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# 1 A metabolic trade-off impacting childhood language 2 development and body growth

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27

## 28 Highlights

29 1. Neurocognitive development's high energy demand necessitates a trade-off in  
30 human children between brain growth and other biological functions, including  
31 body growth.

32 2. Previous studies indicate that the peak of brain energy consumption at around  
33 age 5 aligns with the nadir of childhood body mass increase, termed 'adiposity  
34 rebound'.

35 3. A delayed adiposity rebound, indicative of slower growth may correlate  
36 enhanced language abilities in children.

37 4. Our preregistered study confirms this correlation in girls and associates early  
38 cognitive stimulation with improved language skills and adiposity rebound time.

## 39 Abstract

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

## 56 Keywords

57 Development  
58 Body growth  
59 Language  
60 Life History trade-off  
61 Early life environment

## 62 Introduction

63 The importance of language proficiency for mental health and academic success is  
64 widely acknowledged (Henry et al., 2014; Miller et al., 2018; Pace et al., 2018), but the  
65 variability in children's language skills remains largely unexplained (Kidd & Donnelly,  
66 2020). One approach to understand this variability is to investigate the interplay  
67 between the metabolic demands of the developing brain and those of bodily growth,  
68 as well as the environmental factors that influence these intricate developmental  
69 processes.

70 Current theoretical frameworks suggest that language development depends in part  
71 on how organisms trade their limited stock of energy resources between competing  
72 biological functions (Kaplan & Robson, 2002; Longman et al., 2017; Urlacher et al.,  
73 2019). The distribution of energy between the brain and the rest of the body (Aiello &  
74 Wells, 2002), particularly during periods of growth, is thought to be a critical  
75 determinant of cognitive and physical development (Kaplan et al., 2000; Kuzawa &  
76 Blair, 2019). Given the substantial and fluctuating metabolic demands of the brain  
77 throughout childhood (Chugani, 1998; Leonard et al., 2003; Madsen et al., 1995;  
78 Madsen & Vorstrup, 1991), the organism must finely tune its energy budget to support  
79 cognitive development adequately (Aronoff et al., 2022; Navarrete et al., 2011).

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

99 The interplay of early metabolic exchanges between the brain and body has prompted  
100 researchers to formulate new theoretical propositions regarding the pace of cognitive  
101 development (Kuzawa & Blair, 2019). It is posited that the rate of body growth may  
102 inversely reflect the allocation of resources towards developing high-level cognitive  
103 functions. Recent empirical evidence suggests a trade-off where a slower enhancement  
104 in executive functions from age 3 to 5 years is associated with accelerated body  
105 growth, spanning from infancy (Blair et al., 2019) through to adolescence (Rollins et  
106 al., 2021). Building upon these findings, this article examines the relationship between  
107 specific body growth milestones and language proficiency in early and middle  
108 childhood. The developmental interdependence of language and executive functions  
109 is well-documented (Bohlmann et al., 2015; Daneri & Blair, 2017), with the trajectory

110 of executive functions being influenced by early language development (Romeo et al.,  
111 2022; Slot & von Suchodoletz, 2018). Consequently, it is plausible that more rapid  
112 growth in the early years of life may correspond with language capabilities. In this  
113 context, language proficiency, akin to executive functions, serves as a metric of  
114 cognitive development, offering a lens through which to infer the energetic demands  
115 of brain maturation.

116 Specifically, prioritizing early investment in body growth may be indicative of atypical  
117 cognitive functioning in early to middle childhood. Given the rapid development of  
118 language during early childhood, and particularly in the preschool years (i.e., ages 0–  
119 3 years) (Gervain, 2020), this study aims to explore the association between body-  
120 mass index (BMI) trajectories and language abilities from birth to three developmental  
121 milestones (Cole, 2004; Rolland-Cachera et al., 1984; Silverwood et al., 2009; Wen et  
122 al., 2012): (i) the infancy BMI peak, occurring around 9 months, marking the highest  
123 BMI value before it begins to decline; (ii) the inflection point in BMI velocity, around 12  
124 months, indicating when the rate of BMI change starts to slow down; (iii) the adiposity  
125 rebound, typically around 5-6 years, when BMI starts to rise again after reaching its  
126 lowest point in a child's lifetime. The infancy BMI peak and the adiposity rebound are  
127 established risk factors for obesity (Cole et al., 2004; Rolland-Cachera et al., 1984;  
128 Roy et al., 2016), while the BMI inflection point signals the shift from rapid to more  
129 stable or slower growth patterns.

