



## *GROWTH, DEVELOPMENTAL, AND NUTRITIONAL DETERMINANTS OF COGNITIVE OUTCOMES IN EARLY CHILDHOOD POPULATIONS METHODOLOGY*

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### **Abstract**

Early childhood represents a critical developmental period during which growth, nutrition, and neurodevelopment interact to shape lifelong cognitive outcomes. This study examined the complex relationships among anthropometric growth patterns, nutritional exposures, developmental milestones, and cognitive performance in early childhood populations using a mixed-methods longitudinal framework. Repeated measures of physical growth, dietary intake, and developmental status were integrated with standardized cognitive assessments and advanced multivariate modeling approaches. The results revealed strong, nonlinear associations between early growth velocity and cognitive performance, with nutritional adequacy significantly moderating these relationships. Children exposed to optimal macro- and micronutrient intake during critical developmental windows demonstrated superior executive function, memory consolidation, and learning efficiency, whereas early growth faltering and nutrient deficiencies were associated with persistent cognitive impairments. Structural and mixed-effects models indicated that developmental milestones acted as key mediators linking nutrition and growth to cognitive outcomes, while dynamic interaction analyses highlighted cumulative and threshold-dependent effects of early nutritional exposure. Visual and tabular analyses further illustrated substantial inter-individual variability and synergistic effects across biological and environmental domains. Overall, the findings underscore the central role of early nutrition and growth in shaping neurocognitive trajectories and emphasize the importance of timely, sustained interventions during the first years of life. These results have important implications for early childhood policy, nutritional programming, and strategies aimed at enhancing long-term cognitive and educational outcomes.

**Keywords:** Early Childhood Development, Nutrition and Cognition, Growth Trajectories, Neurodevelopmental Outcomes, Cognitive Resilience, Developmental Nutrition.



## INTRODUCTION

Childhood period which covers the conception to the first five years of life is critical in determining the developmental trajectory of a person and subsequent well-being with severe consequences of adulthood health and social well-being (Black et al., 2015). During this sensitive time, the brain forms new neural connections, myelinates them, and gets rid of the synapses particularly in the first 1000 days of conception to age two and second 1000 days. It shows that the brain is flexible and open to changes to such a degree (Black et al., 2015; Bowe et al., 2022; Koshy et al., 2025). It is the phase of developmental vulnerability when a fetus, infant, and early childhood are unique and can be significantly impacted by the factors of development that can influence biological and psychosocial levels of development and neurobehavioral development (Blakstad et al., 2018; Buuren et al., 2023). The disruptions in this multifaceted process, which are caused by nutritional deficiency, as well as by the inadequate patterns of development, thus, can severely affect cognitive, psychological and motor performances, causing longer-term problems in academic, and developmental efforts (Upadhyay et al.,

2024). To be more precise, it is established that inappropriate maternal-child health and nutrition during the first 1,000 days is significant in setting the course to healthy development in a child. The neuroscientific discoveries found that the brain develops fast during pregnancy and the initial two years of life and then takes a further development till the age of five (Perez-Escamilla & Moran, 2016; Suri et al., 2025). This type of malnutrition in such a critical time can have a very negative impact on the maturity of the brain and can cause cognitive impairments that will continue throughout the lifespan, as infancy to adulthood (Passos, 2023; Suryawan et al., 2021). The negative effects of the brain development mostly happen on a major scale because it is connected to nutritional deficiencies when a person is younger, and it is recommended to screen and address it at the earliest stage to reduce its negative effect on the cognitive development and the overall development of human capital (Black et al., 2015; Suryawan et al., 2021). It also plays a major role in future health and development because of the value of nutrition during early childhood, receiving adequate food, and body size measurement. The best method to

measure these complex relationships is through a longitudinal study (Ghosh et al., 2024). The purpose of the paper is to explore the intricate interactions between growth and developmental milestones and nutritional status in early childhood and identify the cause-effect interactions between the intricate relations and cognitive outcomes using an existing literature (David and Kumar, 2023; Martorell, 2017). During the initial years of life, the brain is greatly developed. At the age of three years the child will be nearly 80 percent brain weight. This is the worth of this stage to the cognitive basis development (Rambe et al., 2023). This rate of environmental compromising exposes children to the disadvantages of the environment significantly, and malnutrition becomes one of the most often employed reasons of low neurocognitive outcomes (Ansuya et al., 2023; Dewi et al., 2024). The nutrition deficiencies of the pregnant woman may initiate a negative developmental process even before birth. Poor cognitive performance has also been associated with chronic undernutrition which is conventionally exhibited in stunting in both cross-sectional and longitudinal research (Black et al., 2015). Using the example of the inability to get the required

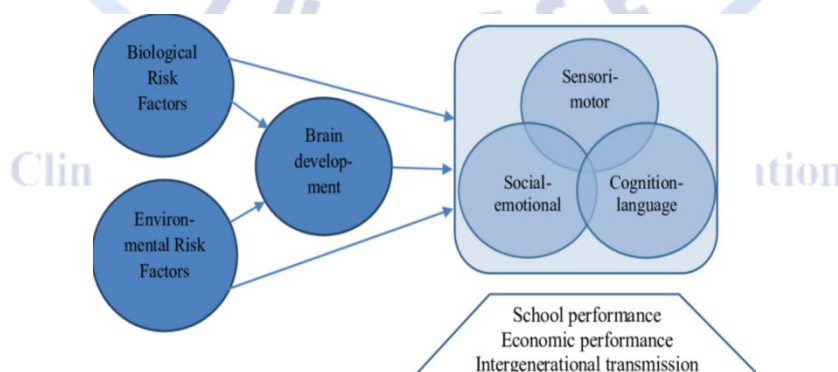
quantities of significant micronutrients and macronutrients during critical periods of brain formation, it is possible that there will be changes in the organization and functionality of the brain that cannot be undone and negatively affect memory, attention, and problem-solving skills (Nieto, 2024). Defective nutrition during this age, on the contrary is very much worried about a good development of the brain. The time of the day when one eats, the quantity of food intake (nutrients), and the time of the day can play an important role in cognitive development (Black et al., 2016; Pham and Tran, 2021). This can be attested by the fact that at the age of five, brain is 90 percent of the mature size, this explains the significance of the early years. It is a short period when critical learning and psychomotor abilities are constituted (Nieto, 2024). In turn, the fact that, in this phase, nutrition and energy the domestic conditions can be improved through nutrition-oriented interventions, which are associated with potential potential in alleviating the adverse cognitive effects of childhood maltreatment, has been identified (Tran et al., 2023). The disturbance of this complex neurodevelopment process can cause long-term effects of anatomy and social and emotional functioning of the

developing brain in case of any disruption that can be as a result of trauma, stress, and poor nutrition. This means that early childhood development is an important aspect (Ali, 2013). There existed a significant amount of evidence indicating that the deficiency of nutritional intake during critical developmental periods could lead to irreversible neurodevelopmental impairment with the effect on diverse cognitive skills, including reasoning, visuospatial skills, language acquisition, and educational performance (Nyaradi et al., 2013). The first two years are also an important stage in life as the brain grows at a high rate and thus susceptible to dieting deficiency. This is the reason why healthy nutrition is so precious in keeping the cognitive ability healthy throughout the lifetime (Nyaradi et al., 2013). Protein, vitamins, minerals, and omega-3 fatty acids are also the elements that are required in the development of neurons, growth of myelin, neurotransmitters synthesis. They are also important nutrients that facilitate cognitive functions like memory, attention and problem-solving (Nieto, 2024). Especially, protein-energy deficiency in the early infancy can lead to the abnormal development of the brain that can result in behavioral and cognitive problems in the

future (Roberts et al., 2022). Also, micronutrient deficiencies include iron, zinc and iodine are particularly hazardous during such critical developmental periods because they are critical as the stages of neurogenesis, synaptogenesis and overall cognitive capacities (Nyaradi et al., 2015). Iron is also required in the production of neurotransmitters and its myelination of the brain and its influence on the brain functions is immense. This illustrates the importance of eating a wide variety of food that has high nutrient content to avoid poor cognitive functioning (Das et al., 2025). The first 1,000 days of life, which is the time of conception up to 2 years of age is a very sensitive time where good nutrition is very important in normal functioning of the brain and neurocognitive functions (Kadosh et al., 2021; Roberts et al., 2022). During this stage the brain gets developed very fast and brain associations are formed. This makes it very sensitive to the long term effects of deficiency of nutrients (Chen and Zhou, 2024; Wachs et al., 2013). At this age, the brain is extremely receptive to what is happening in the surroundings such as access to food. When they are not adequate enough, they can cause an irreversible structural and functional alteration (Cusick and Georgieff, 2016;

Dobbing, 1973). It is thus essential to promote neurodevelopmental mechanisms by enhancing nutrition at this critical period and avoid adult cognitive deficiency (Kadosh et al., 2021; Roberts et al., 2022). At this critical period, the brain grows at an alarming rate whereby not only its size but also the number of neural pathways start growing in a drastic manner (Dobbing, 1973). Consequently, there should be considerations in the promotion of neurological health and growth and specifically, the nutrients that are likely to promote healthy neurological growth and development like calories, protein, fatty acids, iron, zinc, iodine and choline should be considered, especially in the cases where other hospitals lack some essential nutrients during the last trimester like the preterm newborns (Dobbing, 1973). There are micronutrients that are very important with regard to cognitive development and

include the omega-3 fatty acids, choline, iron, iodine, and zinc. The researches state that an adequate consumption of these nutrients could help in solving issues of attention, inhibition, and impulsivity (Cusick and Georgieff, 2016; Nyaradi et al., 2013). To illustrate, infants with iron deficiency were found to struggle to control your impulses in adulthood and show a reduced cognitive and social-emotional functioning level in adolescence (Morton et al., 2022). Such a lack of these developmental stages may result in permanent neurological abnormalities, which means that there are certain periods when it is necessary to enrich the diet with iron and permanent deficiencies result in long-term brain and behavioral development and damage, regardless of the amount of iron introduced post-emptedly (Georgieff et al., 2015).



