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Does early nutrition predict cognitive skills during later childhood? Evidence from two developing countries

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ABSTRACT

The existing evidence linking early undernutrition to educational outcomes in developing countries is largely focused on assessing its impacts on grade attainment and achievement test scores, with limited evidence on the foundational cognitive skills required to perform well at school. We use unique data collected in Ethiopia and Peru as part of the Young Lives Study to investigate the relationship between early undernutrition and four foundational cognitive skills measured later in childhood, the first two of which measure executive functioning: working memory, inhibitory control, long-term memory, and implicit learning. We exploit the rich longitudinal data available to control for potential confounders at the household and individual level and for time-invariant community characteristics. We also take advantage of the availability of data for paired-siblings to obtain household fixed-effects estimates. In the latter specification, we find robust evidence that stunting at ~age 5 is negatively related with executive functions measured years later, predicting reductions in working memory and inhibitory control by 12.6 % and 5.8 % of a standard deviation. Although the main cohort of Young Lives was around 12 years old when executive functions were measured, complementary results and analysis of the data available for the younger siblings suggest that the impact of stunting on executive functions—specifically, on working memory—starts at an earlier age. Our results shed light on the mechanisms that explain the relationship between early nutrition and school achievement tests suggesting that good nutrition is an important determinant of children's learning capacities.

1. Introduction

Despite considerable progress in recent years, early undernutrition is still highly prevalent in low- and middle-income countries (LMICs). An estimated 249 million children under 5 years of age are at risk of not being able to realize their developmental potential, with 170 million of them being undernourished as indicated by stunting (Lu, Black and Richter, 2016; Black, et al., 2017).[1]

While the long-term consequences of early stunting on educational attainment and on school achievement tests are well-known (see a literature review for developing countries by Grantham McGregor et. al. (2007); evidence from four developing countries by Crookston et al. (2011); quasi-experimental evidence by Glewwe et al. (2001), Alderman et al. (2006); and experimental evidence by Maluccio et al. (2009)), there is scarce evidence about the mechanisms through which early stunting leads to poorer educational outcomes, especially in LMIC contexts. A better understanding of the mechanisms linking early nutrition with educational outcomes can be informative to design policies to improve learning. Furthermore, a major limitation of studies investigating effects of early investments in human capital—including, in nutrition—on cognitive development is that most of them measure its impact on domain-specific cognitive-achievement test scores (e.g., learning outcomes in math, reading comprehension and vocabulary knowledge). Comparing children's scores in country settings where language and culture differ is challenging. Even when comparability is feasible, differences in test scores cannot necessarily be attributed to

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[1] Stunting, measured by height (length for children under 2 years of age) less than two standard deviations below the age- and sex-specific medians for well-nourished populations (e.g., WHO Multicentre Growth Reference StudyGroup, 2006), is the standard measure of chronic undernutrition.

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underlying differences in cognitive skills. This is because, achievement tests focus on acquired knowledge (e.g., reading, mathematics) that requires both cognitive skills as well as access to schooling and other investments in human capital. Therefore, stunting could predict learning outcomes in part for behavioral reasons—e.g., parents might delay school enrolment (Glewwe and Jacoby, 1995; Alderman,et al., 2001). Cognitive skills, while also malleable, are less likely to rely on schooling investments.

In this study, we investigate the relationships between early nutrition and four foundational cognitive skills (FCSs) measured years later, the first two of which measure executive functioning (EF): *inhibitory control*, the capacity to control attention or behaviour, resist distractions and override counterproductive impulses; *working memory*, the capacity to hold in mind and manipulate information no longer visible in the environment; *long-term memory*, the capacity to encode, retain, and retrieve information; and, *implicit learning*, the capacity to learn without conscious awareness, sometimes described as "muscle memory". We use unique cognitive data collected in Ethiopia and Peru—as part of the Young Lives Study (YLS), a longitudinal, cohort study—through the administration of RACER, a tablet-based assessment tool for children and adolescents (Behrman et al., 2022, Ford et al., 2019).

Both Ethiopia and Peru face challenges related to socio-economic inequality and uneven access to educational and economic opportunities for the poor, yet they also differ substantially in their level of development and, accordingly, in the prevalence of early stunting and pre-school enrolment. These stark contrasts between these two countries are useful to assess the implications of early nutritional investments in children in different contexts.

Over the last half-century scientists have expanded theories and models that pay more attention to non-domain related skills, skills that apply across a wider array of contexts and knowledge domains–including IQ, organization, self-control, perseverance, and socio-emotional skills (Kimball, 2015; Bowles et al., 2001; Duncan et al., 2007; Heckman, 2007). Neuroscience has also shed light on the role of EF, a set of skills that are critical for controlling behaviour and ensuring that higher-level abstract goals are not supplanted by lower-level, more immediate goals (Diamond, 2013). Although there are studies that have assessed the relationship between stunting and cognitive skills, most of this evidence comes from cross-sectional studies, convenient samples, and/or use IQ scales such as the Raven's tests, which are not informative per se of a childś ability to learn (in fact, Raven's tests have been found to perform poorly in the context of developing countries, see Witcher et al. (2010)). Two notable exceptions that assess the impacts of early stunting on later cognitive skills are two studies based on the Cebu Longitudinal Health and Nutrition Study (Mendez and Adair, 1999) and on the INCAP Longitudinal Study (Behrman et al., 2014). However, these studies do not measure EF.

