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Highlights

1. Neurocognitive development's high energy demand necessitates a trade-off in human children between brain growth and other biological functions, including body growth.
2. Previous studies indicate that the peak of brain energy consumption at around age 5 aligns with the nadir of childhood body mass increase, termed 'adiposity rebound'.
3. A delayed adiposity rebound, indicative of slower growth may correlate enhanced language abilities in children.
4. Our preregistered study confirms this correlation in girls and associates early cognitive stimulation with improved language skills and adiposity rebound time.

Abstract

During human childhood, brain development and body growth compete for limited metabolic resources, resulting in a trade-off where energy allocated to brain development can decrease as body growth accelerates. This preregistered study explores the potential links between language skills, used as a proxy for brain development, and body mass index at 3 distinct developmental stages, serving as proxies for body growth. Analyzing longitudinal data from 2002 children in the EDEN mother-child cohort using structural equation modeling, we identified a compelling pattern of associations: girls with a delayed adiposity rebound, signaling slower growth rate, demonstrated better language proficiency at ages 5-6. Importantly, this correlation appears specific to language skills and does not extend to non-verbal cognitive abilities. Exploratory analyses show that early environmental factors that contribute to enhanced cognitive development, such as higher parental socio-economic status and higher levels of cognitive stimulation, are positively linked to both language skills and the age at which adiposity rebound occurs in girls. Overall, our findings lend support to the existence of an energy allocation trade-off mechanism that appears to prioritize language function over body growth investment, in girls.

Keywords

Development
Body growth
Language
Life History trade-off
Early life environment

Introduction

The importance of language proficiency for mental health and academic success is widely acknowledged (Henry et al., 2014; Miller et al., 2018; Pace et al., 2018), but the variability in children's language skills remains largely unexplained (Kidd & Donnelly, 2020). One approach to understand this variability is to investigate the interplay between the metabolic demands of the developing brain and those of bodily growth, as well as the environmental factors that influence these intricate developmental processes.

Current theoretical frameworks suggest that language development depends in part on how organisms trade their limited stock of energy resources between competing biological functions (Kaplan & Robson, 2002; Longman et al., 2017; Urlacher et al., 2019). The distribution of energy between the brain and the rest of the body (Aiello & Wells, 2002), particularly during periods of growth, is thought to be a critical determinant of cognitive and physical development (Kaplan et al., 2000; Kuzawa & Blair, 2019). Given the substantial and fluctuating metabolic demands of the brain throughout childhood (Chugani, 1998; Leonard et al., 2003; Madsen et al., 1995; Madsen & Vorstrup, 1991), the organism must finely tune its energy budget to support cognitive development adequately (Aronoff et al., 2022; Navarrete et al., 2011).

In human children, a trade-off in resource allocation between brain development and body growth has been shown at the population level (Aronov et al., 2022; Kauzawa et al., 2014), with emerging studies beginning to analyze data from individual children (Blair et al., 2019; Rollins et al., 2021). These investigations propose that an inverse relationship between the rates of body growth and brain development may manifest at various stages, especially during infancy and early childhood. Infants typically have substantial body fat at birth, which predominantly drives the energetic cost of growth during the initial 6-9 months (Kuzawa, 1998; Nilsson et al., 2017). At birth, the body's glucose utilization surpasses that of the brain; however, at around 9 months of age, the body's metabolic expenditure starts to be limited by the brain's glucose consumption (Kuzawa et al., 2014), a growth milestone referred to as the "infancy BMI peak" (Silverwood et al., 2009; Wen et al., 2012). By around 18 months, the brain's glucose consumption exceeds that of the body, peaking at 5 years of age when it accounts for approximately 65% of the organism's metabolism at rest (Holliday, 1986) – in comparison the brain accounts for ~20% of resting metabolic rate at adulthood (Mergenthaler et al., 2013). At age five, when body growth slow to its lowest, a metabolic shift occurs, redirecting resources to body growth during a phase known as the 'adiposity rebound' (Rolland-Cachera et al., 1984), which also marks a decrease in the proportion of energy devoted to brain development (Kuzawa et al., 2014).

The interplay of early metabolic exchanges between the brain and body has prompted researchers to formulate new theoretical propositions regarding the pace of cognitive development (Kuzawa & Blair, 2019). It is posited that the rate of body growth may inversely reflect the allocation of resources towards developing high-level cognitive functions. Recent empirical evidence suggest a trade-off where a slower enhancement in executive functions from age 3 to 5 years is associated with accelerated body growth, spanning from infancy (Blair et al., 2019) through to adolescence (Rollins et al., 2021). Building upon these findings, this article examines the relationship between specific body growth milestones and language proficiency in early and middle childhood. The developmental interdependence of language and executive functions is well-documented (Bohlmann et al., 2015; Daneri & Blair, 2017), with the trajectory of executive functions being influenced by early language development (Romeo et al., 2022; Slot & von Suchodoletz, 2018). Consequently, it is plausible that more rapid growth in the early years of life may correspond with language capabilities. In this context, language proficiency, akin to executive functions, serves as a metric of cognitive development, offering a lens through which to infer the energetic demands of brain maturation.

Specifically, prioritizing early investment in body growth may be indicative of atypical cognitive functioning in early to middle childhood. Given the rapid development of language during early childhood, and particularly in the preschool years (i.e., ages 0–3 years) (Gervain, 2020), this study aims to explore the association between body-mass index (BMI) trajectories and language abilities from birth to three developmental milestones (Cole, 2004; Rolland-Cachera et al., 1984; Silverwood et al., 2009; Wen et al., 2012).: (i) the infancy BMI peak, occurring around 9 months, marking the highest BMI value before it begins to decline; (ii) the inflection point in BMI velocity, around 12 months, indicating when the rate of BMI change starts to slow down; (iii) the adiposity rebound, typically around 5-6 years, when BMI starts to rise again after reaching its lowest point in a child's lifetime. The infancy BMI peak and the adiposity rebound are established risk factors for obesity (Cole et al., 2004; Rolland-Cachera et al., 1984; Roy et al., 2016), while the BMI inflection point signals the shift from rapid to more stable or slower growth patterns.

Three pre-registered hypotheses are tested:

- **Hypothesis 1** states that the individuals' age (model 1a) or BMI magnitude (model 1b) at which the infancy BMI peak is predictive of general language abilities at 5-6 years via the level of vocabulary measured at 24 months.
- **Hypothesis 2** posits that the individuals' age (model 2a) or BMI magnitude (model 2b) at the BMI inflection point is correlated with language abilities at 5-6 years.
- **Hypothesis 3** proposes that the individuals' age (model 3a) or BMI magnitude (model 3b) at the adiposity rebound is associated with language abilities at 5-6-years.