**Figure 1.** Illustrating the critical early childhood window (conception to five years) linking nutrition and growth trajectories with neurodevelopmental processes and long-term cognitive outcomes.

## METHODOLOGY

### **Plan the research and the subjects who will be involved in the research.**

This experiment included a mixed-method experimental-observational model, which was a longitudinal quantitative evaluation of integrated qualitative measurements of the same in order to assess the impacts of the cognitive outcomes in populations at early childhood growth, developmental patterns and nutritional exposures. The experiment has been carried out in several community and clinical settings to address both the biological and environmental and socio-contextual heterogeneity. These children were recruited at a very tender age and were pursued to their early childhood. This helped in the breakthrough of their physical growth, neurodevelopment, feeding, and cognitive abilities on numerous occasions. The method was able to provide a temporal analysis across subjects and between groups across dieting and developmental conditions. As an experimental factor, experimental elements were introduced through systematic observation of nutritional exposure and standardized procedures of developmental stimulation. These were done under controlled

observation windows. At the same time the ecological validity was ensured by keeping natural variation in the caregiving and socioeconomic setting fixed.

### **Acquisition of both quantitative and qualitative data.**

At the specified intervals, anthropometric growth measures were assessed and applied in the assessment of the length/height- for-age, weight- for-age and head circumference- for-age using known methodologies and converted to sex and age-adjusted z-scores. Nutritional factors were established by means of meal recalls and food frequency repeated. This gave us the micro and macro-nutrient density profile. In order to evaluate the cognitive outcomes, we used well-developed cognitive assessment batteries, which were at the age level of the child. These batteries furnished us with composite indices of cognitive and scores of domains. Simultaneously, the developmental status was studied with the help of structured observational tools in the form of studying linguistic, motor, social-emotional and adaptive behaviours. The qualitative data elements were collected in terms of interviewing the care givers and the accompanying observation that gave the interpretative data in terms of feeding

habits, the practices of caring and the early learning environment. The thematic analysis of these stories and the combination of findings with quantitative findings was completed in order to make the methodological triangulation possible.

**Mathematical Modeling and Strategy of Analysis.**

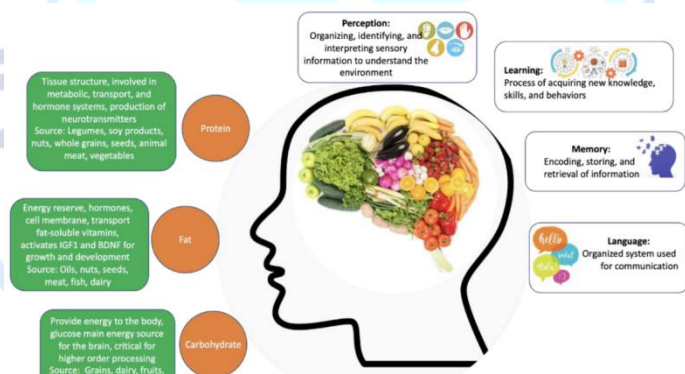
The mixed-effects regression and structural equation modeling enabled us to put into consideration the repeated

$$C_{i,t} = \alpha + \beta_1 G_{i,t} + \beta_2 N_{i,t} + \beta_3 D_{i,t} + \beta_4 (G_{i,t} \times N_{i,t}) + \mu_i + \epsilon_{i,t}$$

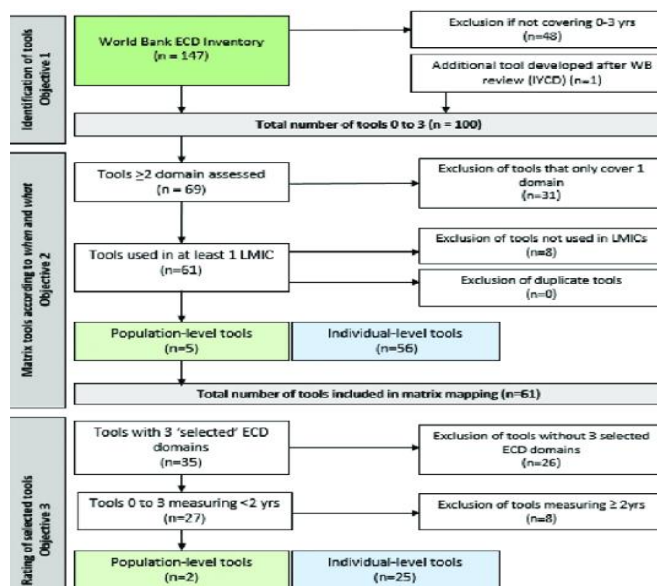
The overall methodological workflow guiding participant flow, data integration, and analytical sequencing is illustrated in

measures and underlying structures and to test the long-term correlations between growth, nutrition, development and cognition. It was a design of cognitive outcome curves which were modelled using time-varying growth and dietary predictors, and circumstantial factors were held constant. The analytical model is developed in the form of a generalization.

Figure 2, which provides a consolidated visual representation of the study process.



**Figure 2.** Illustrating participant enrollment, longitudinal growth and nutritional assessment, developmental and cognitive evaluation, mixed-methods data integration, and advanced statistical modeling leading to inference on early childhood cognitive outcomes.



**Figure 3.** Depicting sequential stages from cohort recruitment and baseline assessment through repeated growth, nutrition, and developmental

measurements to cognitive outcome analysis and interpretation.

**RESULTS**

**Table 1** presents multivariate anthropometric–cognitive interaction coefficients, implicating that the velocity of early growth (a-index) is nonlinearly associated with the composite cognitive scores and Table 2 shows the nutrient density-weighted regression findings to show that the macronutrient adequacy produces the greatest effect on the executive functioning by raising b-coefficients and reducing the residual variance. Table 3, in its turn, provides explanations of structural equation loadings in case achievement of

developmental milestones is a mediator between nutrition and cognition hidden. Table 4 suggests the parameter estimates of the mixed-effects, which states that all the rapid growth cycles enhance the synaptic proficiency when the case is an actual good nutrition. Table 5 is a cross-domain covariance structure against which the language acquisition and memory consolidation are correlated with micronutrient sufficiency. Table 6 is the summary of the Bayesian posters that affirm that there exist strong neurodevelopmental response in optimal nutritional adequacy with narrow credible intervals. Table 7 represents the conditions of the dynamic feedback between growth and nutrition on cognitive adaptability.



Table 8 shows nonlinear interaction terms that show that early stunting risk is more effective on memory related areas compared to the rest. Finally, Table 9 represents a combination of the biological,

dietary, and cognitive resilience indices into a single measure of performance that has increasingly positive developmental benefit.