EF is considered critical for a range of key outcomes, including school readiness (Fernald et al., 2009; Blair and Razza, 2007; Blair, 2002).[2] The existing evidence shows that EF is highly associated with early life household socio-economic status (Noble et al., 2005; Farah et al., 2006; Noble et al., 2007; Klenberg et al., 2001; Ardila et al., 2005). Stressful, challenging, or deprived conditions—such as undernutrition—may impede these skills' development and hasten their decay (Lupien et al., 2009; Shonko and Garner, 2012; Nelson and Sheridan, 2011; McLaughlin et al., 2014; Sheridan and McLaughlin, 2014; Sheridan, et al., 2012; Sheridan et al., 2013). However, there is little population-based evidence on the mechanisms through which undernutrition lead to poorer EF.

Our analysis contributes to the human-capital literature by expanding the evidence available of why early nutrition impacts learning outcomes by assessing its impact on foundational cognitive skills years later that are inputs for learning, including EF. In doing so, we contribute to a deeper understanding of how early nutrition affects grade attainment and achievement test scores (or educational performance more generally speaking), investigating the impact of undernutrition on cognitive abilities and how policy interventions can help to mitigate these effects in contexts of extreme poverty, to promote lifelong-learning opportunities for all (United Nations Sustainable Development Goal #4). Such a route of analysis is particularly important in the context of the current emphasis in research and policy on early childhood as a primary window of opportunity for intervening in child development, particularly with regard to nutrition (Victora et al., 2008, 2010).

The paper unfolds as follows. In section 2 we describe the Young Lives' samples in Ethiopia and Peru. In section 3 we explain how each of the cognitive skills of interest is defined and measured through computer-based tasks (RACER) and explain how RACER was administered in Peru and Ethiopia. Section 4 explains our empirical strategy. Section 5 reports our main results and robustness checks, and Section 6 discusses our findings.

2. The Young Lives study (YLS)

YLS is a longitudinal study that follows two cohorts of children in Ethiopia and Peru—the two study countries for this research—and in India (Andhra Pradesh and Telangana) and Vietnam: older cohorts born in 1994–1995 and younger cohorts born in 2001–2002. We focus on the Ethiopian and Peruvian younger-cohort samples, tracked since ~age 1, because these are the only samples for which the FCS data are available. The first study wave was in 2002 and was followed by four subsequent in-person rounds in 2006 (age 5), 2009 (age 8), 2013 (age 12) and 2016 (age 15) (Favara et al., 2022). YLS was developed as a longitudinal study of child poverty and the sampling design reflects that intent by over-sampling poor households. In each country, 20 clusters (districts in Peru, *woredas* in Ethiopia) were sampled and, within each selected cluster, an area was randomly selected, and households were randomly contacted until approximately 100 eligible families were found.

In Peru, YLS staff enrolled children from 74 communities in 20 districts that were randomly selected after excluding the wealthiest 5 % of districts. After districts were chosen, a census tract was randomly chosen, and then within the census tract a community or housing block was randomly selected. All dwellings in each block or cluster of houses were visited to identify families with children of the eligible ages. On completion of one block, the next available neighbouring block was visited by the fieldworker until the target number of children was found.[3] The sample represents ~95 % of Peruvian children and includes urban and rural areas, the coast, highland (*altiplano*) and jungle.

In Ethiopia 20 *woredas* were purposively chosen (in states of Amhara, Oromiya, the Southern Nations, Nationalities and People's Region (SNNP), Tigray and Addis Ababa) to oversample *woredas* with food-deficit status and to capture Ethiopia's diversity across regions and a mix of geographic settings, levels of development, urban/rural balance and ethnicity. Selection of regions included identification of *woredas* in each region and peasant associations (in rural areas) or *kebeles* (the lowest level of administration in urban areas)0.100 young children of approximately 1 year of age were randomly selected within the chosen sites.

The younger cohorts in Ethiopia and Peru were originally composed of 1,998 and 2,052 index children, respectively. The attrition rate across

[2] Individuals with higher FCSs are less likely to engage in risky behaviors related to health and crime (Cole, Usher, & Cargo, 1993; Speltz et al., 1999; McClelland et al., 2006). Recent studies to investigate the skills that make workers more productive in LMIC contexts (Chile, Argentina) have added tests of FCSs to better understand the skills gaps among young adults (Bassi and Urzua, 2010).

[3] In 6 of the 20 districts, the population was not large enough to yield 100 children 1 year of age. In these cases, neighbouring (contiguous) districts with similar poverty rankings were selected systematically.

Table 1
Descriptive statistics for the Young Lives sample in Ethiopia and Peru.

	Ethiopia		Peru	
	Mean	Std. Dev.	Mean	Std. Dev.
Maternal schooling, in %				
Ethiopia: No education; Peru: Less than primary	50.4	–	35.8	–
Ethiopia: Lower primary (Gr 1–4); Peru: Complete primary	23.6	–	29.0	–
Ethiopia: Upper primary (Gr 5–8); Peru: Complete secondary	16.2	–	20.9	–
Ethiopia: More than Grade 8; Peru: Higher education	9.8	–	14.3	–
Urban area, in % (Round 1, 2002)	34.8	47.7	68.9	46.3
Wealth index (Round 1, 2002)	0.225	0.190	0.431	0.237
Nutritional status (Index Children)				
Stunting, in % (Round 1, 2002)	40.0	–	27.2	–
Height-for-age Z-score (Round 1, 2002)	−1.44	1.725	−1.26	1.249
Stunting, in % (Round 2)	30.3	–	32.4	–
Height-for-age Z-score (Round 2, 2006)	−1.43	1.093	−1.51	1.079
Number of observations	1,787		1,681	

Note: Maternal education is defined differently in the two countries as specified in the table. The sample corresponds to the balanced sample of index children observed in rounds 1, 2 and 4, with non-missing information on the selected variables.

all five survey rounds (14 years) is relatively low compared to other longitudinal studies: 5.4 % in Ethiopia and 8.4 % in Peru (excluding deaths). The low attrition is in part the result of the fact that migrant children and their families are followed within the countries.