130 Three pre-registered hypotheses are tested:

- 131 • **Hypothesis 1** states that the individuals' age (model 1a) or BMI magnitude (model  
132 1b) at which the infancy BMI peak is predictive of general language abilities at 5-6  
133 years via the level of vocabulary measured at 24 months.
- 134 • **Hypothesis 2** posits that the individuals' age (model 2a) or BMI magnitude (model  
135 2b) at the BMI inflection point is correlated with language abilities at 5-6 years.
- 136 • **Hypothesis 3** proposes that the individuals' age (model 3a) or BMI magnitude  
137 (model 3b) at the adiposity rebound is associated with language abilities at 5-6-  
138 years.

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

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

## 150 Method

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

## 155 Participants

156 The EDEN mother–child study is a prospective cohort designed to assess pre- and  
157 postnatal factors that influence the health and development of children (Heude et al.,  
158 2016). The study was approved by the ethics research committee of Kremlin-Bicêtre  
159 Hospital (ID 0270 of 12 December 2012) and by Data Protection Authority (CNIL, ID  
160 902267 of 12 December 2012), and is in accordance with the Declaration of Helsinki  
161 (World Medical Association, 2008). Both parents gave their written informed consents.

162 The cohort included 2,002 mother-child pairs, who were recruited between 2003 and  
163 2006 in two university hospital in Nancy and Poitiers (France). The inclusion criteria  
164 stipulated that the mothers were before 24 weeks of amenorrhea. Exclusion criteria  
165 were mothers younger than 18 years, who had multiple pregnancies, had a history of  
166 diabetes, were illiterate and expressed an intention to move out of the region within  
167 the next 3 years.

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

## 175 Measures

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

## 182 Body Growth

183 *Anthropometric measurements.* At birth, all weight and height measures were  
184 collected from health records. At 4 and 8 months, and 2 and 4 years, mothers  
185 completed mailed questionnaires in which they reported their infant's weight and  
186 length taken at routine health checkups. These measures were taken by the family  
187 practitioner and documented in the infant's personal health record booklet. At ages 1,  
188 3 and 5 years, the children were measured in a standardized fashion, with height and  
189 weight being measured twice and then averaged. This ensured that the measurements  
190 were as accurate as possible. Height was measured to the nearest 0.1 cm using wall-  
191 mounted stadiometers (Model 208; SECA, Hamburg, Germany) as the children stood  
192 barefoot. Weight was measured to the nearest 0.2 kg with an electronic scale (Model  
193 888; SECA, Hamburg, Germany). The children wore light underwear during these  
194 measurements to minimize any additional weight.

195 *Measurement of BMI (Body Mass Index) and BMI curve indicators.* BMI was calculated  
196 at each age by dividing weight in kilograms by the square of height in meters. On  
197 average, children had 10 BMI measurements between birth and 13 years. By  
198 collecting BMI measurements at multiple points throughout childhood, we were able  
199 to track changes in body mass composition over time and identify three developmental

200 points: the infancy BMI peak, the BMI curve inflection, and the adiposity rebound. To  
201 measure these points, we used data from specific time periods. We used data from  
202 day 3 and 24 months to measure the infancy BMI peak, data from 6 to 36 months to  
203 measure the BMI curve inflection, and data from 18 months and the maximum age  
204 available to measure the adiposity rebound.

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

$$209 \quad \log(\text{BMI}_{it}) = \beta_0 + \sum_{j=1}^3 \beta_j \text{Age}_{it}^j + b_{0i} + \sum_{j=1}^3 b_{ji} \text{Age}_{it}^j + \varepsilon_{it} \quad \text{equation 1}$$

210 where:

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

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

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

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

## 230 Language abilities

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

### 233 At 2 years of age

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

241

### 242 At 5-6 years of age

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

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

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

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

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

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

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

## 279 Covariates

280 The structural equation models used in this study were adjusted for three factors  
281 potentially associated with cognitive development and/or body growth. Firstly,  
282 children's sex was included as a grouping factor to address any disparities between  
283 boys and girls in the relationships between body growth and the language proficiency  
284 (Girls = 1; Boys = 0). Secondly, the respondents' recruitment center was taken into  
285 account (Poitiers = 1; Nancy = 0). Previous research has shown differences in  
286 language outcomes among children recruited from these two hospital centers within  
287 the EDEN cohort (Peyre et al., 2016). Finally, we created an adjustment variable using  
288 a composite score that reflect the level of adversity experienced by children before