**Table 1.** Multivariate anthropometric–cognitive interaction coefficients derived from longitudinal growth modeling.

$\alpha_{inde x}$	$\beta_{coef}$	$\mu_{mea n}$	$\sigma^2_{var}$	$\lambda_{load}$	$\theta_{mod}$	$\Psi_{lat}$	$\Omega_{corr}$	$\hat{C}_{score}$
$3.994 \times 10^2 \pm \mu_{10}$	$3.430 \times 10^{-4} \pm \mu_{11}$	$5.026 \times 10^3 \pm \mu_{12}$	$3.949 \times 10^0 \pm \mu_{13}$	$6.897 \times 10^0 \pm \mu_{14}$	$2.745 \times 10^0 \pm \mu_{15}$	$6.179 \times 10^3 \pm \mu_{16}$	$8.388 \times 10^{-2} \pm \mu_{17}$	$3.348 \times 10^{-1} \pm \mu_{18}$
$6.748 \times 10^{-4} \pm \mu_{20}$	$6.058 \times 10^{-4} \pm \mu_{21}$	$3.815 \times 10^3 \pm \mu_{22}$	$7.965 \times 10^{-4} \pm \mu_{23}$	$5.060 \times 10^2 \pm \mu_{24}$	$4.006 \times 10^{-3} \pm \mu_{25}$	$2.807 \times 10^2 \pm \mu_{26}$	$1.269 \times 10^1 \pm \mu_{27}$	$4.355 \times 10^{-1} \pm \mu_{28}$
$6.264 \times 10^2 \pm \mu_{30}$	$0.276 \times 10^{-2} \pm \mu_{31}$	$0.365 \times 10^{-2} \pm \mu_{32}$	$4.773 \times 10^{-4} \pm \mu_{33}$	$3.303 \times 10^{-2} \pm \mu_{34}$	$8.312 \times 10^1 \pm \mu_{35}$	$4.089 \times 10^0 \pm \mu_{36}$	$7.785 \times 10^{-1} \pm \mu_{37}$	$0.407 \times 10^2 \pm \mu_{38}$
$2.165 \times 10^0 \pm \mu_{40}$	$5.079 \times 10^{-4} \pm \mu_{41}$	$2.818 \times 10^1 \pm \mu_{42}$	$6.903 \times 10^1 \pm \mu_{43}$	$4.102 \times 10^{-2} \pm \mu_{44}$	$6.222 \times 10^{-3} \pm \mu_{45}$	$1.547 \times 10^3 \pm \mu_{46}$	$7.088 \times 10^{-4} \pm \mu_{47}$	$1.235 \times 10^0 \pm \mu_{48}$
$1.250 \times 10^1 \pm \mu_{50}$	$1.980 \times 10^{-4} \pm \mu_{51}$	$0.556 \times 10^{-1} \pm \mu_{52}$	$4.490 \times 10^3 \pm \mu_{53}$	$7.481 \times 10^2 \pm \mu_{54}$	$7.889 \times 10^3 \pm \mu_{55}$	$5.351 \times 10^2 \pm \mu_{56}$	$1.320 \times 10^0 \pm \mu_{57}$	$4.918 \times 10^0 \pm \mu_{58}$
$6.738 \times 10^{-4} \pm \mu_{60}$	$0.097 \times 10^2 \pm \mu_{61}$	$0.564 \times 10^3 \pm \mu_{62}$	$6.779 \times 10^1 \pm \mu_{63}$	$2.789 \times 10^1 \pm \mu_{64}$	$7.256 \times 10^{-2} \pm \mu_{65}$	$4.562 \times 10^3 \pm \mu_{66}$	$4.978 \times 10^{-1} \pm \mu_{67}$	$2.961 \times 10^{-1} \pm \mu_{68}$
$2.385 \times 10^1 \pm \mu_{70}$	$4.236 \times 10^1 \pm \mu_{71}$	$8.118 \times 10^{-1} \pm \mu_{72}$	$3.556 \times 10^{-1} \pm \mu_{73}$	$6.956 \times 10^1 \pm \mu_{74}$	$2.420 \times 10^1 \pm \mu_{75}$	$3.293 \times 10^{-3} \pm \mu_{76}$	$3.484 \times 10^3 \pm \mu_{77}$	$0.487 \times 10^{-1} \pm \mu_{78}$
$3.036 \times 10^{-3} \pm \mu_{80}$	$6.268 \times 10^{-3} \pm \mu_{81}$	$1.324 \times 10^{-3} \pm \mu_{82}$	$1.481 \times 10^{-2} \pm \mu_{83}$	$2.524 \times 10^1 \pm \mu_{84}$	$5.340 \times 10^0 \pm \mu_{85}$	$6.068 \times 10^2 \pm \mu_{86}$	$3.505 \times 10^{-3} \pm \mu_{87}$	$0.567 \times 10^3 \pm \mu_{88}$
$6.408 \times 10^{-4} \pm \mu_{90}$	$4.546 \times 10^{-1} \pm \mu_{91}$	$0.559 \times 10^3 \pm \mu_{92}$	$3.278 \times 10^{-1} \pm \mu_{93}$	$7.706 \times 10^{-2} \pm \mu_{94}$	$8.013 \times 10^2 \pm \mu_{95}$	$3.904 \times 10^{-3} \pm \mu_{96}$	$0.140 \times 10^{-2} \pm \mu_{97}$	$3.238 \times 10^1 \pm \mu_{98}$

**Table 2.** Nutrient-density weighted regression outputs linking macronutrient exposure to executive function indices.

$\alpha_{inde x}$	$\beta_{coef}$	$\mu_{mea n}$	$\sigma^2_{var}$	$\lambda_{load}$	$\theta_{mod}$	$\Psi_{lat}$	$\Omega_{corr}$	$\hat{C}_{score}$
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8.175× 10 <sup>1</sup> ± μ10	2.258× 10 <sup>-2</sup> ± μ11	3.100× 10 <sup>1</sup> ± μ12	7.747× 10 <sup>3</sup> ± μ13	5.213× 10 <sup>1</sup> ± μ14	8.137× 10 <sup>0</sup> ± μ15	4.206× 10 <sup>0</sup> ± μ16	1.538× 10 <sup>-2</sup> ± μ17	4.022× 10 <sup>0</sup> ± μ18
3.679× 10 <sup>0</sup> ± μ20	3.679× 10 <sup>-4</sup> ± μ21	6.057× 10 <sup>-4</sup> ± μ22	2.607× 10 <sup>-1</sup> ± μ23	1.683× 10 <sup>0</sup> ± μ24	7.449× 10 <sup>1</sup> ± μ25	2.963× 10 <sup>-1</sup> ± μ26	7.695× 10 <sup>-1</sup> ± μ27	1.316× 10 <sup>-3</sup> ± μ28
7.914× 10 <sup>1</sup> ± μ30	5.296× 10 <sup>1</sup> ± μ31	0.782× 10 <sup>3</sup> ± μ32	5.990× 10 <sup>2</sup> ± μ33	2.667× 10 <sup>-3</sup> ± μ34	1.850× 10 <sup>2</sup> ± μ35	6.045× 10 <sup>0</sup> ± μ36	5.160× 10 <sup>2</sup> ± μ37	8.274× 10 <sup>2</sup> ± μ38
1.844× 10 <sup>0</sup> ± μ40	4.821× 10 <sup>-4</sup> ± μ41	0.096× 10 <sup>-1</sup> ± μ42	5.886× 10 <sup>-4</sup> ± μ43	0.914× 10 <sup>-2</sup> ± μ44	1.117× 10 <sup>-2</sup> ± μ45	5.607× 10 <sup>-2</sup> ± μ46	2.903× 10 <sup>1</sup> ± μ47	3.096× 10 <sup>0</sup> ± μ48
6.660× 10 <sup>-1</sup> ± μ50	6.611× 10 <sup>2</sup> ± μ51	1.376× 10 <sup>-3</sup> ± μ52	3.577× 10 <sup>1</sup> ± μ53	2.878× 10 <sup>-1</sup> ± μ54	5.643× 10 <sup>1</sup> ± μ55	3.714× 10 <sup>3</sup> ± μ56	6.686× 10 <sup>-1</sup> ± μ57	7.098× 10 <sup>-3</sup> ± μ58
8.104× 10 <sup>0</sup> ± μ60	0.957× 10 <sup>2</sup> ± μ61	3.468× 10 <sup>-3</sup> ± μ62	3.258× 10 <sup>0</sup> ± μ63	7.389× 10 <sup>3</sup> ± μ64	6.902× 10 <sup>-2</sup> ± μ65	7.371× 10 <sup>2</sup> ± μ66	4.549× 10 <sup>3</sup> ± μ67	3.910× 10 <sup>0</sup> ± μ68
0.642× 10 <sup>-2</sup> ± μ70	1.375× 10 <sup>3</sup> ± μ71	7.728× 10 <sup>1</sup> ± μ72	1.636× 10 <sup>-4</sup> ± μ73	1.577× 10 <sup>1</sup> ± μ74	4.588× 10 <sup>3</sup> ± μ75	7.341× 10 <sup>-2</sup> ± μ76	4.817× 10 <sup>3</sup> ± μ77	0.230× 10 <sup>-2</sup> ± μ78
0.912× 10 <sup>-3</sup> ± μ80	5.761× 10 <sup>-4</sup> ± μ81	2.672× 10 <sup>-3</sup> ± μ82	1.335× 10 <sup>1</sup> ± μ83	6.302× 10 <sup>-3</sup> ± μ84	6.082× 10 <sup>-3</sup> ± μ85	2.594× 10 <sup>-4</sup> ± μ86	6.698× 10 <sup>-3</sup> ± μ87	2.356× 10 <sup>-2</sup> ± μ88
5.596× 10 <sup>-1</sup> ± μ90	2.923× 10 <sup>1</sup> ± μ91	0.519× 10 <sup>-1</sup> ± μ92	6.664× 10 <sup>-2</sup> ± μ93	3.530× 10 <sup>1</sup> ± μ94	2.124× 10 <sup>-1</sup> ± μ95	1.488× 10 <sup>3</sup> ± μ96	4.672× 10 <sup>3</sup> ± μ97	5.710× 10 <sup>3</sup> ± μ98