In all rounds, the YLS captured various measurements of child development and other characteristics of the index children and their families, including anthropometrics (from age 1) and other individual and household characteristics. Since the third survey round in 2009, additional data were collected on the sibling born immediately after the index child, the so-called *younger sibling*. In Ethiopia, when there was no immediate younger sibling present, data for the immediate older sibling were collected. The original 2009 siblings' sample includes 1,001 younger siblings and 549 older siblings in Ethiopia (aged 3 to 8 and 8 to 17 years, respectively), and 861 younger siblings in Peru (aged 2 to 8 years). Attrition for this sub-group in the 2013 and 2016 survey waves is very low, 7.7 % and 2.2 % in 2016, respectively. For the siblings' sample, anthropometric and vocabulary test data were collected since 2009.

In Table 1 we report the means and standard deviations of selected important characteristics of the YLS Ethiopian and Peruvian samples. A number of differences emerge when comparing the two samples, partially reflecting the different sampling strategies adopted in the two countries and partially reflecting socioeconomic differences between the two countries.[4] The Ethiopian sample is predominantly rural; in 2002, when the YLS data were collected for the first time, only 35 % of the sample was living in urban areas against 69 % of the Peruvian sample. Children in the Ethiopian sample are growing-up in poorer households as reflected by a lower average wealth index and the fact that their mothers, who in 95 % of the cases are also the main caregivers, are significantly less-schooled on average than the mothers of the children in the Peruvian sample. Furthermore, a substantially higher proportion of index children in Ethiopia are stunted at ∼age 1 (40 % versus 27 % in Peru). The differences in children's nutritional status are less marked by the time of the second visit to the families, with index children ∼age 5. The changes in the gap in stunting prevalence over time between the two countries might be due partially to an underestimation of stunting prevalence in Peru ∼age 1 due to the young ages of the Peruvian children (as the children in the Ethiopian sample are on average 2 months older than the ones in the Peruvian sample) and the typical sharp downward pattern in average stunting rates in the first 24 months (see, e.g., Victora et al., 2010).

3. Measuring foundational cognitive skills with RACER

In 2013 (Round 4) when the index children were ∼12 years of age, the YLS administered a series of computer-based tasks in the Ethiopian and Peruvian samples using RACER (Rapid Assessment of Cognitive and Emotional Regulation). RACER is a touch screen computer/tablet application that uses short tasks (1 to 4 min each) to assess cognitive skills in children aged 6 years and older. Four foundational cognitive skills are measured by RACER, the first two of which measure EF: working memory (WM), inhibitory control (IC), long-term memory (LM) and implicit learning (IL).

To measure these cognitive skills, RACER is composed by a set of tasks used to calculate a child's performance in challenge and baseline trials. The childś average performance in challenge trials is the outcome of interest for our analysis—the skills measure for WM, IC, LM, and IL, respectively—, whereas the average performance in baseline trials is designed to capture other aspects not related to the measured skill, including a child's previous exposure to a tablet, motor skills, level of concentration in the task, among others—which are also captured by the challenge trials. Depending on the concept, a childś performance is measured in terms of response time (in seconds), accuracy (distance to the correct answer, in pixels), and/or whether the child answered the trial correctly. In Table A1 (Appendix A) we describe the tasks included in RACER and how they relate to the cognitive skills of interest A detailed description of the trials involved in each task and how cognitive skills are measured based on this information can be found in Behrman et al. (2022).

Prior to its administration, the assessment tool was pre-piloted in Lima City (Peru) and protocols adjusted subsequently.[5] Following the pre-pilot, enumerators were trained, and RACER and all the other instruments of Round 4 were piloted with children aged 6 to 12 years in urban and rural areas in both countries. In total, RACER was administered to 5,759 children: in Ethiopia, 1,801 index children (aged 11 to 12 at the time) and 1,305 siblings (aged 6 to 18); in Peru, 1,902 index children (aged 11 to 12) and 784 younger siblings (aged 6 to 12). Administration time ranged between 30 and 45 min. Among the index children, RACER was administered to 96 % of the sample available for interviews in Ethiopia and 99 % in Peru. In comparison, the Peabody Picture Vocabulary Test (PPVT), a test that measures receptive vocabulary was administered to 88 % of the index children in Ethiopia and 99 % in Peru (Behrman et al., 2022). The distributions of the performance measures reported in Appendix A show that children perform better in

[4] Ethiopia is classified by the World Bank i as a low-income country (per capita income in 2013 when Round 4 was collected = $491) and Peru as a upper-middle-income country (per capita income in 2012 = $6,697): https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups and https://databank.worldbank.org/source/world-development-indicators.

[5] Although the software has on-screen instructions, it was decided that prior to the beginning of each task, the enumerator had to explain the task to the child using coloured-papers that replicated what the child was about to see on the screen. After this, the enumerator was asked to watch the on-screen instructions with the child and to make sure the child understood that these instructions were the same that s/he had just explained. Other adjustments to the protocol are reported in Behrman et al. (2022).