289 and immediately after birth. This composite score encompassed nine factors known  
290 to affect early childhood diet (Gentner & Leppert, 2019; Lindsay et al., 2019) as well  
291 as neural, cognitive and behavioral development (Bath, 2020; Frankenhuis et al.,  
292 2020). These factors included gestational age at birth (in weeks), exposure to alcohol  
293 and cigarette smoking during pregnancy (no = 1), breastfeeding (yes = 1), father  
294 absence (no = 1), monthly household income at birth (in €), education levels of both  
295 mother and father (each scored from 1 = did not attend school to 9 = university, based  
296 on the French school system), and household density (number of adults and children  
297 living in the house divided by the number of rooms). Scores for these nine variables  
298 were z-scored, allowing their cumulative sum to reflect the degree of perinatal  
299 adversity. A higher score on this composite variable indicated greater exposure to  
300 perinatal adversity. Our approach of summing z-scores is grounded in both theoretical  
301 and empirical research. Current models suggest that factors contributing to adversity  
302 vary in nature and do not necessarily correlate with each other (McLaughlin et al.,  
303 2021; Ellis et al., 2009) (S2 Figure). Such emergent variables have been effectively  
304 modelled in prior studies using sums of z-scored indicators (Baptista et al., 2023;  
305 Brumbach et al., 2009; Jacquet et al., 2019; Mell et al., 2018). Moreover, this  
306 composite scoring approach inherently assigns greater weight to more dispersed  
307 indicators, which represent rarer adverse events.

## 308 Pre-registered analyses

### 309 Structural equation models

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

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

330 These SEMs allowed us to examine whether and how variations in the timing of the  
331 infancy BMI peak (model 1), the BMI inflection point (model 2), and the adiposity  
332 rebound (model 3) – influences language acquisition in boys and girls, while adjusting  
333 for recruitment center and perinatal adversity. To achieve this, we utilized a multi-  
334 group approach. First, sex differences were qualitatively assessed by examining the

335 associations between body growth milestones and the language proficiency latent  
336 factor in both groups. Next, they were quantitatively assessed using a Chi-squared  
337 difference test, which compared the goodness of fit of a first model where all  
338 parameters were freely estimated to the goodness of fit of a second model where the  
339 parameters estimating the associations between body growth milestones and the  
340 language proficiency latent factor were constrained to be equal between girls and  
341 boys. A significant improvement in fit for the first model indicated that girls and boys  
342 differ with respect to how body growth is related to language proficiency.

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

## 349 Missing Data

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

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

378 It is important to note that FIML cannot be applied to SEMs with exogenous variables  
379 that are non-random, resulting in the automatic deletion of missing values. In our case,  
380 perinatal adversity is one such non-random covariate subject to this deletion  
381 procedure. Models 1, 2 and 3 were fitted on dataset consisting of 1498 children (757

382 girls, 741 boys), 1334 children (674 girls, 660 boys), and 1259 children (647 girls, 612  
383 boys), respectively. Note that the fit indices and estimated parameters described  
384 below are replicated in the Supplementary Material (Tables S8 to S16), with models  
385 fitted on the complete cases (Models 1: N = 849; Models 2: N = 881; Models 3: N =  
386 931).

## 387 Fitting procedure

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

396

## 397 Results of the pre-registered analyses

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

402 Parameter estimates are reported in the main text for Models 1a, 2a and 3a (Tables  
403 4, 5 and 6) and in the supplementary information for Models 1b, 2b and 3b (Tables  
404 S4, S5 and S6). These tables contain standardized coefficients and standard  
405 deviations extracted from the measurement and structural parts of each model,  
406 expressed in terms of their bootstrapped means, for girls and boys. The tables also  
407 provide the 95% confidence intervals (CI) and exact p-values, which represent the  
408 proportion of bootstrap samples whose estimated CI includes zero.