We expect that earlier attainment of these key growth milestones may be inversely related to language proficiency at 24 months and/or 5-6 years. Specifically, children who experience an early infancy BMI peak should display weaker language abilities at 24 months, potentially influencing language abilities at 5-6 years. A similar relationship is expected between adiposity rebound (or BMI inflection point) and language abilities, with an early adiposity rebounds possibly leading to poorer language outcomes at 5-6 years.

To test these hypotheses, we applied multivariate structural equation modelling (SEM) (Kline, 2016) on longitudinal data from the EDEN mother-child study, a prospective cohort designed to assess pre- and postnatal determinants of child health and development (Heude et al., 2016).

Method

The data were collected as part of the EDEN cohort project (Heude et al., 2016). The methodology described in this report differs by three points from the pre-recorded report. A comprehensive explanation of these modifications is provided in the supplementary material.

Participants

The EDEN mother–child study is a prospective cohort designed to assess pre- and postnatal factors that influence the health and development of children (Heude et al., 2016). The study was approved by the ethics research committee of Kremlin-Bicêtre Hospital (ID 0270 of 12 December 2012) and by Data Protection Authority (CNIL, ID 902267 of 12 December 2012), and is in accordance with the Declaration of Helsinki (World Medical Association, 2008). Both parents gave their written informed consents.

The cohort included 2,002 mother-child pairs, who were recruited between 2003 and 2006 in two university hospital in Nancy and Poitiers (France). The inclusion criteria stipulated that the mothers were before 24 weeks of amenorrhea. Exclusion criteria were mothers younger than 18 years, who had multiple pregnancies, had a history of diabetes, were illiterate and expressed an intention to move out of the region within the next 3 years.

Among the 2,002 children included in the EDEN study, we focus on a subset of children who had complete data at which one of the 3 milestones of body growth were calculated, i.e., age at infancy BMI peak, age at BMI inflection point, and age at adiposity rebound. Consequently, we were left with a sample of N=1713 children who had complete data for the age at infancy BMI peak, a sample of N=1519 children with complete data for the age at BMI inflection point, and a sample of N=1415 with complete data for the age at adiposity rebound.

Measures

Two types of measures are analyzed: (i) measures related to body growth and (ii) measures related to language skill. We provide an overview of the age range for each of the measures in table 1. In table 2, we present the descriptive statistics for the raw variables for boys and girls, respectively. These tables provide a comprehensive summary of our data, including mean values, standard deviations, and other key statistical measures.

Body Growth

Anthropometric measurements. At birth, all weight and height measures were collected from health records. At 4 and 8 months, and 2 and 4 years, mothers completed mailed questionnaires in which they reported their infant's weight and length taken at routine health checkups. These measures were taken by the family practitioner and documented in the infant's personal health record booklet. At ages 1, 3 and 5 years, the children were measured in a standardized fashion, with height and weight being measured twice and then averaged. This ensured that the measurements were as accurate as possible. Height was measured to the nearest 0.1 cm using wall-mounted stadiometers (Model 208; SECA, Hamburg, Germany) as the children stood barefoot. Weight was measured to the nearest 0.2 kg with an electronic scale (Model 888; SECA, Hamburg, Germany). The children wore light underwear during these measurements to minimize any additional weight.

Measurement of BMI (Body Mass Index) and BMI curve indicators. BMI was calculated at each age by dividing weight in kilograms by the square of height in meters. On average, children had 10 BMI measurements between birth and 13 years. By collecting BMI measurements at multiple points throughout childhood, we were able to track changes in body mass composition over time and identify three developmental points: the infancy BMI peak, the BMI curve inflection, and the adiposity rebound. To measure these points, we used data from specific time periods. We used data from day 3 and 24 months to measure the infancy BMI peak, data from 6 to 36 months to measure the BMI curve inflection, and data from 18 months and the maximum age available to measure the adiposity rebound.

We modeled separate BMI curves for each time period using a cubic mixed-effects models with random effects for intercept, slope, quadratic, and cubic terms (equation 1). The following equation describes the general model applied for the i^{th} individual at the t^{th} time point, whatever the period considered (Cissé et al., 2021).

$$\log(\mathrm{BMI}_{it}) = \beta_0 + \sum_{j=1}^{3} \beta_j \mathrm{Age}_{it}{}^{j} + b_{0i} + \sum_{j=1}^{3} b_{ji} \mathrm{Age}_{it}{}^{j} + \varepsilon_{it} \qquad \textit{equation 1}$$

where:

- $\beta_0, \beta_1, \beta_2, \beta_3$ are the parameters for the fixed effects,
- $b_{0i}, b_{1i}, b_{2i}, b_{3i}$ are the parameter estimates for the random effects on the polynomial coefficients for each individual.

This equation allowed us to obtain individual period-specific BMI curves for each child.

We then calculated the first and second derivatives functions for each curve, which provide information about the rate of change in BMI over time. Specifically, the first derivative, or velocity, helps us pinpoint when the BMI growth rate is at its peak or when it reaches a rebound. The second derivative, or acceleration, is crucial for identifying inflection points in the BMI curve that signal transitions in the growth trajectory.

Thus, to determine the age at which the infancy BMI peak occurred, we looked for the point at which the first derivative was zero, and the second derivative was negative or zero (S1a-b Figure). Similarly, to determine the age at which the adiposity rebound occurred, we looked for the point at which the first derivative was zero, and the second derivative was positive or zero (S1c-d Figure). After the infancy BMI peak, the BMI decreased rapidly until it reached an inflection point where the decrease slowed down and the BMI velocity increased. The inflection point was assessed as the age at which the second derivative of the BMI curve was zero and the third derivative was positive (S1e-f Figure).

Language abilities

The language proficiency was assessed using the following measures at different ages.

At 2 years of age

Expressive vocabulary was evaluated using the short French version of the MacArthur-Bates Communicative Development Inventory (CDI-2) (Kern et al., 2010; Kern & Gayraud, 2010; Peyre et al., 2014). Parents were asked to indicate which words from a list of 100 words their children could say spontaneously, and the child's score was the sum of the words produced. This measure of vocabulary growth is important as early word production is one of the earliest reliable indicators of language acquisition and is a stable linguistic trait in childhood (Rowe et al., 2012).

At 5-6 years of age

Trained psychologists administered neuropsychological tests from the Wechsler Preschool and Primary Scale of Intelligence (WPPSI-III) (Wechsler, 1967) and the Developmental NEuroPSYchological Assessment (NEPSY) (Korkman et al., 2003) to assess each child's cognitive skill. The WPPSI-III subtests were used to assess several skills contributing to verbal intelligence, which is an overall score of linguistic ability. In contrast, the sub-tests of the NEPSY were designed to provide a score on a specific language skill, namely the ability to manipulate short units of speech.