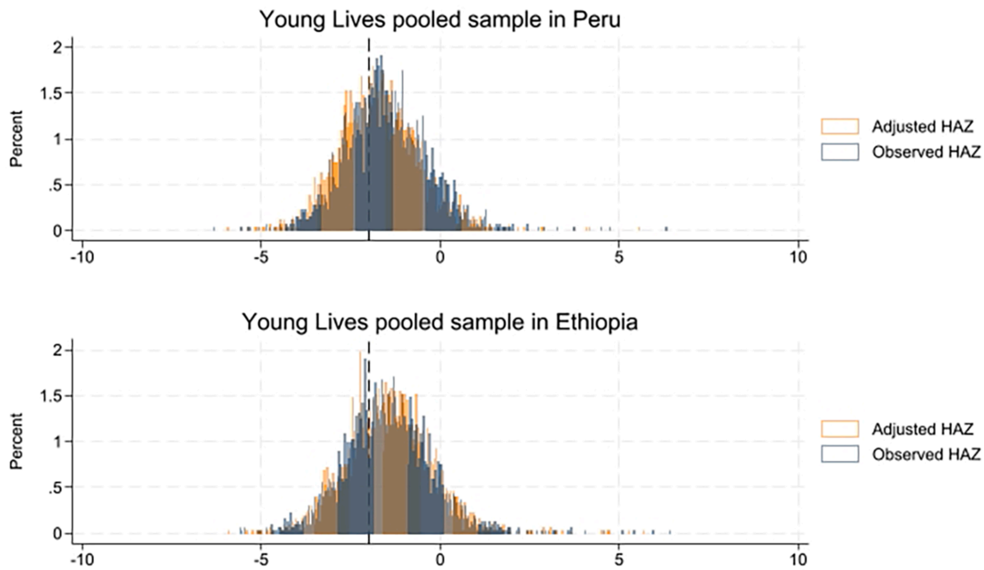

Figure 1. Height-for-age Z-score (HAZ) in the Young Lives samples in Ethiopia and Peru: observed versus adjusted.

Table 2
Correlation between early life nutritional status and later foundational cognitive skills.

		Working memory (WM) **(1)**	Inhibitory control (IC) **(2)**	Long-term memory (LM) **(3)**	Implicit learning (IL) **(4)**
Panel A (nutritional indicator: stunting)					
Pooled sample	Coef.	−0.112***	−0.087***	−0.100**	−0.018
	Std. Error	(0.024)	(0.022)	(0.037)	(0.022)
	Adjusted R2	0.252	0.343	0.069	0.557
Peru	Coef.	−0.219***	−0.134***	−0.094**	−0.031
	Std. Error	(0.026)	(0.024)	(0.040)	(0.037)
	Adjusted R2	0.255	0.342	0.035	0.500
Ethiopia	Coef.	−0.064*	−0.045*	−0.168***	−0.030
	Std. Error	(0.033)	(0.024)	(0.056)	(0.021)
	Adjusted R2	0.261	0.311	0.129	0.634
Panel B (nutritional indicator: HAZ)					
Pooled sample	Coef.	0.051***	0.045***	0.054***	0.019*
	Std. Error	(0.012)	(0.011)	(0.016)	(0.010)
	Adjusted R2	0.252	0.345	0.071	0.557
Peru	Coef.	0.110***	0.079***	0.065***	0.024
	Std. Error	(0.015)	(0.014)	(0.017)	(0.018)
	Adjusted R2	0.259	0.348	0.038	0.501
Ethiopia	Coef.	0.034**	0.022*	0.076***	0.028***
	Std. Error	(0.016)	(0.011)	(0.024)	(0.009)
	Adjusted R2	0.262	0.312	0.131	0.635
Sample size					
Peru		2,556	2,561	2,561	2,550
Ethiopia		3,038	3,038	3,038	3,037

Note: All coefficients are standardized. Each coefficient comes from a different bivariate model, controlling for whether the child is an index children, younger sibling, or older siblings. Also, each estimation controls for performance in the baseline task. Standard errors (reported in parentheses) are clustered at cluster level. * $p < 0.1$ ** $p < 0.05$ *** $p < 0.01$.

baseline trials than on challenge trials, as expected.[6] Further analysis shows that older children and children from wealthier household and whose mothers have higher levels of schooling perform better in the tasks (Behrman et al., 2022).

To facilitate the interpretation of the results, we re-scale each of the measurements (average performance at challenges and baseline trials) so that higher scores represent higher levels of abilities. Furthermore, each of the re-scaled variables is standardized by age in years within the pooled sample. As a reference, Table A2 (Appendix A) reports country-sample averages of children performance in challenge and baseline trials. As can be seen, Peruvian children perform better than Ethiopian children across all challenge tasks, whereas for the baseline tasks the differences are less pronounced—only in the case of LM Ethiopian children perform better than Peruvian children.

4. Indicators of early nutritional status

We are interested in measuring the relationship between early nutrition and later-childhood (foundational) cognitive skills. For this purpose, we used stunting at ~5 as our primary measurement of early

[6] Children find it more difficult to answer accurately in the WM trials with multiple dots (compared to single-dot trials) and require more time to respond in the IC opposite-side trials (compared to same-side trials). Similarly, children need less time to respond to patterned trials in the IL task (versus un-patterned trials). For LM, the proportion of correct answers at first touch is less in the challenge trials compared to the baseline trials.

Table 3
Main results: Predictions of early life nutritional status on later foundational cognitive skills.