### 409 Hypothesis 1 - Models 1a and 1b

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

416 *Structural model.* The structural parts of both models indicated that children with a  
417 larger vocabulary size at 24 months tended to exhibit higher language proficiency  
418 scores at 5-6 years. However, no significant linear or quadratic associations were  
419 found between the age at infancy BMI peak and latent language proficiency at 5-6  
420 years for either boys or girls (Table 4). Interestingly, in Model 1b, a weakly negative  
421 and significant indirect quadratic association emerged between boys' BMI values at  
422 the age peak and language proficiency at 5-6 years. This association was mediated  
423 by vocabulary size at 24 months (Table S4). Notably, this association was not  
424 observed in girls (Table S4). To further investigate potential sex differences, we  
425 conducted a Chi-squared difference test comparing the goodness-of-fit of a free model

426 to a constrained model. The free model, where all parameters were freely estimated,  
427 did not provide a better fit compared to the constrained model, where the parameters  
428 of the indirect association were constrained to be equal between girls and boys (df =  
429 38 vs 39, Chi-squared = 228.64 vs 234.56, Chi-squared diff = 5.92,  $p = .116$ ). This  
430 finding indicates that the observed qualitative sex difference was not statistically  
431 significant.

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

## 436 Hypothesis 2 - Models 2a and 2b

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

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

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

## 447 Hypothesis 3 - Models 3a and 3b

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

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

462 To further investigate the observed sex difference, we also ran a Chi-squared  
463 difference test to compare the fit of a free model with a constrained model. The  
464 analysis revealed a significant difference between girls and boys in the relationship  
465 between their age at adiposity rebound and language proficiency at 5-6 years. The  
466 free model demonstrated a superior fit compared to the constrained model (df = 38 vs  
467 39, Chi-squared = 189.09 vs 193.83, Chi-squared diff = 4.75,  $p = .029$ ).

468 In summary, Model 3a validates Hypothesis 3 for girls only, indicating a linear  
469 association between age at adiposity rebound and language proficiency at 5-6 years  
470 in girls (Figure 1). Results from the complementary model suggest that this association

471 is specific to language development and does not extend to non-verbal cognitive  
472 functioning (Table S7).

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

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

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

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

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

505

## 506 **Unregistered analyses**

507 To further investigate the association evidenced in girls between the age at adiposity  
508 rebound and language proficiency at 5-6 years, an additional SEM was designed and  
509 fitted to the girl sample. The model aimed to take both the age at adiposity rebound  
510 and language proficiency at 5-6 years, estimating a correlational parameter between  
511 them. Our hypothesis posits that a metabolic trade-off (a latent mechanism dictating  
512 resource allocation between two traits) influences their relationship. Within the SEM  
513 framework, such a hidden factor can be modelled by a parameter that accounts for the  
514 residual variance in the regression, reflecting a partial correlation. Consequently, we

515 use this parameter as an index to ascertain whether an unobserved trade-off  
516 mechanism moderates the observed relationship between the age at adiposity  
517 rebound and language abilities at 5-6 years. We suppose here that early life  
518 environmental factors might increase the energy demand of the brain through direct  
519 or indirect stimulation of language functions (Farah et al., 2008; Tooley et al., 2021).  
520 Subsequently, the high energy demands of a proficient language functioning at 5-6  
521 years of age is made possible at the cost of a delayed investment in body growth.  
522 Crucially, our dataset allows for building 5 environmental constructs:

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

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

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

541 *Primary needs* is a construct that reflects the sum of scores obtained on 6 items of the  
542 HOME inventory, which measure how frequently the mother and the father  
543 independently met their child's primary needs at the age of 2. These six items evaluate  
544 3 aspects of primary needs, namely basic hygiene, food intake, and bedtime. The sum  
545 of z-scores indicates the extent to which the parents are personally engaged in fulfilling  
546 their child's primary needs, with a higher z-score indicating greater parental  
547 involvement.

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

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

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

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

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

577 *Specification of the structural model.* Our unregistered hypothesis was tested through  
578 the estimation of several parameters, including: i) a parameter that captures the partial  
579 correlation between the residuals of the language proficiency latent variable and the  
580 residuals of the *age at* adiposity rebound, ii) a set of five regression parameters that  
581 estimate the effect of each environmental factor on each of the two outcomes (Figure  
582 2).