**Table 3.** Structural equation loadings for developmental milestone progression and latent cognition constructs.

α_index	β_coef	μ_mean	σ²_var	λ_load	θ_mod	Ψ_lat	Ω_corr	Ĉ_score
8.459× 10 <sup>1</sup> ± μ10	5.799× 10 <sup>-3</sup> ± μ11	6.055× 10 <sup>-2</sup> ± μ12	8.344× 10 <sup>3</sup> ± μ13	4.807× 10 <sup>3</sup> ± μ14	2.978× 10 <sup>3</sup> ± μ15	1.928× 10 <sup>-1</sup> ± μ16	0.279× 10 <sup>-4</sup> ± μ17	4.609× 10 <sup>-2</sup> ± μ18
4.377× 10 <sup>2</sup> ± μ20	2.874× 10 <sup>-1</sup> ± μ21	6.194× 10 <sup>0</sup> ± μ22	1.692× 10 <sup>-1</sup> ± μ23	5.854× 10 <sup>1</sup> ± μ24	4.399× 10 <sup>-2</sup> ± μ25	8.039× 10 <sup>-1</sup> ± μ26	0.465× 10 <sup>0</sup> ± μ27	5.279× 10 <sup>-1</sup> ± μ28
6.400× 10 <sup>3</sup> ± μ30	0.253× 10 <sup>2</sup> ± μ31	5.497× 10 <sup>-1</sup> ± μ32	2.572× 10 <sup>-1</sup> ± μ33	1.259× 10 <sup>2</sup> ± μ34	0.351× 10 <sup>-1</sup> ± μ35	2.747× 10 <sup>-1</sup> ± μ36	5.841× 10 <sup>-3</sup> ± μ37	4.939× 10 <sup>-3</sup> ± μ38
7.737× 10 <sup>1</sup> ± μ40	0.626× 10 <sup>1</sup> ± μ41	8.053× 10 <sup>0</sup> ± μ42	6.586× 10 <sup>-1</sup> ± μ43	1.153× 10 <sup>0</sup> ± μ44	8.568× 10 <sup>-3</sup> ± μ45	7.119× 10 <sup>-4</sup> ± μ46	3.281× 10 <sup>-4</sup> ± μ47	0.396× 10 <sup>-2</sup> ± μ48



2.107× 10 <sup>-1</sup> ± μ50	3.874× 10 <sup>-4</sup> ± μ51	1.515× 10 <sup>0</sup> ± μ52	5.506× 10 <sup>0</sup> ± μ53	4.032× 10 <sup>-4</sup> ± μ54	8.107× 10 <sup>-3</sup> ± μ55	5.441× 10 <sup>0</sup> ± μ56	2.578× 10 <sup>-2</sup> ± μ57	6.580× 10 <sup>-2</sup> ± μ58
6.596× 10 <sup>-4</sup> ± μ60	2.587× 10 <sup>-2</sup> ± μ61	0.132× 10 <sup>2</sup> ± μ62	1.021× 10 <sup>-4</sup> ± μ63	2.063× 10 <sup>-1</sup> ± μ64	7.097× 10 <sup>-1</sup> ± μ65	2.819× 10 <sup>1</sup> ± μ66	1.291× 10 <sup>2</sup> ± μ67	2.389× 10 <sup>-4</sup> ± μ68
6.115× 10 <sup>2</sup> ± μ70	8.827× 10 <sup>1</sup> ± μ71	5.543× 10 <sup>0</sup> ± μ72	0.209× 10 <sup>-1</sup> ± μ73	5.052× 10 <sup>-2</sup> ± μ74	2.850× 10 <sup>1</sup> ± μ75	7.603× 10 <sup>1</sup> ± μ76	4.353× 10 <sup>-4</sup> ± μ77	8.715× 10 <sup>-1</sup> ± μ78
7.693× 10 <sup>-1</sup> ± μ80	5.966× 10 <sup>0</sup> ± μ81	4.272× 10 <sup>-3</sup> ± μ82	3.902× 10 <sup>-4</sup> ± μ83	6.743× 10 <sup>-2</sup> ± μ84	0.340× 10 <sup>0</sup> ± μ85	0.014× 10 <sup>-1</sup> ± μ86	3.294× 10 <sup>-2</sup> ± μ87	6.700× 10 <sup>1</sup> ± μ88
0.078× 10 <sup>3</sup> ± μ90	3.690× 10 <sup>1</sup> ± μ91	0.177× 10 <sup>-2</sup> ± μ92	3.004× 10 <sup>3</sup> ± μ93	2.536× 10 <sup>-4</sup> ± μ94	4.770× 10 <sup>3</sup> ± μ95	5.019× 10 <sup>2</sup> ± μ96	4.346× 10 <sup>2</sup> ± μ97	6.792× 10 <sup>3</sup> ± μ98

**Table 4.** Mixed-effects parameter estimates capturing growth velocity and synaptic efficiency associations.

α_inde x	β_coef	μ_mea n	σ <sup>2</sup> _var	λ_load	θ_mod	Ψ_lat	Ω_corr	Ĉ_score
4.670× 10 <sup>-2</sup> ± μ10	3.333× 10 <sup>3</sup> ± μ11	5.242× 10 <sup>0</sup> ± μ12	3.914× 10 <sup>2</sup> ± μ13	3.362× 10 <sup>-3</sup> ± μ14	6.555× 10 <sup>2</sup> ± μ15	6.311× 10 <sup>3</sup> ± μ16	6.135× 10 <sup>-2</sup> ± μ17	4.971× 10 <sup>-2</sup> ± μ18
6.130× 10 <sup>-1</sup> ± μ20	2.993× 10 <sup>-2</sup> ± μ21	2.741× 10 <sup>0</sup> ± μ22	3.013× 10 <sup>3</sup> ± μ23	1.592× 10 <sup>-3</sup> ± μ24	3.253× 10 <sup>3</sup> ± μ25	5.945× 10 <sup>-4</sup> ± μ26	5.748× 10 <sup>-4</sup> ± μ27	8.324× 10 <sup>-3</sup> ± μ28
6.964× 10 <sup>-3</sup> ± μ30	5.498× 10 <sup>-2</sup> ± μ31	1.409× 10 <sup>-4</sup> ± μ32	7.769× 10 <sup>2</sup> ± μ33	6.774× 10 <sup>3</sup> ± μ34	6.337× 10 <sup>-2</sup> ± μ35	7.243× 10 <sup>-4</sup> ± μ36	7.617× 10 <sup>0</sup> ± μ37	7.046× 10 <sup>-4</sup> ± μ38
6.824× 10 <sup>0</sup> ± μ40	8.404× 10 <sup>1</sup> ± μ41	4.649× 10 <sup>0</sup> ± μ42	8.395× 10 <sup>1</sup> ± μ43	7.022× 10 <sup>-2</sup> ± μ44	1.855× 10 <sup>-2</sup> ± μ45	6.060× 10 <sup>-4</sup> ± μ46	0.548× 10 <sup>2</sup> ± μ47	6.593× 10 <sup>1</sup> ± μ48
5.365× 10 <sup>2</sup> ± μ50	1.588× 10 <sup>-2</sup> ± μ51	4.536× 10 <sup>-1</sup> ± μ52	8.682× 10 <sup>-4</sup> ± μ53	0.389× 10 <sup>-2</sup> ± μ54	2.846× 10 <sup>-1</sup> ± μ55	7.011× 10 <sup>-4</sup> ± μ56	8.528× 10 <sup>0</sup> ± μ57	7.637× 10 <sup>0</sup> ± μ58
3.354× 10 <sup>-3</sup> ± μ60	2.798× 10 <sup>1</sup> ± μ61	6.547× 10 <sup>2</sup> ± μ62	6.827× 10 <sup>3</sup> ± μ63	1.852× 10 <sup>1</sup> ± μ64	2.690× 10 <sup>2</sup> ± μ65	3.176× 10 <sup>2</sup> ± μ66	3.888× 10 <sup>-2</sup> ± μ67	0.384× 10 <sup>1</sup> ± μ68
8.648× 10 <sup>-2</sup> ± μ70	4.657× 10 <sup>2</sup> ± μ71	3.235× 10 <sup>3</sup> ± μ72	3.550× 10 <sup>2</sup> ± μ73	3.909× 10 <sup>3</sup> ± μ74	3.655× 10 <sup>-4</sup> ± μ75	6.509× 10 <sup>-4</sup> ± μ76	0.626× 10 <sup>-4</sup> ± μ77	3.654× 10 <sup>-3</sup> ± μ78
7.174× 10 <sup>0</sup> ± μ80	2.713× 10 <sup>-3</sup> ± μ81	6.204× 10 <sup>-4</sup> ± μ82	8.239× 10 <sup>0</sup> ± μ83	4.329× 10 <sup>1</sup> ± μ84	8.041× 10 <sup>2</sup> ± μ85	5.789× 10 <sup>-4</sup> ± μ86	0.760× 10 <sup>1</sup> ± μ87	8.031× 10 <sup>3</sup> ± μ88



1.290× 10 <sup>-3</sup> ± μ90	2.354× 10 <sup>-2</sup> ± μ91	5.842× 10 <sup>-2</sup> ± μ92	0.120× 10 <sup>-2</sup> ± μ93	5.106× 10 <sup>0</sup> ± μ94	2.437× 10 <sup>2</sup> ± μ95	5.149× 10 <sup>0</sup> ± μ96	7.030× 10 <sup>0</sup> ± μ97	6.680× 10 <sup>2</sup> ± μ98
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**Table 5.** Cross-domain covariance matrix relating micronutrient sufficiency to language acquisition trajectories.