		Working memory (WM) **(1)**	Inhibitory control (IC) **(2)**	Long-term memory (LM) **(3)**	Implicit learning (IL) **(4)**
Panel A: multivariate OLS					
Pooled sample	Coef.	−0.079***	−0.045**	−0.036	0.009
	Std. Error	(0.023)	(0.018)	(0.030)	(0.019)
	Adjusted R2	*0.315*	*0.388*	*0.184*	*0.572*
Peru	Coef.	−0.102***	−0.051*	0.052	0.001
	Std. Error	(0.026)	(0.029)	(0.044)	(0.035)
	Adjusted R2	*0.310*	*0.390*	*0.080*	*0.517*
Ethiopia	Coef.	−0.051	−0.038	−0.126***	0.011
	Std. Error	(0.038)	(0.022)	(0.037)	(0.017)
	Adjusted R2	*0.289*	*0.353*	*0.268*	*0.638*
Panel B: household fixed effects					
Pooled sample	Coef.	−0.126***	−0.058**	0.014	0.006
	Std. Error	(0.044)	(0.030)	(0.048)	(0.036)
Peru	Coef.	−0.130**	−0.051	0.023	−0.011
	Std. Error	(0.065)	(0.056)	(0.086)	(0.067)
Ethiopia	Coef.	−0.103*	−0.063*	−0.034	−0.000
	Std. Error	(0.059)	(0.034)	(0.055)	(0.041)
Sample size					
Peru		2,497	2,501	2,501	2,491
Ethiopia		2,901	2,901	2,901	2,900

Note: All coefficients are standardized. Each coefficient comes from a different estimation linking early life stunting to a given later FCS. Results from Panel A correspond to equation (1) (pooled OLS). Controls included: childś age (in months) and sex; native tongue of the mother and maternal education; wealth index (in quintiles) at age 1, area of location at age 1, household size at age 1; community fixed effects at age 1 (specific to the index child); performance in the baseline tasks, whether the task was administered during the weekend, and the time of the day when the tasks were administered. Results from Panel B correspond to a household fixed effects specification (equation (2)). Standard errors (reported in parentheses) are clustered at cluster level. * $p < 0.1$ ** $p < 0.05$ *** $p < 0.01$.

Table 4
Predictions of early life nutritional status on later foundational cognitive skills – using unadjusted stunting.

		Working memory (WM) **(5)**	Inhibitory control (IC) **(6)**	Long-term memory (LM) **(7)**	Implicit learning (IL) **(8)**
Panel A: multivariate OLS					
Pooled sample	Coef.	−0.084***	−0.053***	−0.070**	−0.007
	Std. Error	(0.026)	(0.018)	(0.029)	(0.019)
	Adjusted R2	0.315	0.392	0.177	0.560
Peru	Coef.	−0.140***	−0.068**	−0.011	−0.031
	Std. Error	(0.031)	(0.028)	(0.038)	(0.033)
	Adjusted R2	0.309	0.388	0.078	0.519
Ethiopia	Coef.	−0.025	−0.036	−0.121***	0.018
	Std. Error	(0.037)	(0.022)	(0.041)	(0.016)
	Adjusted R2	0.285	0.357	0.260	0.616
Panel B: household fixed effects					
Pooled sample	Coef.	−0.128***	−0.076**	0.006	−0.007
	Std. Error	(0.048)	(0.031)	(0.050)	(0.039)
Peru	Coef.	−0.147**	−0.100*	0.026	−0.010
	Std. Error	(0.073)	(0.055)	(0.082)	(0.065)
Ethiopia	Coef.	−0.086	−0.078**	−0.003	−0.004
	Std. Error	(0.067)	(0.038)	(0.062)	(0.048)
Sample size					
Peru		2,497	2,501	2,501	2,491
Ethiopia		2,587	2,587	2,587	2,586

Note: All coefficients are standardized. Each coefficient comes from a different estimation linking stunting (as observed in the dataset, using the observation closest to age of five) to a given later FCS. This sample excludes the older siblings from Ethiopia. Results from Panel A correspond to equation (1) (pooled OLS). Controls included: childś age (in months) and sex; native tongue of the mother and maternal education; wealth index (in quintiles) at age 1, area of location at age 1, household size at age 1; community fixed effects at age 1 (specific to the index child); performance in the baseline tasks, whether the task was administered during the weekend, and the time of the day when the tasks were administered. Results from Panel B correspond to a household fixed effects specification (equation (2)). Standard errors (reported in parentheses) are clustered at cluster level. * $p < 0.1$ ** $p < 0.05$ *** $p < 0.01$.

nutrition. Stunting is a measure of chronic or recurrent undernutrition that is widely used in the nutritional literature and in development economics (see, for instance, Alderman, 2000).[7] A child is identified as stunted if his/her height-for-age z-score (HAZ) is two standard deviations or more below the WHO age-gender specific medians. Height-for-age is standardized according to age- and gender-specific child growth standards provided by the World Health Organization (WHO Multicentre Growth Reference StudyGroup, 2006) which are universally comparable. The resulting HAZ is an indicator of cumulative deficient growth. We use stunting as our primary measure of undernourishment and HAZ as a secondary measure because the literature suggests that the left tail of the HAZ distribution, as indicated by stunting, is particularly important for child development (e.g., Victora et al., 2008, 2010).

We focus on stunting measured at ~5 years of age, which marks the end of the pre-school period. However, not all children in the samples

[7] Height-for-age is less sensitive than weight-for-age and weight-for-height to temporary shocks due to morbidity and illnesses or seasonal variations in food availabilities.

Table 5
Predictions of early nutritional status on later foundational cognitive skills –controlling for earlier vocabulary test scores (PPVT).