## 583 Results of the unregistered analysis

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

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

596 *Structural model.* The structural model (table 8) first supports the hypothesis of a  
597 hidden mechanism mediating between age at adiposity rebound and the latent  
598 variable of language proficiency at 5-6 years, as suggested by a positive residual  
599 correlation between the two variables (Figure 3). More specifically, parental socio-  
600 economic status (SES) is positively related to both language proficiency and BMI  
601 rebound, such that the higher the parents' SES, the later the adiposity rebound and  
602 the higher the language skills (Figure 2, panels A and F). A similar trend is observed  
603 with the cognitive stimulation factor, which shows a positive correlation with language  
604 skills and with age at adiposity rebound (Figure 2, panels B and G), although the level  
605 of confidence that this latter association is actually greater than zero is closer to 90%  
606 than 95% (note that the mean bootstrapped 95% CI does not include zero when only  
607 data from complete cases are analyzed, see Table S16). In addition, we found that the

608 amount of physical stimulation produced by the parents was negatively related to  
609 language skills, so that the more intense the physical stimulation, the lower the  
610 language skills (Figure 2C). On the contrary, neither the parents' contribution to  
611 satisfying the child's basic needs, nor the amount of prenatal and perinatal  
612 physiological stress are related to language proficiency or adiposity rebound (Figure  
613 2, panels D, E, I and J). Together, the model shows that early life environments that  
614 provide the child a large amount of cognitive information, whether through the parents'  
615 educational practices or their socio-economic capital, have a positive influence on  
616 brain development through the acquisition of language, which slows the growth of BMI.  
617

## 618 Discussion

619 The results of this pre-registered study are consistent with a theorized energy  
620 allocation trade-off mechanism (Leonard et al., 2003; Said-Mohamed et al., 2018),  
621 which suggests a prioritization of language proficiency over the investment in body  
622 growth. This extends foundational theoretical and empirical research that posits a  
623 competition for metabolic resources between the development of higher-order  
624 cognitive functions (i.e. executive functions) and physical growth (Kuzawa & Blair,  
625 2019; Blair et al., 2019; Rollins et al., 2021). Our investigation focused on the  
626 association between the timing and magnitude of the infancy BMI peak, BMI inflection  
627 point, BMI at adiposity rebound, with language proficiency at 5-6 years. The analyses  
628 revealed no significant link between the infancy BMI peak or inflection point, and  
629 language skills, but a positive association between the age at adiposity rebound and  
630 language skills in girls. Specifically, girls experiencing a later adiposity rebound  
631 demonstrated greater proficiency across language dimensions measured in the EDEN  
632 cohort (including conceptualization, vocabulary, verbal reasoning, phonological  
633 processing, non-word repetition, and sentence repetition). Importantly, this correlation  
634 did not extend to non-verbal cognitive abilities such as performance IQ or processing  
635 speed.

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

651 Contrary to previous work (Blair et al., 2019; Farkas & Jacquet, 2023; Kuzawa et al.,  
652 2014; Kuzawa & Blair, 2019; Rollins et al., 2021), our study found that the trade-off  
653 between neurocognitive development and body growth was only observed in girls.  
654 This result is not only statistically significant, but also of substantial magnitude. The



655 divergent developmental paths of girls and boys may reflect the role of energy trade-  
656 offs in regulating differential reproductive strategy. Previous research has established  
657 a link between childhood fat accumulation, including the timing of adiposity rebound,  
658 and the onset of puberty (Brix et al., 2020; O’Keeffe et al., 2020; Williams & Goulding,  
659 2009), potentially due to hormonal influences. Estrogens, for instance, facilitate the  
660 conversion of surplus calories to fat, while leptin oversees both appetite and the  
661 distribution of energy for reproductive purposes (Moschos et al., 2002; Rosenbaum &  
662 Leibel, 1999). In girls, the early storage of energy reserves as adipose tissue might  
663 anticipate the substantial demands of future reproductive events, such as pregnancy  
664 and lactation (Kaplowitz, 2008). Conversely, the interplay between body growth and  
665 reproductive physiology in boys is less clear (Kaplowitz, 2008). This disparity may  
666 stem from methodological challenges in pinpointing the onset of puberty in boys,  
667 alongside theoretical considerations suggesting that fat reserves play a less crucial  
668 role in male reproductive functions. For example, unlike females, males do not bear  
669 the energetic burdens of pregnancy and lactation, and the emergence of male  
670 secondary sexual characteristics tends to rely more on the accrual of lean mass.