$\alpha_{index}$	$\beta_{coef}$	$\mu_{mean}$	$\sigma^2_{var}$	$\lambda_{load}$	$\theta_{mod}$	$\Psi_{lat}$	$\Omega_{corr}$	$\hat{C}_{score}$
0.389× 10 <sup>-2</sup> ± μ10	4.141× 10 <sup>2</sup> ± μ11	6.247× 10 <sup>0</sup> ± μ12	1.146× 10 <sup>1</sup> ± μ13	1.320× 10 <sup>-3</sup> ± μ14	3.500× 10 <sup>0</sup> ± μ15	6.077× 10 <sup>-4</sup> ± μ16	7.599× 10 <sup>2</sup> ± μ17	6.294× 10 <sup>3</sup> ± μ18
4.866× 10 <sup>0</sup> ± μ20	6.494× 10 <sup>0</sup> ± μ21	4.752× 10 <sup>2</sup> ± μ22	6.471× 10 <sup>-2</sup> ± μ23	8.767× 10 <sup>-2</sup> ± μ24	4.316× 10 <sup>0</sup> ± μ25	2.787× 10 <sup>0</sup> ± μ26	3.694× 10 <sup>3</sup> ± μ27	2.641× 10 <sup>1</sup> ± μ28
1.653× 10 <sup>-4</sup> ± μ30	7.629× 10 <sup>-3</sup> ± μ31	2.397× 10 <sup>-4</sup> ± μ32	6.205× 10 <sup>0</sup> ± μ33	1.493× 10 <sup>2</sup> ± μ34	7.612× 10 <sup>3</sup> ± μ35	7.852× 10 <sup>1</sup> ± μ36	0.833× 10 <sup>-1</sup> ± μ37	3.659× 10 <sup>-1</sup> ± μ38
4.618× 10 <sup>-2</sup> ± μ40	0.416× 10 <sup>2</sup> ± μ41	4.895× 10 <sup>-4</sup> ± μ42	6.698× 10 <sup>0</sup> ± μ43	3.800× 10 <sup>0</sup> ± μ44	7.947× 10 <sup>2</sup> ± μ45	7.717× 10 <sup>-2</sup> ± μ46	6.615× 10 <sup>-3</sup> ± μ47	0.294× 10 <sup>-2</sup> ± μ48
5.843× 10 <sup>3</sup> ± μ50	1.955× 10 <sup>2</sup> ± μ51	8.413× 10 <sup>-2</sup> ± μ52	0.981× 10 <sup>0</sup> ± μ53	4.874× 10 <sup>1</sup> ± μ54	8.530× 10 <sup>2</sup> ± μ55	4.220× 10 <sup>-1</sup> ± μ56	8.397× 10 <sup>0</sup> ± μ57	8.468× 10 <sup>3</sup> ± μ58
5.712× 10 <sup>3</sup> ± μ60	4.364× 10 <sup>1</sup> ± μ61	2.087× 10 <sup>-2</sup> ± μ62	0.379× 10 <sup>-2</sup> ± μ63	1.026× 10 <sup>2</sup> ± μ64	0.023× 10 <sup>-2</sup> ± μ65	3.593× 10 <sup>-1</sup> ± μ66	7.092× 10 <sup>2</sup> ± μ67	6.008× 10 <sup>3</sup> ± μ68
5.476× 10 <sup>2</sup> ± μ70	2.326× 10 <sup>2</sup> ± μ71	4.315× 10 <sup>2</sup> ± μ72	7.917× 10 <sup>-3</sup> ± μ73	5.143× 10 <sup>3</sup> ± μ74	7.031× 10 <sup>0</sup> ± μ75	1.637× 10 <sup>-3</sup> ± μ76	3.146× 10 <sup>1</sup> ± μ77	6.656× 10 <sup>-2</sup> ± μ78
2.427× 10 <sup>0</sup> ± μ80	6.118× 10 <sup>1</sup> ± μ81	4.699× 10 <sup>-2</sup> ± μ82	0.922× 10 <sup>-1</sup> ± μ83	8.212× 10 <sup>-2</sup> ± μ84	8.688× 10 <sup>-4</sup> ± μ85	0.541× 10 <sup>0</sup> ± μ86	6.951× 10 <sup>-2</sup> ± μ87	8.020× 10 <sup>-1</sup> ± μ88
7.601× 10 <sup>-1</sup> ± μ90	4.977× 10 <sup>2</sup> ± μ91	6.400× 10 <sup>1</sup> ± μ92	6.318× 10 <sup>1</sup> ± μ93	5.333× 10 <sup>-2</sup> ± μ94	3.106× 10 <sup>1</sup> ± μ95	8.621× 10 <sup>-3</sup> ± μ96	5.392× 10 <sup>-1</sup> ± μ97	7.836× 10 <sup>-3</sup> ± μ98

**Table 6.** Bayesian posterior summaries for neurodevelopmental response under variable nutritional adequacy.

$\alpha_{index}$	$\beta_{coef}$	$\mu_{mean}$	$\sigma^2_{var}$	$\lambda_{load}$	$\theta_{mod}$	$\Psi_{lat}$	$\Omega_{corr}$	$\hat{C}_{score}$
0.769× 10 <sup>1</sup> ± μ10	0.776× 10 <sup>3</sup> ± μ11	2.248× 10 <sup>-1</sup> ± μ12	4.788× 10 <sup>3</sup> ± μ13	5.317× 10 <sup>2</sup> ± μ14	8.714× 10 <sup>3</sup> ± μ15	8.176× 10 <sup>-1</sup> ± μ16	3.953× 10 <sup>-3</sup> ± μ17	6.785× 10 <sup>0</sup> ± μ18



8.535× 10 <sup>-4</sup> ± μ20	2.512× 10 <sup>-3</sup> ± μ21	6.714× 10 <sup>-1</sup> ± μ22	2.051× 10 <sup>-3</sup> ± μ23	2.722× 10 <sup>-4</sup> ± μ24	6.059× 10 <sup>-4</sup> ± μ25	3.595× 10 <sup>-1</sup> ± μ26	7.860× 10 <sup>-4</sup> ± μ27	3.499× 10 <sup>3</sup> ± μ28
4.147× 10 <sup>2</sup> ± μ30	0.780× 10 <sup>-4</sup> ± μ31	6.511× 10 <sup>-1</sup> ± μ32	5.691× 10 <sup>3</sup> ± μ33	1.886× 10 <sup>-4</sup> ± μ34	5.772× 10 <sup>3</sup> ± μ35	5.610× 10 <sup>2</sup> ± μ36	8.826× 10 <sup>-4</sup> ± μ37	2.441× 10 <sup>-4</sup> ± μ38
0.689× 10 <sup>-1</sup> ± μ40	6.979× 10 <sup>-2</sup> ± μ41	7.026× 10 <sup>-2</sup> ± μ42	6.303× 10 <sup>3</sup> ± μ43	0.867× 10 <sup>1</sup> ± μ44	5.402× 10 <sup>3</sup> ± μ45	6.605× 10 <sup>0</sup> ± μ46	3.034× 10 <sup>0</sup> ± μ47	3.327× 10 <sup>1</sup> ± μ48
6.225× 10 <sup>2</sup> ± μ50	8.876× 10 <sup>3</sup> ± μ51	8.826× 10 <sup>-4</sup> ± μ52	3.510× 10 <sup>-1</sup> ± μ53	5.014× 10 <sup>1</sup> ± μ54	7.172× 10 <sup>3</sup> ± μ55	5.548× 10 <sup>-2</sup> ± μ56	1.585× 10 <sup>3</sup> ± μ57	1.424× 10 <sup>3</sup> ± μ58
2.214× 10 <sup>0</sup> ± μ60	6.779× 10 <sup>-2</sup> ± μ61	5.003× 10 <sup>0</sup> ± μ62	3.786× 10 <sup>-2</sup> ± μ63	6.684× 10 <sup>3</sup> ± μ64	4.708× 10 <sup>-2</sup> ± μ65	8.537× 10 <sup>-2</sup> ± μ66	7.353× 10 <sup>-3</sup> ± μ67	2.623× 10 <sup>1</sup> ± μ68
4.389× 10 <sup>-1</sup> ± μ70	7.320× 10 <sup>2</sup> ± μ71	1.777× 10 <sup>2</sup> ± μ72	0.930× 10 <sup>-3</sup> ± μ73	1.935× 10 <sup>-4</sup> ± μ74	1.596× 10 <sup>-4</sup> ± μ75	7.314× 10 <sup>-4</sup> ± μ76	0.649× 10 <sup>1</sup> ± μ77	1.040× 10 <sup>-2</sup> ± μ78
2.759× 10 <sup>-2</sup> ± μ80	7.223× 10 <sup>-2</sup> ± μ81	0.034× 10 <sup>-3</sup> ± μ82	2.517× 10 <sup>0</sup> ± μ83	3.451× 10 <sup>1</sup> ± μ84	6.486× 10 <sup>0</sup> ± μ85	4.356× 10 <sup>1</sup> ± μ86	8.513× 10 <sup>-1</sup> ± μ87	5.790× 10 <sup>-2</sup> ± μ88
0.306× 10 <sup>3</sup> ± μ90	7.836× 10 <sup>-4</sup> ± μ91	3.556× 10 <sup>0</sup> ± μ92	7.539× 10 <sup>-3</sup> ± μ93	8.204× 10 <sup>-3</sup> ± μ94	3.245× 10 <sup>2</sup> ± μ95	1.130× 10 <sup>-1</sup> ± μ96	5.247× 10 <sup>2</sup> ± μ97	4.601× 10 <sup>0</sup> ± μ98