		Baseline		Controlling for PPVT by early/mid childhood		Controlling for PPVT by mid/late childhood	
		Working memory (WM) **(1)**	Inhibitory control (IC) **(2)**	Working memory (WM) **(3)**	Inhibitory control (IC) **(4)**	Working memory (WM) **(5)**	Inhibitory control (IC) **(6)**
Panel A: multivariate OLS							
Pooled sample	Coef.	−0.070**	−0.056***	−0.063**	−0.055***	−0.056*	−0.055***
	Std. Error	(0.029)	(0.019)	(0.029)	(0.019)	(0.030)	(0.019)
	Adjusted R2	0.303	0.398	0.305	0.398	0.312	0.398
Peru	Coef.	−0.132***	−0.076**	−0.124***	−0.074**	−0.112***	−0.071**
	Std. Error	(0.037)	(0.028)	(0.036)	(0.028)	(0.038)	(0.028)
	Adjusted R2	0.303	0.398	0.306	0.398	0.316	0.399
Ethiopia	Coef.	−0.007	−0.037	−0.001	−0.037	−0.001	−0.037
	Std. Error	(0.040)	(0.024)	(0.041)	(0.024)	(0.042)	(0.024)
	Adjusted R2	0.270	0.354	0.271	0.353	0.276	0.354
Panel B: household fixed effects							
Pooled sample	Coef.	−0.124**	−0.090**	−0.122**	−0.090**	−0.114**	−0.090**
	Std. Error	(0.054)	(0.037)	(0.054)	(0.037)	(0.054)	(0.037)
Peru	Coef.	−0.146*	−0.164**	−0.136	−0.164**	−0.142*	−0.164**
	Std. Error	(0.085)	(0.069)	(0.084)	(0.070)	(0.084)	(0.069)
Ethiopia	Coef.	−0.098	−0.070	−0.098	−0.070	−0.094	−0.070
	Std. Error	(0.073)	(0.044)	(0.073)	(0.044)	(0.073)	(0.044)
Sample size							
Peru		2,202	2,205	2,202	2,205	2,202	2,205
Ethiopia		2,407	2,413	2,407	2,413	2,407	2,413

Note: All coefficients are standardized. Each coefficient comes from a different estimation linking early life stunting (as observed in the dataset, using the observation closest to age of five) to a given later FCS. This sample excludes the older siblings from Ethiopia. Results from panel A correspond to equation (1). Controls included: childś age (in months) and sex; native tongue of the mother and maternal education; wealth index (in quintiles) at age 1, area of location at age 1, household size at age 1; community fixed effects at age 1 (specific to the index child); performance in the baseline tasks, whether the task was administered during the weekend, and the time of the day when the tasks were administered. In addition, results in columns (3) and (4) control for a childś score in the earliest measurement available of the PPVT (scores standardized by age in years). Results from panel B correspond to a household fixed effects version of the same specification. Standard errors (reported in parentheses) are clustered at cluster level. * $p < 0.1$ ** $p < 0.05$ *** $p < 0.01$.

Table 6
Predictions of early life nutritional status on later performance on baseline tasks.

		Multivariate (OLS)		Household fixed effects	
		Working memory (WM) **(1)**	Inhibitory control (IC) **(2)**	Working memory (WM) **(3)**	Inhibitory control (IC) **(4)**
Pooled sample	Coef.	−0.101***	−0.056***	−0.078	−0.059*
	Std. Error	(0.028)	(0.020)	(0.053)	(0.033)
	Adjusted R2	*0.050*	*0.172*		
Peru	Coef.	−0.049	0.003	0.079	−0.034
	Std. Error	(0.043)	(0.031)	(0.092)	(0.062)
	Adjusted R2	*0.058*	*0.128*		
Ethiopia	Coef.	−0.121***	−0.124***	−0.144**	−0.106***
	Std. Error	(0.038)	(0.020)	(0.065)	(0.038)
	Adjusted R2	*0.047*	*0.094*		
Sample size					
Peru		2,497	2,501	2,497	2,501
Ethiopia		2,901	2,901	2,901	2,901

Note: All coefficients are standardized. Each coefficient comes from a different estimation linking early life stunting to a childś later performance in each baseline task. Results from columns (1) and (2) correspond to a pooled OLS specification. Controls included: childś age (in months) and sex; native tongue of the mother and maternal education; wealth index (in quintiles) at age 1, area of location at age 1, household size at age 1; community fixed effects at age 1 (specific to the index child); whether the task was administered during the weekend, and the time of the day when the tasks were administered. Results from columns (3) and (4) correspond to a household fixed-effects specification controlling for the same variables. Standard errors (reported in parentheses) are clustered at cluster level. * $p < 0.1$ ** $p < 0.05$ *** $p < 0.01$.

have their HAZ observed at that age (see the distribution by age in months in Figure B1 in Appendix B). The index children and younger siblings are approximately 5 years of age in rounds 2 and 3 (respectively), albeit with dispersion around the mean (4 to 5 years of age for the index children, 3 to 7 years for the younger siblings). Furthermore, for the older siblings the earliest measurement of HAZ is observed at ages 9 to 14. As shown in Figure B2 (Appendix B), in both country samples HAZ improves as children age. Therefore, the HAZ observed, might not be the best approximation for age 5 HAZ.

To deal with this, we apply two different strategies depending on whether HAZ is measured close to the age of 5 (index children and younger siblings) or not (older siblings). If HAZ is measured at approximately 5 years of age, we adjust a child's HAZ taking into account average differences in HAZ observed by age in months in each

Table 7
Predictions of early life nutritional status on later foundational cognitive skills, heterogenous effects by age and sex.