Conceptualization (WPPSI-III). This subtest is used to assess a child's ability to understand and use abstract concepts and relationships. The test measures a child's ability to categorize and group objects based on their similarities and differences. The test involves showing to the child a series of pictures and asking them to describe how they are related or how they are different. The subtest conceptualization is a measure of a child's ability to think abstractly and use reasoning skills to solve problems.

Vocabulary (WPPSI-III). This subtest is used to measure a child's ability to understand and use language. The subtest consists of a series of pictures, and the child is asked to name the objects or actions depicted in the pictures. The child's responses are then evaluated to determine their level of vocabulary knowledge and understanding.

Verbal reasoning (WPPSI-III). This subtest consists of a series of questions that require the child to use their language and reasoning skills to identify similarities and differences between objects, to complete sentences and to identify missing words. The questions are designed to be progressively more difficult, so that the child's level of verbal reasoning can be accurately assessed.

Nonword repetition (NEPSY). This subtest assesses a child's phonological processing and verbal short-term memory skills. In this task, the child is asked to repeat a series of pseudowords, which have been designed to be progressively more difficult. The subtest measures the child's ability to accurately repeat the sounds and syllables of the pseudowords.

Phonological processing (NEPSY). This subtest is composed of two tasks designed to assess a child ability to process and manipulate the sounds of language (i.e., phonological awareness). In the word segment recognition task, the child is asked to identify words from short sentences. In the phonological segmentation task, the child is asked to repeat a word and then to create a new word by omitting a syllable or a phoneme, or by substituting one phoneme for another.

Sentence repetition (NEPSY). This subtest is designed to assess the ability to repeat sentences of increasing complexity and length. The child is read a series of sentences and asked to recall each sentence immediately after it is presented.

Covariates

The structural equation models used in this study were adjusted for three factors potentially associated with cognitive development and/or body growth. Firstly, children's sex was included as a grouping factor to address any disparities between boys and girls in the relationships between body growth and the language proficiency (Girls = 1; Boys = 0). Secondly, the respondents' recruitment center was taken into account (Poitiers = 1; Nancy = 0). Previous research has shown differences in language outcomes among children recruited from these two hospital centers within the EDEN cohort (Peyre et al., 2016). Finally, we created an adjustment variable using a composite score that reflect the level of adversity experienced by children before and immediately after birth. This composite score encompassed nine factors known to affect early childhood diet (Gentner & Leppert, 2019; Lindsay et al., 2019) as well as neural, cognitive and behavioral development (Bath, 2020; Frankenhuis et al., 2020). These factors included gestational age at birth (in weeks), exposure to alcohol and cigarette smoking during pregnancy (no = 1), breastfeeding (yes = 1), father absence (no = 1), monthly household income at birth (in €), education levels of both mother and father (each scored from 1 = did not attend school to 9 = university, based on the French school system), and household density (number of adults and children living in the house divided by the number of rooms). Scores for these nine variables were z-scored, allowing their cumulative sum to reflect the degree of perinatal adversity. A higher score on this composite variable indicated greater exposure to perinatal adversity. Our approach of summing z-scores is grounded in both theoretical and empirical research. Current models suggest that factors contributing to adversity vary in nature and do not necessarily correlate with each other (McLaughlin et al., 2021; Ellis et al., 2009) (S2 Figure). Such emergent variables have been effectively modelled in prior studies using sums of z-scored indicators (Baptista et al., 2023; Brumbach et al., 2009; Jacquet et al., 2019; Mell et al., 2018). Moreover, this composite scoring approach inherently assigns greater weight to more dispersed indicators, which represent rarer adverse events.

Pre-registered analyses

Structural equation models

Our study employed structural equation modeling (SEM) to conduct multivariate analyses on our three samples. These SEMs were carried out using R (https://www.r-project.org/) with R Studio using the R package *lavaan* (Rosseel, 2012). These SEMs involved a measurement model that relates observed indicators to a smaller set of unobservable latent variables, and a structural model that estimates the strength of the link between latent variables and single indicators by specifying paths between them. The detailed specification of the measurement and structural models of each SEM used in our analysis are provided in supplementary materials section ‘Supplementary Methods. Detailed specification of the structural equation models’).

We specified three sets of SEMs: Models 1a and 1b test Hypothesis 1 on Sample 1, Models 2a and 2b test Hypothesis 2 on Sample 2, and Models 3a and 3b test Hypothesis 3 on Sample 3. Each model involved one reflective latent variable aimed at capturing language proficiency in 5-6-year-old children, which was modeled either as the indirect (Model 1) or direct (Models 2 and 3) outcome of body growth parameters. Models 1a and 1b incorporated a variable assessing early vocabulary size, as a mediator of the association between body growth parameters and language proficiency. Moreover, if we observe a relationship between adiposity rebound and language proficiency at 5-6 years, a complementary model testing whether the effect of the adiposity rebound is specifically related to language skills, or whether it can be generalized to non-verbal cognitive functioning, will be fitted.

These SEMs allowed us to examine whether and how variations in the timing of the infancy BMI peak (model 1), the BMI inflection point (model 2), and the adiposity rebound (model 3) – influences language acquisition in boys and girls, while adjusting for recruitment center and perinatal adversity. To achieve this, we utilized a multi-group approach. First, sex differences were qualitatively assessed by examining the associations between body growth milestones and the language proficiency latent factor in both groups. Next, they were quantitatively assessed using a Chi-squared difference test, which compared the goodness of fit of a first model where all parameters were freely estimated to the goodness of fit of a second model where the parameters estimating the associations between body growth milestones and the language proficiency latent factor were constrained to be equal between girls and boys. A significant improvement in fit for the first model indicated that girls and boys differ with respect to how body growth is related to language proficiency.

To minimize the risk of overfitting, all coefficients, standard errors and their 95% confidence intervals were estimated using a non-parametric bootstrapping procedure, which involved 1000 random samplings with replacement for each model (MacKinnon et al., 2004; Preacher & Hayes, 2008). This approach does not rely on normality assumptions and allows for the calculation uncertainty in any confidence interval of any kind of distribution**.**

Missing Data

Two approaches were used to explore assumptions related to missing data. Firstly, we conducted Little's test (Little, 1988) to examine whether the data conformed to the 'Missing Completely At Random' (MCAR) assumption, which postulates that the absence of data is independent of any observed and unobserved variable). The test results rejected the null hypothesis of MCAR ($\chi^2_{(1463)} = 2361.6$, $p < .001$). Secondly, we investigated patterns of missingness by conducting pairwise comparisons. For continuous data, we used Kruskal-Wallis tests, while for discrete data, we used Chi squared tests. These comparisons examined the relationship between missingness and explanatory variables for the six indicators of language proficiency at 5-6 years. After controlling for the false discovery rate (FDR) using the Benjamini-Hochberg approach (Benjamini & Hochberg, 1995), the comparisons revealed a systematic relationship between missingness and two out of nine indicators of perinatal adversity. In each case, children with missing scores on the language proficiency indicators had higher values for these adversity indicators.