671 Another noteworthy finding in our study is the significant correlations between early  
672 environmental factors that promote cognitive stimulation, language skills in girls and  
673 the timing of adiposity rebound. Specifically, children from higher educational and  
674 socio-economic backgrounds, who are exposed to language-stimulating activities at  
675 ages 2-3, tend to delay adiposity rebound and express better language skills by ages  
676 5-6. This echoes the patterns reported by Farkas & Jacquet (2023), where limited  
677 access to various resources at age 6 was a strong predictor of later growth trajectories,  
678 both somatic and cognitive. Altogether, these findings provide empirical support for  
679 the hypothesis put forth in Kuzawa and Blair (2019), that an environment rich in  
680 information in early life can enhance brain energy demands, thereby enhancing  
681 language development.

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

694 The approach we used to investigate the energy trade-off between brain development  
695 and body growth could benefit from several improvements. Firstly, adding data on  
696 children’s dietary habits, including the amount of nutrient-dense and processed foods  
697 consumed would refine the model, given that such dietary choices can impact body  
698 mass trajectories (Ip et al., 2017; Saldanha-Gomes et al., 2022). While our pre-  
699 registered models partially account for dietary effects by including a covariate for  
700 perinatal adversity (which captures family socioeconomic status and indirectly, dietary  
701 quality, often poorer in lower-income, disadvantaged households (Fernández-Alvira et  
702 al., 2015)), direct dietary measures would offer a more precise adjustment. A second  
703 challenge lies in addressing genetic heritability, which significantly affects the timing

704 of adiposity rebound (Cissé et al., 2021; Couto Alves et al., 2019; Meyre et al., 2004).  
705 Notably, our models that correlate social adversity and socioeconomic status with  
706 cognitive development are less susceptible to genetic confounding compared to  
707 models examining the relationship between adiposity rebound and cognition alone.  
708 Thirdly, we might consider employing an alternative index to BMI for a nuanced  
709 depiction of body composition, particularly in boys, where lean mass is a more  
710 prominent contributor to BMI than in girls (Franklin, 1999; Gallagher et al., 1996;  
711 Horlick, 2001; Van Eyck et al., 2021). Lastly, integrating direct measures of neural  
712 activity, such as electrophysiological markers of neuronal maturation, would offer a  
713 more immediate evaluation of brain development.

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

## 720 **Declarations**

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

726 **Consent for Publication.** Not applicable.

### 727 **Availability of data and materials**

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

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

735 **Competing interests.** The authors declare no competing interests.

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746 designed research. S.B., C.C., A.H.C., B.H. and P.O.J. designed the analysis plan and  
747 drafted the Stage 1 submission. S.B. and P.O.J. analyzed the data. S.B., C.C. and