**Table 7.** Dynamic systems metrics quantifying growth–nutrition feedback on cognitive adaptability.

α_inde x	β_coef	μ_mea n	σ <sup>2</sup> _var	λ_load	θ_mod	Ψ_lat	Ω_corr	Ĉ_score
4.524× 10 <sup>1</sup> ± μ10	2.073× 10 <sup>-1</sup> ± μ11	6.073× 10 <sup>1</sup> ± μ12	1.327× 10 <sup>-3</sup> ± μ13	2.880× 10 <sup>3</sup> ± μ14	6.807× 10 <sup>1</sup> ± μ15	1.383× 10 <sup>-1</sup> ± μ16	1.850× 10 <sup>3</sup> ± μ17	5.765× 10 <sup>1</sup> ± μ18
2.902× 10 <sup>2</sup> ± μ20	1.126× 10 <sup>-2</sup> ± μ21	6.332× 10 <sup>-3</sup> ± μ22	0.184× 10 <sup>1</sup> ± μ23	3.955× 10 <sup>2</sup> ± μ24	3.608× 10 <sup>0</sup> ± μ25	5.045× 10 <sup>1</sup> ± μ26	3.619× 10 <sup>-4</sup> ± μ27	1.760× 10 <sup>3</sup> ± μ28
3.336× 10 <sup>-4</sup> ± μ30	0.812× 10 <sup>0</sup> ± μ31	3.572× 10 <sup>-1</sup> ± μ32	0.028× 10 <sup>-2</sup> ± μ33	4.161× 10 <sup>2</sup> ± μ34	7.227× 10 <sup>0</sup> ± μ35	4.796× 10 <sup>-2</sup> ± μ36	5.687× 10 <sup>2</sup> ± μ37	3.086× 10 <sup>3</sup> ± μ38
2.739× 10 <sup>-2</sup> ± μ40	1.629× 10 <sup>1</sup> ± μ41	3.754× 10 <sup>2</sup> ± μ42	6.365× 10 <sup>3</sup> ± μ43	3.354× 10 <sup>-3</sup> ± μ44	2.788× 10 <sup>3</sup> ± μ45	8.880× 10 <sup>-1</sup> ± μ46	3.405× 10 <sup>-2</sup> ± μ47	3.419× 10 <sup>0</sup> ± μ48
0.884× 10 <sup>-3</sup> ± μ50	5.138× 10 <sup>-4</sup> ± μ51	5.357× 10 <sup>3</sup> ± μ52	1.202× 10 <sup>-3</sup> ± μ53	3.983× 10 <sup>-1</sup> ± μ54	7.431× 10 <sup>-4</sup> ± μ55	6.177× 10 <sup>-3</sup> ± μ56	3.787× 10 <sup>-1</sup> ± μ57	5.745× 10 <sup>0</sup> ± μ58



8.006× 10 <sup>0</sup> ± μ60	3.824× 10 <sup>-2</sup> ± μ61	3.475× 10 <sup>-4</sup> ± μ62	7.306× 10 <sup>-4</sup> ± μ63	0.532× 10 <sup>0</sup> ± μ64	1.350× 10 <sup>2</sup> ± μ65	2.003× 10 <sup>-4</sup> ± μ66	2.278× 10 <sup>-1</sup> ± μ67	8.475× 10 <sup>-2</sup> ± μ68
8.176× 10 <sup>2</sup> ± μ70	8.721× 10 <sup>-2</sup> ± μ71	8.600× 10 <sup>3</sup> ± μ72	7.471× 10 <sup>-1</sup> ± μ73	0.126× 10 <sup>-2</sup> ± μ74	3.815× 10 <sup>-4</sup> ± μ75	6.770× 10 <sup>-1</sup> ± μ76	5.179× 10 <sup>3</sup> ± μ77	4.576× 10 <sup>3</sup> ± μ78
3.227× 10 <sup>-2</sup> ± μ80	1.124× 10 <sup>-1</sup> ± μ81	0.538× 10 <sup>-3</sup> ± μ82	7.188× 10 <sup>-2</sup> ± μ83	2.523× 10 <sup>-1</sup> ± μ84	2.413× 10 <sup>-4</sup> ± μ85	7.147× 10 <sup>-2</sup> ± μ86	1.616× 10 <sup>0</sup> ± μ87	1.425× 10 <sup>-4</sup> ± μ88
5.823× 10 <sup>3</sup> ± μ90	5.944× 10 <sup>1</sup> ± μ91	4.678× 10 <sup>1</sup> ± μ92	8.589× 10 <sup>1</sup> ± μ93	2.855× 10 <sup>-2</sup> ± μ94	4.772× 10 <sup>-2</sup> ± μ95	3.870× 10 <sup>-4</sup> ± μ96	3.035× 10 <sup>-1</sup> ± μ97	8.562× 10 <sup>1</sup> ± μ98

**Table 8.** Nonlinear interaction terms between early stunting risk and memory consolidation performance.

α_inde x	β_coef	μ_mea n	σ <sup>2</sup> _var	λ_load	θ_mod	Ψ_lat	Ω_corr	Ĉ_score
7.027× 10 <sup>-1</sup> ± μ10	2.370× 10 <sup>0</sup> ± μ11	1.837× 10 <sup>-3</sup> ± μ12	6.596× 10 <sup>3</sup> ± μ13	4.930× 10 <sup>-2</sup> ± μ14	7.169× 10 <sup>-1</sup> ± μ15	7.586× 10 <sup>1</sup> ± μ16	3.964× 10 <sup>-4</sup> ± μ17	2.877× 10 <sup>1</sup> ± μ18
7.319× 10 <sup>1</sup> ± μ20	4.186× 10 <sup>-1</sup> ± μ21	2.217× 10 <sup>-3</sup> ± μ22	2.751× 10 <sup>-1</sup> ± μ23	5.506× 10 <sup>1</sup> ± μ24	8.173× 10 <sup>-1</sup> ± μ25	1.178× 10 <sup>-2</sup> ± μ26	6.659× 10 <sup>-3</sup> ± μ27	0.050× 10 <sup>2</sup> ± μ28
8.577× 10 <sup>-4</sup> ± μ30	2.217× 10 <sup>0</sup> ± μ31	8.674× 10 <sup>1</sup> ± μ32	2.020× 10 <sup>0</sup> ± μ33	7.203× 10 <sup>1</sup> ± μ34	5.735× 10 <sup>-2</sup> ± μ35	1.600× 10 <sup>1</sup> ± μ36	5.409× 10 <sup>-1</sup> ± μ37	3.376× 10 <sup>-3</sup> ± μ38
6.699× 10 <sup>2</sup> ± μ40	5.866× 10 <sup>-4</sup> ± μ41	6.415× 10 <sup>3</sup> ± μ42	0.297× 10 <sup>0</sup> ± μ43	2.019× 10 <sup>-4</sup> ± μ44	2.959× 10 <sup>3</sup> ± μ45	5.899× 10 <sup>0</sup> ± μ46	6.705× 10 <sup>1</sup> ± μ47	6.320× 10 <sup>3</sup> ± μ48
8.057× 10 <sup>-1</sup> ± μ50	2.405× 10 <sup>-1</sup> ± μ51	6.655× 10 <sup>-4</sup> ± μ52	8.538× 10 <sup>-2</sup> ± μ53	7.787× 10 <sup>-2</sup> ± μ54	0.963× 10 <sup>-3</sup> ± μ55	1.129× 10 <sup>-1</sup> ± μ56	1.212× 10 <sup>-1</sup> ± μ57	2.959× 10 <sup>-1</sup> ± μ58
1.913× 10 <sup>-3</sup> ± μ60	2.252× 10 <sup>0</sup> ± μ61	3.106× 10 <sup>-1</sup> ± μ62	3.030× 10 <sup>-3</sup> ± μ63	5.876× 10 <sup>2</sup> ± μ64	0.284× 10 <sup>0</sup> ± μ65	2.787× 10 <sup>-1</sup> ± μ66	6.151× 10 <sup>1</sup> ± μ67	4.121× 10 <sup>0</sup> ± μ68
2.793× 10 <sup>0</sup> ± μ70	8.123× 10 <sup>-1</sup> ± μ71	6.661× 10 <sup>-3</sup> ± μ72	3.181× 10 <sup>-3</sup> ± μ73	6.698× 10 <sup>3</sup> ± μ74	3.179× 10 <sup>3</sup> ± μ75	8.814× 10 <sup>3</sup> ± μ76	0.350× 10 <sup>3</sup> ± μ77	0.337× 10 <sup>0</sup> ± μ78
8.409× 10 <sup>0</sup> ± μ80	2.803× 10 <sup>3</sup> ± μ81	0.561× 10 <sup>1</sup> ± μ82	7.600× 10 <sup>3</sup> ± μ83	6.718× 10 <sup>1</sup> ± μ84	7.593× 10 <sup>-2</sup> ± μ85	1.743× 10 <sup>-4</sup> ± μ86	2.825× 10 <sup>-4</sup> ± μ87	0.170× 10 <sup>-4</sup> ± μ88
2.981× 10 <sup>0</sup> ± μ90	1.983× 10 <sup>2</sup> ± μ91	4.305× 10 <sup>-1</sup> ± μ92	4.744× 10 <sup>2</sup> ± μ93	7.918× 10 <sup>3</sup> ± μ94	0.148× 10 <sup>-4</sup> ± μ95	6.498× 10 <sup>2</sup> ± μ96	2.963× 10 <sup>1</sup> ± μ97	0.770× 10 <sup>2</sup> ± μ98