		Working memory (WM) (1)	Inhibitory control (IC) (2)
Panel A (nutritional indicator interacted with age)			
Pooled sample	Coef. (Stunting)	−0.265***	−0.022
	Std. Error	(0.163)	(0.119)
	Coef. (Stunting*AGE)	0.001	-0.000
	Std. Error	(0.001)	(0.001)
Peru	Coef. (Stunting)	−0.495*	−0.341
	Std. Error	(0.283)	(0.217)
	Coef. (Stunting*AGE)	0.003	0.002
	Std. Error	(0.002)	(0.002)
Ethiopia	Coef. (Stunting)	−0.127	0.183
	Std. Error	(0.217)	(0.128)
	Coef. (Stunting*AGE)	0.001	−0.002
	Std. Error	(0.002)	(0.001)
Panel B (nutritional indicator interacted with female dummy)			
Pooled sample	Coef. (Stunting)	−0.071**	−0.027
	Std. Error	(0.030)	(0.024)
	Coef. (Stunting*Female)	−0.016	−0.037
	Std. Error	(0.055)	(0.033)
Peru	Coef. (Stunting)	−0.080*	−0.033
	Std. Error	(0.042)	(0.041)
	Coef. (Stunting*Female)	−0.043	−0.034
	Std. Error	(0.066)	(0.054)
Ethiopia	Coef. (Stunting)	−0.073	−0.031
	Std. Error	(0.048)	(0.028)
	Coef. (Stunting*Female)	0.047	−0.015
	Std. Error	(0.086)	(0.039)
Sample size			
Peru		2497	2501
Ethiopia		2901	2901

Note: All coefficients are standardized. Same control variables as in equation (1). Each control variable is also interacted with age in months (Panel A) and a female dummy (Panel B), respectively. Standard errors (reported in parentheses) are clustered at cluster level. * p < 0.1 ** p < 0.05 *** p < 0.01.

country sample, thus purging differences in HAZ that are likely to be purely driven by the age at which the child is observed. Conversely, if no HAZ measures at the age of 5 are available, we estimate a model that assumes that two measurements of a child́s HAZ are observed, one at around 60 months (5 years) of age, and one at a later age. This model is calibrated using data from the index children and younger siblings for which this assumption holds, and the predicted coefficients are used to extrapolate the HAZ that older siblings might have had if they had been observed at the age of 5 years (60 months). More details about the procedure followed in each case are reported in Appendix B.

Figure 1 reports the observed and adjusted HAZ of the pooled sample, separately for each country sample. For the Ethiopian sample, both distributions appear to be similar and lead to similar stunting levels (32 % and 33 % in the observed and adjusted scenarios, respectively), whereas in the Peruvian sample the adjusted HAZ distribution is shifted to the left, which leads to a larger prevalence of stunted children (40 % compared to 33 % in the observed distribution). This is expected since the Peruvian sample is the one where most recovery from stunting was observed after the age of 5 compared to the other Young Lives study country samples (Lundeen et al., 2013). From here onwards, unless otherwise expressed, we focus on the adjusted HAZ.

5. Empirical strategy

The main objective is to test whether early undernutrition predicts later child foundational cognitive skills. The specification used is as follows:

$$FCS_{ij} = \alpha_1 + \alpha_2 NUT_{ij} + \gamma_1 Baseline_{ij} + C_{ij}\Gamma_1 + X_{ij}\Gamma_2 + Z_{ij}\Gamma_3 + \theta_j + \varepsilon_{ij} \quad (1)$$

where FCS_{ij} is a generic variable used to denote measurements of foundational cognitive skills (IC, WM, LM and IL) of child *i* in cluster *j* at ~age 12 in R4; NUT_{ij} is an indicator of the early nutritional status of child *i* in cluster *j* at ~age 5, proxied by stunting; X_{ij} is a vector that includes child́s age (in months) at the time FCS_{ij} was measured, sex, the native tongue of the mother (as a proxy of ethnicity); Z_{ij} is a vector that captures measures of early life household poverty and a number of household characteristics at ~age 1 (maternal schooling, wealth index,[8] area of location, household size); $Baseline_{ij}$ measures child performance at the baseline tasks in the RACER application–this controls for other domain-general skills and capabilities different from the skill being tested (e.g., the fact that some children had never seen a tablet before); C_{ij} is a vector that controls the day of the week (weekend or not) and the time of the day (morning or afternoon) when the tasks were administered; θ_j is a cluster fixed effect to control for unobserved characteristics common to all children in cluster *j* at ~age 1, and ε_{ij} is a measurement error. To increase statistical power and allow for more variation in the skills and nutritional variables we use data from index children and younger siblings in Peru and Ethiopia, as well as older siblings in Ethiopia. As part of the robustness checks, we report additional results excluding the older siblings and splitting the sample by age-groups. Equation (1) is estimated for the pooled sample of Ethiopia and Peru, and separately by country.

The coefficient of interest is α_2, which links later foundational cognitive skills to early stunting. Our main specification might still be afflicted by omitted variable bias. A key concern is that parents that have a higher preference for child quality might invest more in the health and education of their children, thus explaining differences in nutritional status and in the cognitive skills measured by RACER. To account for this possibility, we implement a household fixed-effects estimation, as follows:

$$FCS_{ik} = \alpha_1 + \alpha_2 NUT_{ik} + \gamma_1 Baseline_{ik} + C_{ik}\Gamma_1 + X_{ik}\Gamma_2 + Z_{ik}\Gamma_3 + \theta_k + \varepsilon_{ik} \quad (2)$$

where FCS_{ik} represents the outcome of interest of child *i* from household *k*, and θ_k represents unobserved heterogeneity that is common across siblings—including parental preferences for child quality. By construction, this specification controls for differences between siblings in sex, age, in performance in the baseline tasks, time of administration (weekday or weekend; time during the day), and in time-varying early life household characteristics (wealth index, area of location, and household size)—among the control variables included in equation (1), only maternal schooling and maternal native tongue were time invariant.