Thus, the missingness of our data is unlikely to satisfy the 'Missing Completely At Random' (MCAR) assumption, where missingness is independent of any studied variable. While we cannot entirely rule out the potential for the 'Missing Not At Random' (MNAR) assumption (where missingness is related to the unobserved study factors), it is more pragmatic and parsimonious to adopt the 'Missing At Random' (MAR) assumption. This assumption hypothesizes that the missingness of data is related to the observed variables (e.g., the demographic characteristics or the recruitment center) and not to the unobserved factors we aim to study (e.g., the BMI trajectories or the latent variable 'language proficiency at 5-6 years'). To handle missing data, we employed a statistical technique known as full information maximum likelihood estimation (FIML). Previous research has indicated that FIML performs relatively well in several situations, even in scenarios where data may be MNAR. It demonstrates reduced bias and sampling variability when compared to ad hoc methods (Muthén et al., 1987; Enders & Bandalos, 2001; Baraldi & Enders, 2010).

It is important to note that FIML cannot be applied to SEMs with exogenous variables that are non-random, resulting in the automatic deletion of missing values. In our case, perinatal adversity is one such non-random covariate subject to this deletion procedure. Models 1, 2 and 3 were fitted on dataset consisting of 1498 children (757 girls, 741 boys), 1334 children (674 girls, 660 boys), and 1259 children (647 girls, 612 boys), respectively. Note that the fit indices and estimated parameters described below are replicated in the Supplementary Material (Tables S8 to S16), with models fitted on the complete cases (Models 1: N = 849; Models 2: N = 881; Models 3: N = 931).

Fitting procedure

The fitting of all the models described above was accomplished by using a Maximum Likelihood estimator (ML) coupled with a Full Information Maximum Likelihood (FIML) algorithm, as this method is able to handle Missing At Random (MAR) data. The goodness of fit was assessed by considering several statistics, namely $\chi 2$, Comparative Fit Index (CFI), Root Mean Square Error of Approximation (RMSEA) and standardized Root Mean Square Residual (SRMR) statistics. In general, a model's fit is considered excellent when the RMSEA is close to 0.05, the CFI is close to 0.95 and SRMR is close to 0.08 (Hu & Bentler, 1999).

Results of the pre-registered analyses

The results reported in Table 3 indicate that all models exhibit good-to-excellent fit indices (with CFI values greater than 0.93, RMSEA values around 0.03, and SRMR values <= .08). The models performed better than their null versions, which included only the variance of the indicators as parameters.

Parameter estimates are reported in the main text for Models 1a, 2a and 3a (Tables 4, 5 and 6) and in the supplementary information for Models 1b, 2b and 3b (Tables S4, S5 and S6). These tables contain standardized coefficients and standard deviations extracted from the measurement and structural parts of each model, expressed in terms of their bootstrapped means, for girls and boys. The tables also provide the 95% confidence intervals (CI) and exact p-values, which represent the proportion of bootstrap samples whose estimated CI includes zero.

Hypothesis 1 - Models 1a and 1b

Measurement model. The measurement parts of Models 1a and 1b showed that the 6 language-related indicators were positively correlated with the latent variable language proficiency, indicating that children who scored high on the latent variable also scored high in conceptualization, vocabulary, verbal reasoning, non-word repetition, sentence repetition and, to a lesser extent, phonological processing. This association was observed in both girls and boys.

Structural model. The structural parts of both models indicated that children with a larger vocabulary size at 24 months tended to exhibit higher language proficiency scores at 5-6 years. However, no significant linear or quadratic associations were found between the age at infancy BMI peak and latent language proficiency at 5-6 years for either boys or girls (Table 4). Interestingly, in Model 1b, a weakly negative and significant indirect quadratic association emerged between boys' BMI values at the age peak and language proficiency at 5-6 years. This association was mediated by vocabulary size at 24 months (Table S4). Notably, this association was not observed in girls (Table S4). To further investigate potential sex differences, we conducted a Chi-squared difference test comparing the goodness-of-fit of a free model to a constrained model. The free model, where all parameters were freely estimated, did not provide a better fit compared to the constrained model, where the parameters of the indirect association were constrained to be equal between girls and boys (df = 38 vs 39, Chi-squared = 228.64 vs 234.56, Chi-squared diff = 5.92, p = .116). This finding indicates that the observed qualitative sex difference was not statistically significant.

Overall, we provide evidence that early vocabulary size is a strong predictor of later language proficiency in both boys and girls (an established fact, (Lee, 2011; Peyre et al., 2014)), but our analyses failed to verify that the infancy BMI peak is related to later language proficiency (at 2 or 5-6 years).

Hypothesis 2 - Models 2a and 2b

Measurement model. The measurement part of Models 2a and 2b showed results that were fully identical to those reported for Models 1a and 1b, indicating high correlations between the latent language proficiency at 5-6 years and 5 out of its 6 indicators (a smaller correlation is again observed for the phonological processing indicator). This pattern was observed in both girls and boys (Table 5, Table S5).

Structural model. The structural part of both models showed no significant linear or quadratic associations between the age at BMI inflection (or the BMI value at that age) and language proficiency at 5-6 years, for either boys or girls.

Therefore, Models 2a and 2b did not validate Hypothesis 2, that the BMI infection point is related to later language skills (at 5-6 years).

Hypothesis 3 - Models 3a and 3b

Measurement model. The measurement part of models 3a and 3b showed the same results as the previous models, indicating a high correlation between the latent language proficiency at 5-6 years and its indicators for both girls and boys. Specifically, high scores on the latent language proficiency at 5-6 years were associated with high scores in conceptualization, vocabulary, verbal reasoning, non-word repetition, sentence repetition and, to a lesser extent, phonological processing.

Structural model. The structural parts of these models show no quadratic association between the age at adiposity rebound (or the BMI magnitude at that age) and language proficiency at 5-6 years for both girls and boys (Table 6, Table S6). Interestingly, a modest albeit significant linear association is observed in Model 3a between the age at adiposity rebound and language proficiency at 5-6 years for girls only (Table 6). This suggests that girls who reach the nadir of their body growth at a later age are more likely than others to express better language proficiency at 5-6 years than those who reach it earlier.