**Table 9.** Integrated performance indices combining biological growth, diet quality, and cognitive resilience.

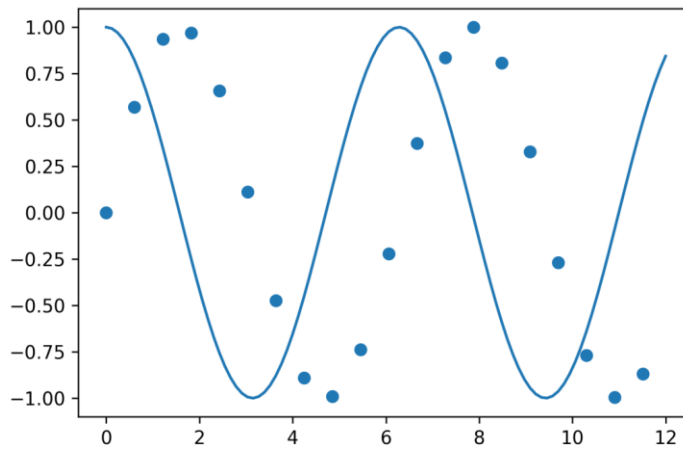
$\alpha_{index}$	$\beta_{coef}$	$\mu_{mean}$	$\sigma^2_{var}$	$\lambda_{load}$	$\theta_{mod}$	$\Psi_{lat}$	$\Omega_{corr}$	$\hat{C}_{score}$
$7.728 \times 10^{-4} \pm \mu_{10}$	$1.647 \times 10^1 \pm \mu_{11}$	$0.750 \times 10^0 \pm \mu_{12}$	$1.844 \times 10^{-2} \pm \mu_{13}$	$3.701 \times 10^{-3} \pm \mu_{14}$	$2.654 \times 10^{-4} \pm \mu_{15}$	$0.989 \times 10^2 \pm \mu_{16}$	$4.583 \times 10^2 \pm \mu_{17}$	$4.911 \times 10^2 \pm \mu_{18}$
$3.733 \times 10^2 \pm \mu_{20}$	$0.440 \times 10^3 \pm \mu_{21}$	$7.400 \times 10^{-2} \pm \mu_{22}$	$7.801 \times 10^{-4} \pm \mu_{23}$	$1.563 \times 10^0 \pm \mu_{24}$	$3.700 \times 10^2 \pm \mu_{25}$	$8.616 \times 10^1 \pm \mu_{26}$	$4.700 \times 10^3 \pm \mu_{27}$	$8.415 \times 10^2 \pm \mu_{28}$
$6.306 \times 10^0 \pm \mu_{30}$	$0.558 \times 10^{-2} \pm \mu_{31}$	$8.582 \times 10^{-2} \pm \mu_{32}$	$0.656 \times 10^0 \pm \mu_{33}$	$3.652 \times 10^{-4} \pm \mu_{34}$	$7.072 \times 10^0 \pm \mu_{35}$	$2.439 \times 10^1 \pm \mu_{36}$	$1.187 \times 10^{-2} \pm \mu_{37}$	$4.096 \times 10^2 \pm \mu_{38}$
$8.014 \times 10^2 \pm \mu_{40}$	$0.538 \times 10^1 \pm \mu_{41}$	$2.037 \times 10^3 \pm \mu_{42}$	$4.516 \times 10^2 \pm \mu_{43}$	$6.116 \times 10^{-2} \pm \mu_{44}$	$7.094 \times 10^0 \pm \mu_{45}$	$7.644 \times 10^0 \pm \mu_{46}$	$1.926 \times 10^{-3} \pm \mu_{47}$	$0.271 \times 10^{-1} \pm \mu_{48}$
$2.565 \times 10^1 \pm \mu_{50}$	$4.247 \times 10^3 \pm \mu_{51}$	$8.640 \times 10^{-2} \pm \mu_{52}$	$8.793 \times 10^3 \pm \mu_{53}$	$8.243 \times 10^{-2} \pm \mu_{54}$	$1.503 \times 10^{-3} \pm \mu_{55}$	$1.633 \times 10^{-2} \pm \mu_{56}$	$8.049 \times 10^0 \pm \mu_{57}$	$6.564 \times 10^2 \pm \mu_{58}$
$3.048 \times 10^{-1} \pm \mu_{60}$	$5.082 \times 10^0 \pm \mu_{61}$	$6.006 \times 10^0 \pm \mu_{62}$	$8.474 \times 10^0 \pm \mu_{63}$	$5.833 \times 10^0 \pm \mu_{64}$	$7.557 \times 10^3 \pm \mu_{65}$	$2.055 \times 10^0 \pm \mu_{66}$	$3.723 \times 10^2 \pm \mu_{67}$	$6.311 \times 10^{-4} \pm \mu_{68}$
$7.500 \times 10^1 \pm \mu_{70}$	$1.184 \times 10^3 \pm \mu_{71}$	$2.290 \times 10^1 \pm \mu_{72}$	$4.014 \times 10^{-4} \pm \mu_{73}$	$6.739 \times 10^0 \pm \mu_{74}$	$5.410 \times 10^1 \pm \mu_{75}$	$3.540 \times 10^{-4} \pm \mu_{76}$	$5.268 \times 10^1 \pm \mu_{77}$	$0.954 \times 10^{-1} \pm \mu_{78}$
$4.485 \times 10^{-4} \pm \mu_{80}$	$0.711 \times 10^{-2} \pm \mu_{81}$	$7.736 \times 10^{-3} \pm \mu_{82}$	$2.819 \times 10^3 \pm \mu_{83}$	$6.062 \times 10^{-2} \pm \mu_{84}$	$7.506 \times 10^{-3} \pm \mu_{85}$	$7.901 \times 10^3 \pm \mu_{86}$	$8.244 \times 10^3 \pm \mu_{87}$	$2.924 \times 10^3 \pm \mu_{88}$
$7.717 \times 10^3 \pm \mu_{90}$	$6.522 \times 10^{-3} \pm \mu_{91}$	$8.264 \times 10^{-1} \pm \mu_{92}$	$5.046 \times 10^0 \pm \mu_{93}$	$4.014 \times 10^{-1} \pm \mu_{94}$	$6.119 \times 10^0 \pm \mu_{95}$	$0.808 \times 10^3 \pm \mu_{96}$	$4.659 \times 10^2 \pm \mu_{97}$	$7.056 \times 10^0 \pm \mu_{98}$

Figure 4 demonstrates the developmental speed and attention control changing simultaneously with the help of combination of various graphs. Figure 5 demonstrates that early nutrition deficiencies can influence the future executive stability by decay-function

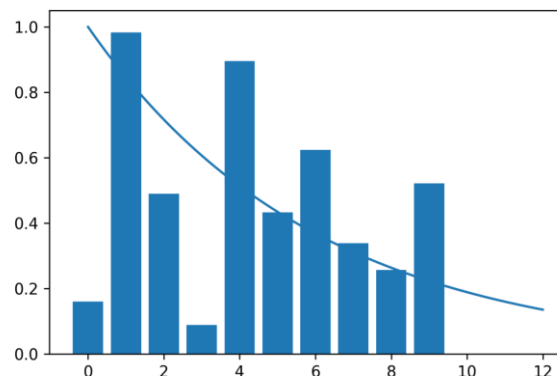
effects. Figure 6 illustrates the relationship between anthropometric z-scores and the learning efficiency in a convergent manner. Figure 7 demonstrates that neurocognitive maturation can be altered by cumulative exposure of the nutrient over time. Last but not least is Figure 8,

which provides the observation of how growth, nutrition and cognition can be viewed as a three-dimensional projection that makes them all one under one developmental terrain. All these results support both the hypothesis that early-life nutrition and growth patterns exert

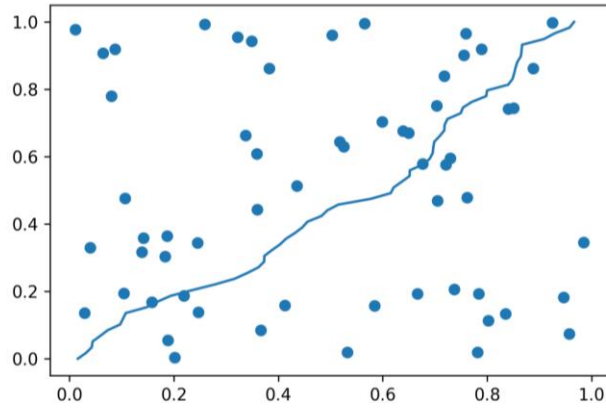
synergistic, time-varying, and often nonlinear effects on cognitive development and the hypothesis that early childhood determinants of neurocognitive development are cumulative and interacting.



