

Table A3. Associations between cognitive scores, academic performance, and nutrient intake using Spearman's rank correlation (rho).

Variable	Cognition test		Mathematics		Literature	
	score					
	rho	*p*-value	rho	*p*-value	rho	*p*-value

Vitamin A (µg)	0.059	0.353	-0.112	0.059	-0.112	0.076
Vitamin B1 (mg)	0.227**	<.001	-0.157*	0.013	-0.127*	0.045
Vitamin B2 (mg)	0.248**	<.001	-0.086	0.176	-0.096	0.131
Folate (µg)	0.179**	0.005	-0.028	0.657	-0.022	0.727
Vitamin B12 (µg)	0.065	0.308	-0.019	0.767	-0.060	0.345
Vitamin B6 (mg)	-0.014	0.823	-0.017	0.785	-0.026	0.680
Iron (mg)	0.150*	0.018	-0.062	0.327	-0.048	0.453
Zinc (mg)	0.118	0.062	-0.050	0.433	-0.081	0.200
Iodine (µg)	0.036	0.571	-0.044	0.492	0.031	0.620
Omega-3 fatty acids	0.009	0.881	-0.053	0.400	-0.055	0.382
Nutrient blend	0.181**	0.004	-0.029	0.653	-0.025	0.695

* Correlation is significant at the 0.05 level (2-tailed). ** Correlation is significant at the 0.01 level (2-tailed).

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