To further investigate the observed sex difference, we also ran a Chi-squared difference test to compare the fit of a free model with a constrained model. The analysis revealed a significant difference between girls and boys in the relationship between their age at adiposity rebound and language proficiency at 5-6 years. The free model demonstrated a superior fit compared to the constrained model (df = 38 vs 39, Chi-squared = 189.09 vs 193.83, Chi-squared diff = 4.75, p = .029).

In summary, Model 3a validates Hypothesis 3 for girls only, indicating a linear association between age at adiposity rebound and language proficiency at 5-6 years in girls (Figure 1). Results from the complementary model suggest that this association is specific to language development and does not extend to non-verbal cognitive functioning (Table S7).

Complementary model. Is adiposity rebound specifically tied to language proficiency at 5-6 years or does it extend to more general cognitive functioning?

In this complementary model, our aim was to investigate whether the relationship between adiposity rebound and language proficiency, as observed in Model 3a extends to other cognitive measures. Due to the observed sex effect in Model 3a, we focused on analyzing data exclusively from the girl sample. This model does not involve a measurement component as no latent variable is being estimated. Therefore, absolute and comparative fit indices are not informative.

The analysis did not reveal a significant association between age at adiposity rebound and girls' processing speed. However, a positive linear trend was observed with the non-verbal performance score. This association was qualitatively weaker compared to the significant one found with the verbal score (Table S7).

To further quantify this relationship, we fitted two additional models called Complementary Model PERF and Complementary Model VERB. In Complementary Model PERF, the regression parameter linking age at adiposity rebound and the non-verbal performance score was fixed at zero, while all other parameters were freely estimated. The same approach was applied in Complementary Model VERB, with the parameter linking age at adiposity rebound and the verbal score fixed to zero. We then compared the fit of each model with the original model using a chi-squared difference test. The rationale behind these comparisons is that fixing a parameter that significantly contributes to variance explanation to zero should result in a decrease in model fit compared to the original model. Therefore, if the age at adiposity rebound is specifically tied to language ability, then only the fit of Complementary Model VERB should be significantly degraded. On the other hand, if the age at adiposity rebound generalizes its effect on non-verbal cognition, then the fit of Complementary Model PERF should also be degraded.

The chi-squared difference tests showed a degraded fit for Complementary Model VERB (df = 0 vs 2, Chi-squared = 0 vs 7.86, Chi-squared diff = 7.86, p = .02), but not for Complementary Model PERF (df = 0 vs 2, Chi-squared = 0 vs 3.57, Chi-squared diff = 3.57, p = .17). These results suggest a specific association between body growth and language development.

Unregistered analyses

To further investigate the association evidenced in girls between the age at adiposity rebound and language proficiency at 5-6 years, an additional SEM was designed and fitted to the girl sample. The model aimed to take both the age at adiposity rebound and language proficiency at 5-6 years, estimating a correlational parameter between them. Our hypothesis posits that a metabolic trade-off (a latent mechanism dictating resource allocation between two traits) influences their relationship. Within the SEM framework, such a hidden factor can be modelled by a parameter that accounts for the residual variance in the regression, reflecting a partial correlation. Consequently, we use this parameter as an index to ascertain whether an unobserved trade-off mechanism moderates the observed relationship between the age at adiposity rebound and language abilities at 5-6 years. We suppose here that early life environmental factors might increase the energy demand of the brain through direct or indirect stimulation of language functions (Farah et al., 2008; Tooley et al., 2021). Subsequently, the high energy demands of a proficient language functioning at 5-6 years of age is made possible at the cost of a delayed investment in body growth. Crucially, our dataset allows for building 5 environmental constructs:

Parents socio-economic status (SES) is determined by the combined scores of 3 items, which include the educational level of both the mother and the father, as well as the household density and yearly household income collected at the child's 24^{th} months of life. A higher sum of z-scores indicates a higher socio-economic status for the parents, i.e. a higher level of education and a more affluent life.

Cognitive stimulation reflects the sum of scores obtained on 9 items of the HOME inventory (Home Observation Measurement of the Environment) (Bradley et al., 1992), which assesses the quality of cognitive stimulation and emotional support provided by the child's family. The number of times per week the mother and father engaged with their child in activities based on active linguistic interactions through singing, telling stories and playing indoor games, at 2 and 3 years of age, are reported. The higher the sum of z-score, the more the parents stimulated the child's cognitive and language functions at these ages.

Physical stimulation reflects the sum of scores obtained on 6 items of the HOME inventory that assess the number of times per week the mother and father engaged in physical activities with their child through walking or playing outdoor games (e.g., ball play), at 2 and 3 years of age. The higher the sum of z-score, the more the parents stimulate the child's physical capacities at these ages.

Primary needs is a construct that reflects the sum of scores obtained on 6 items of the HOME inventory, which measure how frequently the mother and the father independently met their child's primary needs at the age of 2. These six items evaluate 3 aspects of primary needs, namely basic hygiene, food intake, and bedtime. The sum of z-scores indicates the extent to which the parents are personally engaged in fulfilling their child's primary needs, with a higher z-score indicating greater parental involvement.

Physiological stress is measured by the combined scores of 4 items, namely tobacco and alcohol exposure during gestation, gestational age, and absence of breastfeeding. These items assess the level of exposure to factors that may impact the child's physiological development during gestation and immediate post-natal period. A higher sum of z-scores indicates a greater level of exposure to physiological stress during this critical period.

The model fitting procedure used in this analysis was identical to the one employed in the pre-registered SEMs. Missing values of endogenous variables (i.e., the 6 indicators of the latent factor) were handled using a FILM method, while missing cases of exogenous variables (i.e., the five early environmental variables described above) were automatically removed, resulting in a sample size of N = 442 girls. All coefficients, standard errors, and 95% confidence intervals estimated by the model were obtained using a non-parametric bootstrapping procedure, with 1000 random samplings with replacement (MacKinnon et al., 2004; Preacher & Hayes, 2008).

Unregistered Model. Is there a link between environmental factors that stimulate cognition in children aged 2-3 years, their language proficiency at 5-6 years, and the age at which adiposity rebound occurs?

Specification of the measurement model. Language proficiency at 5-6 years of age is modelled as an endogenous latent factor, which captures the shared variance of 6 indicators: conceptualization, vocabulary, verbal reasoning, non-word repetition, sentence repetition, and phonological processing. These indicators were scored and z-transformed such that higher scores indicate greater language proficiency, and the variance of this latent variable was scaled to 1. Additionally, the age at adiposity rebound was entered as the second endogenous outcome, with a greater score indicating a later rebound. All indicators were adjusted for the effect of Recruitment center.

The exogenous predictors of the two outcomes, including parental socio-economic status (SES), cognitive stimulation, physical stimulation, primary needs, and physiological stress, were also entered in this model.