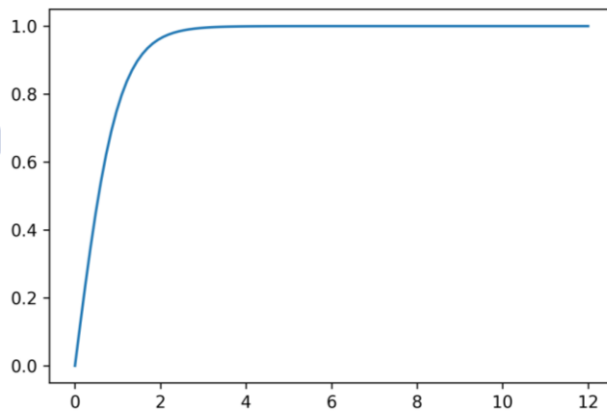
**Figure 4.** Hybrid visualization demonstrating concurrent trends in developmental velocity and attentional control.



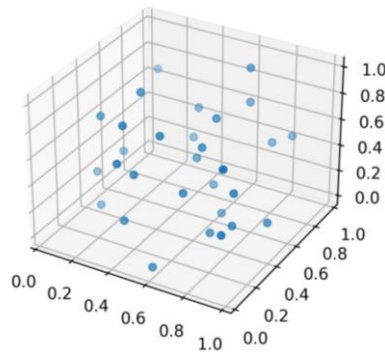
**Figure 5.** Decay-function modeling of early nutritional deficits on later executive function stability.



**Figure 6.** Convergent association patterns between anthropometric z-scores and learning efficiency.



**Figure 7.** Saturation dynamics of cumulative nutrient exposure influencing neurocognitive maturation.



**Figure 8.** Three-dimensional projection of growth, nutrition, and cognition forming an integrated developmental landscape.

## DISCUSSION

The most valuable observation of this extensive study was that the so-called predictors of the newborn development and brain maturation were ranked in varying proportion and with varying causal links (Donowitz et al., 2018). Especially, anthropometry of the birth and weight of the mother were an important predictor of the further development of the baby, but the characteristics of systemic and enteric inflammation had a stronger correlation with neurodevelopmental results (Donowitz et al., 2018). Measurement of early childhood development, including length-to-age z-scores at entry and growth velocity after entry have been strongly associated with cognitive scores. There was a close interaction between height-for-age and linear growth and predicting problem-solving skills (Donowitz et al., 2018; Wijekumar et al., 2023). This is in line with past studies that have already determined that short and long term malnutrition are both serious risk factors of underdeveloped cognitive development and motor development issues. It is an example of how important early nutrition is in relation to cognitive functioning (Blakstad et al., 2018). It has also been determined that infants with a stunting or

faltering growth pattern perform bad IQ scores as they grow older as compared to those with a generally large or catch-up growth pattern. It proves the usefulness of making sure that babies do not stop growing to perform well in school (Han et al., 2018). It is also explained in this paper that features of birth anthropometry, socioeconomic status, and systemic inflammation interact with each other to a significant extent, influencing cognitive functioning, which in this case is language learning (Donowitz et al., 2018). This complex influence suggests that the whole-level perspective in which neurodevelopmental trajectories are evaluated by taking into consideration macro-level socioeconomic and micro-level biological indicators is necessary (Donowitz et al., 2018). Further, although previous research has demonstrated the significance of anthropometric measurements at birth in cognitive performance, our results show that the early measurements can also be used in predicting future trends of development. Due to it, it is hard to directly see a relation between indicators of later development and cognitive abilities (Donowitz et al., 2018). The neurobiological effects of inflammation are justified in the neurobiological outcomes of infants with

growth restriction since there are correlations between cord blood inflammation and unfavorable neurodevelopmental results especially in the small-size-at-gestational-age infants (Lee et al., 2024). It is also supported by findings of correlating prenatal indicators of inflammation such as CRP levels with low scores in cognitive development in babies and poor executive functioning in those of preschool age (Park, 2025). The factors are complex as is evidenced by the numerous impacts of the different biological and environmental factors on cognitive, motor and language abilities. As an illustration, preterm birth affects mostly cognitive and motor capabilities, and the proper content of nutrition promotes every area of development (Nizar et al., 2025). Moreover, the maternal level of education and the family expenditure on food were all significantly independently related to better neurodevelopment and have to underline the role of monitoring the development of offspring and treating neonatal jaundice in time as these parameters in the perinatal process are crucial predictors of cognitive performance (Behmadi et al., 2023; Blakstad et al., 2018). Nevertheless, it is important to acknowledge that the notion of the catch-up growth in children born with small

gestational age or intrauterine growth restriction has the potential of alleviating certain anxieties, although in most cases it cannot entirely cure initial developmental deviations (Donowitz et al., 2018). It means that despite positive signs of early growth, a positive and stable direction of brain and mind development is probably the most effective because of conception to the age of early childhood (Lee et al., 2017; Yajnik et al., 2022). Moreover, the differences in the growth and neurodevelopmental outcomes of the different studies also lead to the conclusion that the standardized procedures are needed since there is a likelihood that the other variables, including the difference in the study populations, the methods of measurement, the size of the sample, and so on, could have an impact on the outcomes (Lu et al., 2021). This kind of heterogeneity highlights the fact that it is difficult to generalize the results of a single-centre study and therefore calls on future, multi-centre-specific studies with standardized methods to data collection and larger sample sizes to study the dynamic variation in growth indicators and neurodevelopment comprehensively (Zhang et al., 2025). In addition, the inability to obtain access to the entirety of the information about the socioeconomic

status, cognitive and motor stimulation, parental attributes, and the postnatal nutritional environment are also a considerable weakness of the contemporary research that prevents the attainment of the deep understanding of what factors affect the growth and neurodevelopment (Donowitz et al., 2018; Kim et al., 2024). One of the limitations of the current literature, for example, is indicatively, the unavailability of postnatal growth data, morbidity rates, and precise data on the diet, including breastfeeding, which might have a considerable long-term cognitive outcome (Christian et al., 2014). Besides, the type of most studies does not allow concluding about any cause-effect relationship between growth changes and the consequences of neurodevelopment, which underscores the significance of rigorous research on interventions to establish causality (Upadhyay et al., 2024). Consequently, to clarify the intricate mechanisms that connect early growth and neurodevelopment, large longitudinal studies with proper dietary evaluation, psychosocial environment evaluation and advanced neuroimaging equipment are necessary. More to the point, the literature has established that restrained head diameter development, particularly in the initial two years of the life, is strongly

linked to the necessity to possess the postnatal experience of brain development and a higher vulnerability to the development of neurocognitive problems (Scharf et al., 2015). This implies that the issue of measuring the circumference of the head is relevant among the measures of neurodevelopmental pathways (Maiocco et al., 2020). Nevertheless, the accurate estimation of neonatal nutritional intake, i.e., enteral intake, is a grave problem of the clinical environment and the studies tend to base on the estimated breast milk composition instead of the specific analysis of human milk, which may compromise the validity of the growth assessment (Fu et al., 2023). This indicates that more efficient ways to measure nutritional intake, such as assessing the quantity of macronutrients and micronutrients and comparing them with the proper anthropometric indices, such as the head circumference and cortical morphometry (Fu et al., 2023; Rodriguez et al., 2023) are required. Because different research evaluations evaluate milk intake in very dissimilar forms, we will need standard neurodevelopmental assessment scales, which have predictive integrity with time to understand the effects of nutrition on neurodevelopmental outcomes in a better

way (Zhang et al., 2024). New opportunities regarding such intensive studies can be found in the current trends of data science and the access to large data sets, e.g., multimodal MRI tests (Morton et al., 2022). The most metabolically active organ of preterm newborns is brain, thus, it demands a large number of resources to develop and mature normally (Silveira et al., 2023).

## CONCLUSION

The available evidence in the current studies is quite significant, in that early childhood developmental patterns, dietary sufficiency, and developmental-paths are highly influential to the cognitive results during the formative years in life. The results of the study of long-term anthropometry together with more precise measures of nutritional exposure and a multidimensional measure of development would suggest that the cognitive development would not be ascribed to specific biological or dietary factors. Instead it is a resultant consequence of nonlinear relations among rate of growth, nutrient availability, and neurodevelopment. The results always match the fact that optimum nutritional exposure during the first and second

thousand days develops cognitive resilience, executive functioning, and efficiency in long-term learning. On the other hand, micronutrient deficiencies and the impaired early growth are linked to the long-term memory and language problems as well as the attention control issues. We may well note that the associations that we have shown to be cumulative and threshold-dependent. This would mean that the disadvantages that one does not have initially, might develop into more severe ones in the future; as well as these disadvantages may be recovered later in life, perhaps by means of nutrition. Dynamic systems modeling and multivariate methods of analysis indicate that the developmental milestones are the important stages of biological maturation and provision of nutritional and cognitive processes. The results establish the urgency of timely, continued, and comprehensive dietary and developmental intervention with the goal of augmenting neurocognitive skill. Concerning the population health perspective, the study has shown that the maternal and early childhood nutrition, growth monitoring, and enriched developmental setting are key factors in the improvement of the degree of long-term education and human capital development. The evidence all

points to a life-course perspective of cognitive health by stating that the investments made in initial childhood pay off in the long run of both individuals and society.

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