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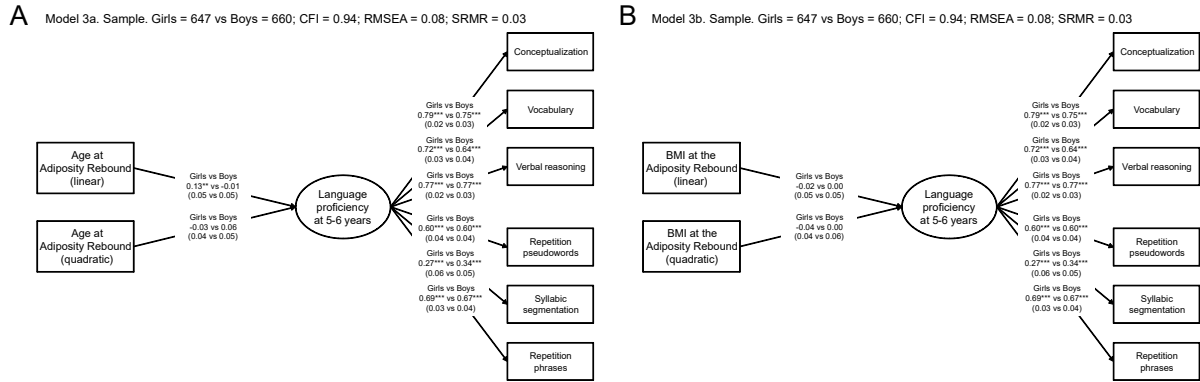
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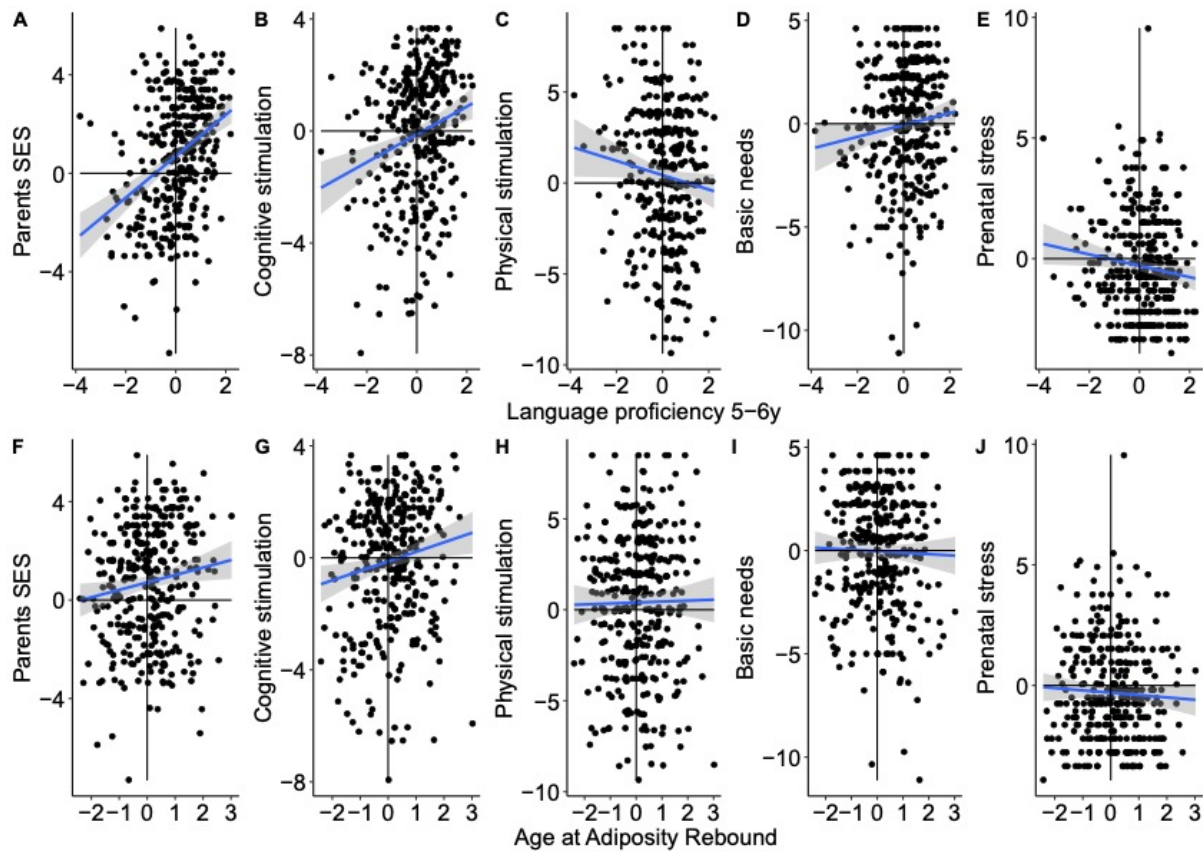
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# Figure legends