Specification of the structural model. Our unregistered hypothesis was tested through the estimation of several parameters, including: i) a parameter that captures the partial correlation between the residuals of the language proficiency latent variable and the residuals of the *age at* adiposity rebound, ii) a set of five regression parameters that estimate the effect of each environmental factor on each of the two outcomes (Figure 2).

Results of the unregistered analysis

The goodness of fit of the model is reported in Table 7, which shows that the model had good-to-excellent fits, as indicated by the CFI values >.94, RMSEA values <.06, and SRMR values <.03. Table 8 reports all the parameter estimates that corroborate the description of the unregistered model. It contains the standardized coefficients and standard deviations extracted from the measurement and the structural parts of the model, expressed in terms of their bootstrapped means, as well as the bootstrap 95% confidence intervals (CIs) and exact p-values.

Measurement model. The results of the measurement model were similar to those reported in the registered model's description. Girls who scored high on the latent language proficiency at 5-6 years also scored high in conceptualization, vocabulary, verbal reasoning, non-word repetition, sentence repetition and, to a lesser extent, phonological processing.

Structural model. The structural model (table 8) first supports the hypothesis of a hidden mechanism mediating between age at adiposity rebound and the latent variable of language proficiency at 5-6 years, as suggested by a positive residual correlation between the two variables (Figure 3). More specifically, parental socio-economic status (SES) is positively related to both language proficiency and BMI rebound, such that the higher the parents' SES, the later the adiposity rebound and the higher the language skills (Figure 2, panels A and F). A similar trend is observed with the cognitive stimulation factor, which shows a positive correlation with language skills and with age at adiposity rebound (Figure 2, panels B and G), although the level of confidence that this latter association is actually greater than zero is closer to 90% than 95% (note that the mean bootstrapped 95% CI does not include zero when only data from complete cases are analyzed, see Table S16). In addition, we found that the amount of physical stimulation produced by the parents was negatively related to language skills, so that the more intense the physical stimulation, the lower the language skills (Figure 2C). On the contrary, neither the parents' contribution to satisfying the child's basic needs, nor the amount of prenatal and perinatal physiological stress are related to language proficiency or adiposity rebound (Figure 2, panels D, E, I and J). Together, the model shows that early life environments that provide the child a large amount of cognitive information, whether through the parents' educational practices or their socio-economic capital, have a positive influence on brain development through the acquisition of language, which slows the growth of BMI.

Discussion

The results of this pre-registered study are consistent with a theorized energy allocation trade-off mechanism (Leonard et al., 2003; Said-Mohamed et al., 2018), which suggests a prioritization of language proficiency over the investment in body growth. This extends foundational theoretical and empirical research that posits a competition for metabolic resources between the development of higher-order cognitive functions (i.e. executive functions) and physical growth (Kuzawa & Blair, 2019; Blair et al., 2019; Rollins et al., 2021). Our investigation focused on the association between the timing and magnitude of the infancy BMI peak, BMI inflection point, BMI at adiposity rebound, with language proficiency at 5-6 years. The analyses revealed no significant link between the infancy BMI peak or inflection point, and language skills, but a positive association between the age at adiposity rebound and language skills in girls. Specifically, girls experiencing a later adiposity rebound demonstrated greater proficiency across language dimensions measured in the EDEN cohort (including conceptualization, vocabulary, verbal reasoning, phonological processing, non-word repetition, and sentence repetition). Importantly, this correlation did not extend to non-verbal cognitive abilities such as performance IQ or processing speed.

The absence of a correlation between body mass index and indicators of non-verbal cognitive skills may reflect the specific role of language in human developmental. Yet, the development of another cognitive domain, executive functions, has been linked to BMI variations throughout early, middle and late childhood (Blair et al., 2019; Rollins et al., 2021). This link is further supported by evidence of deficits in executive functions, such as problem-solving, decision-making, and impulse control among obese individuals (Yang et al., 2018). Developmental studies have consistently shown that development of language and executive functions are closely intertwined (Bohlmann et al., 2015; Daneri & Blair, 2017), with early language abilities significantly influencing the trajectory of executive function development (Romeo et al., 2022; Slot & von Suchodoletz, 2018). There remains, however, a substantial research agenda to fully understand the complex interplay between body growth and cognitive development. From this perspective, the elaboration of comprehensive models that encapsulate multiple cognitive domains (i.e., executive functions, language skills, and non-verbal cognitive abilities) could prove to be a fruitful line of inquiry.

Contrary to previous work (Blair et al., 2019; Farkas & Jacquet, 2023; Kuzawa et al., 2014; Kuzawa & Blair, 2019; Rollins et al., 2021), our study found that the trade-off between neurocognitive development and body growth was only observed in girls. This result is not only statistically significant, but also of substantial magnitude. The divergent developmental paths of girls and boys may reflect the role of energy trade-offs in regulating differential reproductive strategy. Previous research has established a link between childhood fat accumulation, including the timing of adiposity rebound, and the onset of puberty (Brix et al., 2020; O'Keeffe et al., 2020; Williams & Goulding, 2009), potentially due to hormonal influences. Estrogens, for instance, facilitate the conversion of surplus calories to fat, while leptin oversees both appetite and the distribution of energy for reproductive purposes (Moschos et al., 2002; Rosenbaum & Leibel, 1999). In girls, the early storage of energy reserves as adipose tissue might anticipate the substantial demands of future reproductive events, such as pregnancy and lactation (Kaplowitz, 2008). Conversely, the interplay between body growth and reproductive physiology in boys is less clear (Kaplowitz, 2008). This disparity may stem from methodological challenges in pinpointing the onset of puberty in boys, alongside theoretical considerations suggesting that fat reserves play a less crucial role in male reproductive functions. For example, unlike females, males do not bear the energetic burdens of pregnancy and lactation, and the emergence of male secondary sexual characteristics tends to rely more on the accrual of lean mass.

Another noteworthy finding in our study is the significant correlations between early environmental factors that promote cognitive stimulation, language skills in girls and the timing of adiposity rebound. Specifically, children from higher educational and socio-economic backgrounds, who are exposed to language-stimulating activities at ages 2-3, tend to delay adiposity rebound and express better language skills by ages 5-6. This echoes the patterns reported by Farkas & Jacquet (2023), where limited access to various resources at age 6 was a strong predictor of later growth trajectories, both somatic and cognitive. Altogether, these findings provide empirical support for the hypothesis put forth in Kuzawa and Blair (2019), that an environment rich in information in early life can enhance brain energy demands, thereby enhancing language development.

Contrastingly, environmental factors less directly associated with cognitive enrichment, such as parental investment in primary needs or prenatal stress levels, seemingly have no bearing on the energy trade-off between body growth and brain development. Additionally, our data indicate a negative correlation between physical stimulation at ages 2-3 and language proficiency at ages 5-6, implying that early physical activities might temporarily re-route resources from language development. The observation that environmental factors promoting physical skills could impede from cognitive functions as language presents an evolutionary paradox. Inhibiting neurocognitive development during infancy and childhood could increase mortality risks, which are notably high in the first 15 years. This could, for instance, decelerate the acquisition of cognitive strategies essential for achieving efficient resource productivity (see Burger et al., 2012; Gurven & Kaplan, 2007).

The approach we used to investigate the energy trade-off between brain development and body growth could benefit from several improvements. Firstly, adding data on children's dietary habits, including the amount of nutrient-dense and processed foods consumed would refine the model, given that such dietary choices can impact body mass trajectories (Ip et al., 2017; Saldanha-Gomes et al., 2022). While our pre-registered models partially account for dietary effects by including a covariate for perinatal adversity (which captures family socioeconomic status and indirectly, dietary quality, often poorer in lower-income, disadvantaged households (Fernández-Alvira et al., 2015)), direct dietary measures would offer a more precise adjustment. A second challenge lies in addressing genetic heritability, which significantly affects the timing of adiposity rebound (Cissé et al., 2021; Couto Alves et al., 2019; Meyre et al., 2004). Notably, our models that correlate social adversity and socioeconomic status with cognitive development are less susceptible to genetic confounding compared to models examining the relationship between adiposity rebound and cognition alone. Thirdly, we might consider employing an alternative index to BMI for a nuanced depiction of body composition, particularly in boys, where lean mass is a more prominent contributor to BMI than in girls (Franklin, 1999; Gallagher et al., 1996; Horlick, 2001; Van Eyck et al., 2021). Lastly, integrating direct measures of neural activity, such as electrophysiological markers of neuraonal maturation, would offer a more immediate evaluation of brain development.

In this study, we analyzed data from a large sample and obtained result that align with a trade-off mechanism between brain development and body growth. Using the BMI trajectories as an indicator of body growth and language proficiency as a metric for cognitive development, we also demonstrate that environmental factors promoting cognitive stimulation at ages 2 and 3 concurrently influenced the timing of adiposity rebound and the language skill levels measured three years later.

Declarations

Ethics approval and consent to participate. The study was approved by the ethics research committee of Kremlin-Bicêtre Hospital (ID 0270 of 12 December 2012) and by Data Protection Authority (CNIL, ID 902267 of 12 December 2012), and is in accordance with the Declaration of Helsinki (World Medical Association, 2008). Both parents gave their written informed consents.

Consent for Publication. Not applicable.

Availability of data and materials

Data availability statement. Simulated data used in this report are publicly available from the Open Science Framework (https://osf.io/8x4pm/). Any researcher interested in exploring EDEN data should contact directly the director of the EDEN mother-child cohort [barbara.heude@inserm.fr] to complete a dedicated project form for evaluation by the EDEN steering committee.

Code availability statement. All the codes needed to reproduce the results in the paper are available on the Open Science Framework (https://osf.io/8x4pm/).

Competing interests. The authors declare no competing interests.

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Figure legends

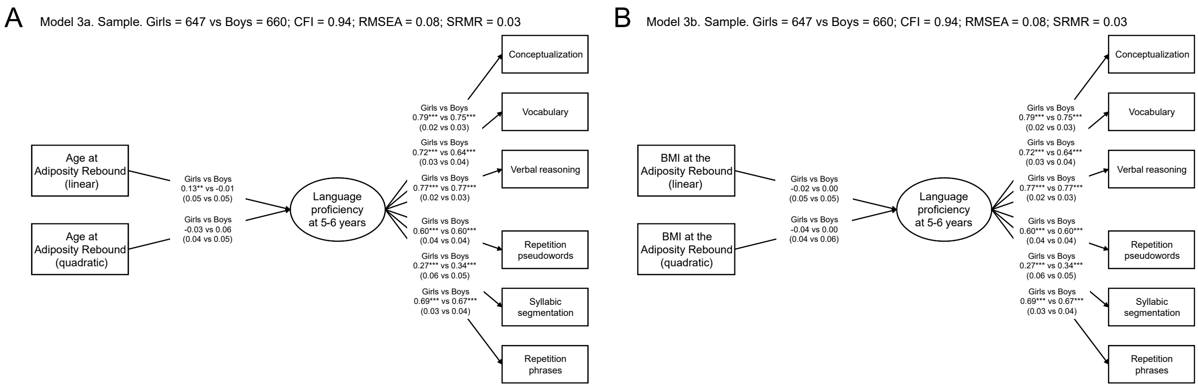

Figure 1. Association between age at adiposity rebound and language skills at age 5-6, estimated by the structural equation model 3a (A) and model 3b (B). Standardized parameter values (and standard deviation reported in brackets) for the girls' sample and the boys' sample are shown for each path. The ellipse represents the latent variable; the rectangles represent the indicators. The paths between the indicators and the latent variables represent factor loadings. Paths between the single composite and the latent variable represent regressions. Significant paths are represented with *, such that * indicates $p < .05$, ** indicates $p < .01$, *** indicates $p < .001$. We observed that girls who reach the nadir of their body growth at a later age are more likely than others to express better language proficiency at 5-6 years than those who reach it earlier.