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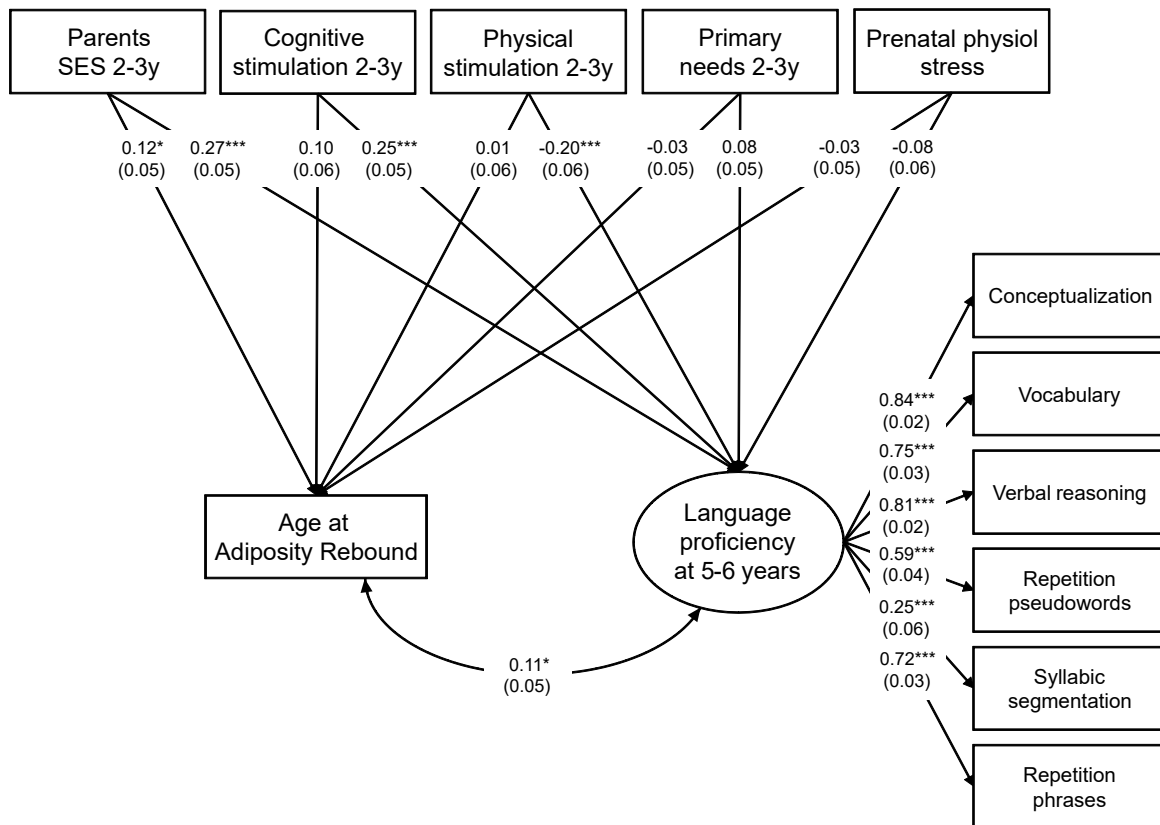
1002 **Figure 1.** Association between age at adiposity rebound and language skills at age 5-  
 1003 6, estimated by the structural equation model 3a (A) and model 3b (B). Standardized  
 1004 parameter values (and standard deviation reported in brackets) for the girls' sample  
 1005 and the boys' sample are shown for each path. The ellipse represents the latent  
 1006 variable; the rectangles represent the indicators. The paths between the indicators  
 1007 and the latent variables represent factor loadings. Paths between the single composite  
 1008 and the latent variable represent regressions. Significant paths are represented with  
 1009 \*, such that \* indicates  $p < .05$ , \*\* indicates  $p < .01$ , \*\*\* indicates  $p < .001$ . We observed  
 1010 that girls who reach the nadir of their body growth at a later age are more likely than  
 1011 others to express better language proficiency at 5-6 years than those who reach it  
 1012 earlier.



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1015 **Figure 2.** Scatterplots of environmental factors (column) according to language  
 1016 proficiency score (top row) or age at adiposity rebound (bottom row) in girls. Five  
 1017 environmental factors are used in this analysis: cognitive stimulation, physical  
 1018 stimulation, basic needs, prenatal stress and perinatal SES. To ensure comparability  
 1019 of the indicators, all scores were transformed into z-scores. We found that the amount  
 1020 of cognitive and physical stimulation provided by parents, as well as their socio-  
 1021 economic status, were positively related to language proficiency at age 5-6. In  
 1022 contrast, neither the parents' contribution to meeting the child's basic physiological  
 1023 needs nor the extent of prenatal and perinatal physiological stress were related to  
 1024 language proficiency scores. We observed that among the 5 early life environmental  
 1025 factors, only the parental socio-economic status is related to the age of the child at the  
 1026 time of adiposity rebound, so that the highest the SES, the more the adiposity rebound  
 1027 is delayed.

Unregistered model. Girl sample. N = 442; CFI = 0.95; RMSEA = 0.06; SRMR = 0.03



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**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.