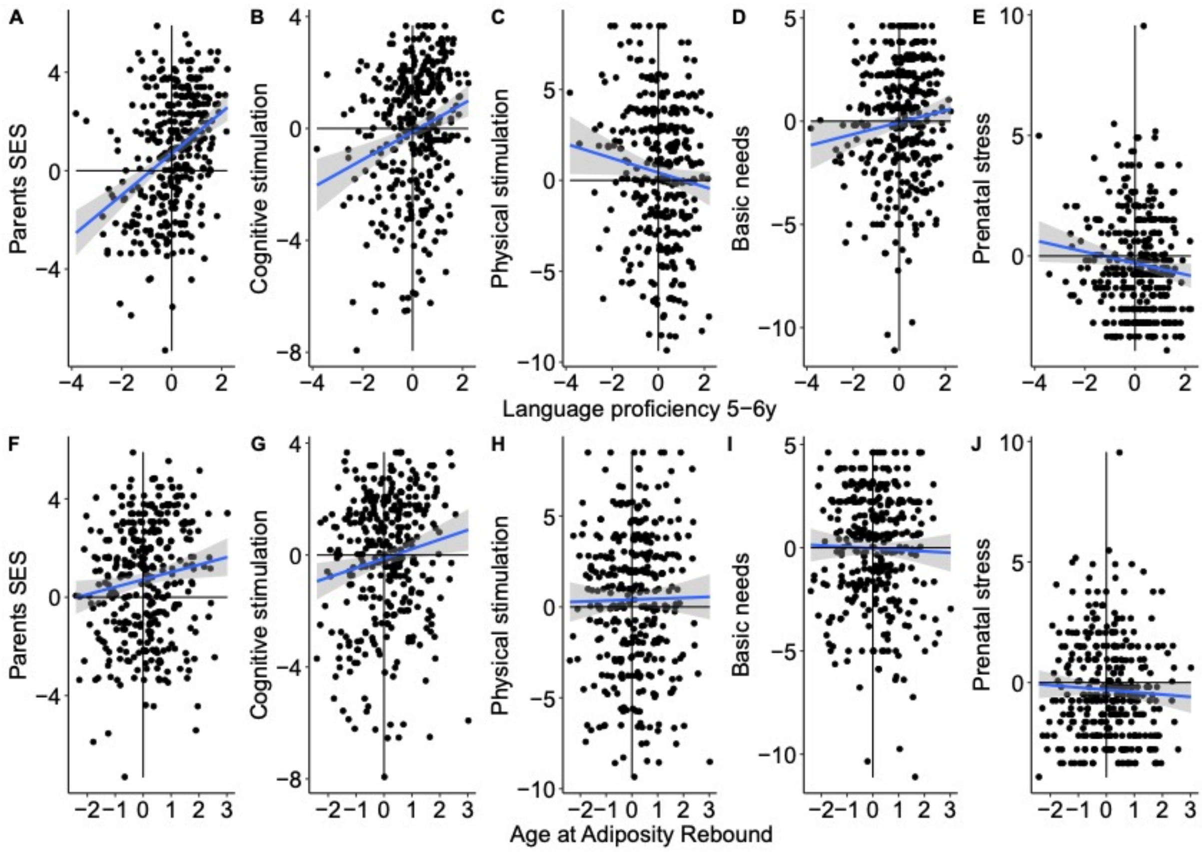

Figure 2. Scatterplots of environmental factors (column) according to language proficiency score (top row) or age at adiposity rebound (bottom row) in girls. Five environmental factors are used in this analysis: cognitive stimulation, physical stimulation, basic needs, prenatal stress and perinatal SES. To ensure comparability of the indicators, all scores were transformed into z-scores. We found that the amount of cognitive and physical stimulation provided by parents, as well as their socio-economic status, were positively related to language proficiency at age 5-6. In contrast, neither the parents' contribution to meeting the child's basic physiological needs nor the extent of prenatal and perinatal physiological stress were related to language proficiency scores. We observed that among the 5 early life environmental factors, only the parental socio-economic status is related to the age of the child at the time of adiposity rebound, so that the highest the SES, the more the adiposity rebound is delayed.

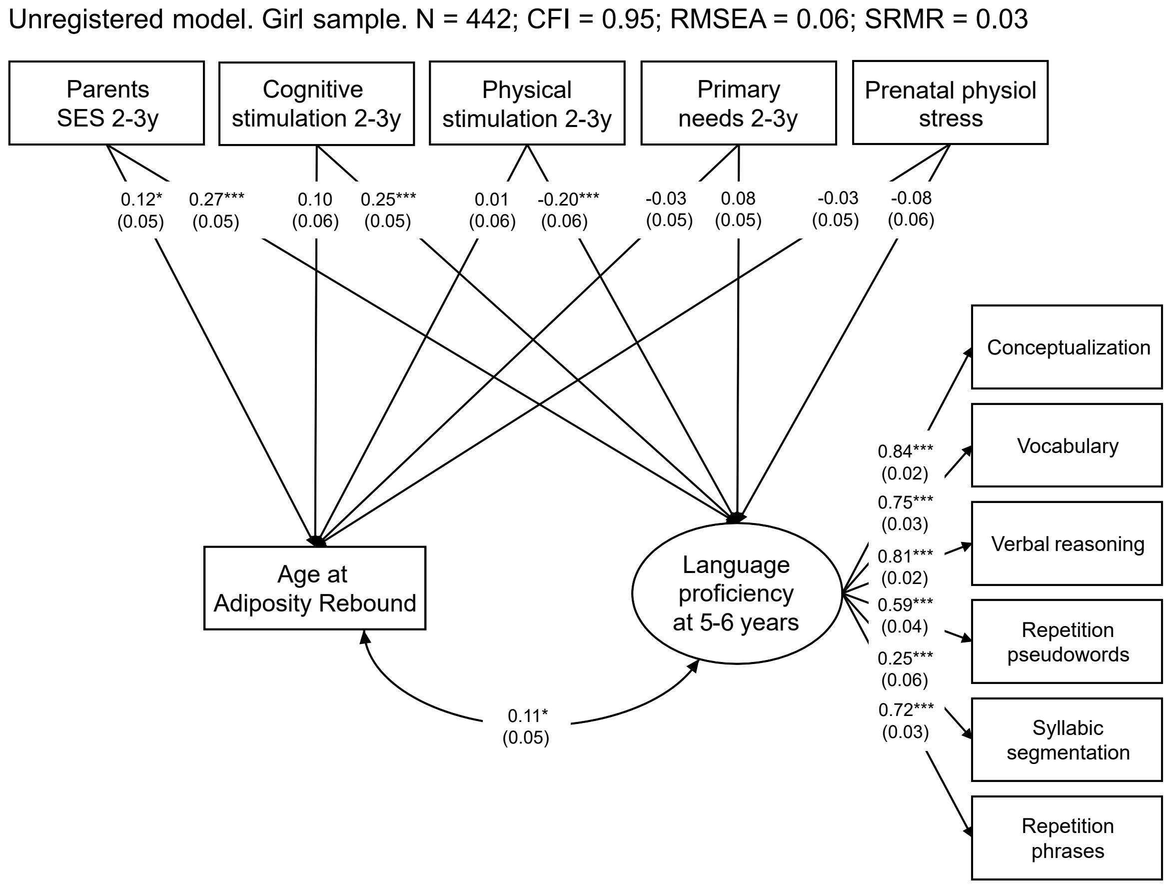

Figure 3. Results of the unregistered model, estimating whether environmental factors are associated with the relationship between age at adiposity rebound and language proficiency at age 5-6, in girls. Standardized parameter values (and standard deviation in brackets) for the sample of girls are shown for each path. The ellipse represents the latent variable; the rectangles represent the indicators. The paths between the indicators and the latent variables represent factor loadings. Paths between the single composite and the latent variable represent regressions. Significant paths are represented by *, such that * indicates p < .05, ** indicates p < .01, *** indicates p < .001. Among the 5 early life environmental factors, we found a significant positive association between parents' socio-economic status and both the age at adiposity rebound and language skills, and between cognitive stimulation at 2-3 years and language skills at 5-6 years.