6. Results

6.1. Main results

Before looking at the main results, in Table 2**, Panel A**, we report the correlation between nutritional status as indicated by early life stunting

[8] The wealth index is a composite index combining an access-to-basic-services index (safe drinking water, adequate sanitation and electricity); a housing-quality index (main materials of walls, roof and floor satisfy basic norms of quality); and, an index of consumer durables (household owns radio, television, bicycle, motorbike, automobile, landline phone, mobile phone, refrigerator, stove, blender, iron, record player, computer or laptop) (Briones, 2017). For each country, households are categorised into quintiles based on their wealth index, with the households with lowest wealth belonging to the bottom quintile, and those with the highest wealth belonging to the top quintile.

Table A1
Description of cognitive skills measured by RACER tasks.

Cognitive skill (1)	Order of task (3)	Cognitive Task (4)	Preferred outcome measure (5)	Baseline performance (6)	Challenge performance (7)
Long-term memory	Task 1 & 5	Paired Associate Learning Task "Memory Game 1″ Task 1, two presentations of the (same) six pairs "Memory Game 2" Task 5 (same as Task 1, excluding tutorial & practice test)	Correct answer is provided at first touch	First time the six pairs are presented (trials) Number of trials: 6	Second, third and fourth time the (same) six pairs are presented (trials) Number of trials: 18
Inhibitory Control	Task 2	Simon Task "Sides Game"	Equally weighted average of response time, and Euclidean distance (log scale)	Same-side trials Number of trials: 7	Opposite-side trials Number of trials: 14
Working Memory	Task 3	Spatial Delayed-Match-to-Sample Task "Finding the Dots"	Euclidean distance (log scale)	Short-delay, single-dot trials Number of trials: 30	Long-delay, multiple-dots trials Number of trials: 30
Implicit Learning	Task 4	Adapted Serial Reaction Time Task"Catching Chickens/ Chasing dots"	Response time	Non-patterned trials Number of trials: 70	Patterned trials Number of trials: 105

Source: adapted from Behrman et al. (2022).

Table A2
Average performance at challenge and baseline tasks in Peru and Ethiopia.

		Working memory (WM) (1)	Inhibitory control (IC) (2)	Long-term memory (LM) (3)	Implicit learning (IL) (4)
Panel A (challenge task)					
Peru	Mean	0.17	0.12	0.13	0.09
	Std. Dev.	(0.981)	(0.776)	(0.996)	(1.106)
Ethiopia	Mean	−0.15	−0.10	−0.10	−0.08
	Std. Dev.	(0.989)	(0.636)	(0.986)	(0.886)
	T-test (p-value)	*0.000*	*0.000*	*0.000*	*0.000*
Panel B (baseline task)					
Peru	Mean	0.02	0.20	−0.13	0.03
	Std. Dev.	(0.976)	(0.710)	(0.916)	(1.045)
Ethiopia	Mean	−0.02	−0.17	0.11	−0.02
	Std. Dev.	(1.006)	(0.602)	(1.056)	(0.952)
	T-test (p-value)	*0.088*	*0.000*	*0.000*	*0.061*
Sample size					
Peru		2,556	2,561	2,561	2,554
Ethiopia		3,038	3,038	3,038	3,038

and each of the later foundational cognitive skills measurements, for the pooled sample and separately by country. Results come from an OLS model that controls for whether the child is the index child, a younger sibling, or an older sibling; and, for the child performance in the baseline task (which captures abilities required to perform well using the tablet). All the coefficient estimates have the expected signs. Focusing on the pooled sample, stunting is significantly associated with subsequent reductions in WM, IC, and LM by 11.2 %, 8.7 %, and 10.0 % of a standard deviation, respectively. The point estimate related to IL is smaller (1.8 %), and statistically insignificant. For comparison, the analogous associations using HAZ as a nutritional indicator are reported in Panel B. HAZ is associated with subsequent significant improvements in WM, IC, LM, and IL, by 5.1 %, 4.5 %, 5.4 %, and 1.9 % of a standard deviation, respectively. In both cases, the magnitude of the coefficients for WM and IC are larger for the Peruvian sample (in absolute values), and the differences are statistically significant, whereas the coefficients for LM and IL are not statistically different between the two countries.

In Table 3, Panel A, we report results of estimating equation (1) for Ethiopia and Peru. This model controls for child and household characteristics, community at age ~1 fixed effects, and performance in the baseline tasks. Full results for Ethiopia and Peru are reported in Table C1 (Appendix C).[9] Focusing on the pooled sample, the adjusted R-squared ranges between 32 % and 39 % for the EF measurements, has its lowest value (18 %) for LM, and its highest value (58 %) for IL. In the case of LM, the low value of the adjusted R-squared (in relative terms) is driven by the Peruvian sample (8 %, compared to 27 % in Ethiopia). Results suggests that nutrition has a role in explaining EF. Stunting leads to a reduction of WM and IC by 7.9 % and 4.5 % of a standard deviation in the pooled sample, respectively. The point estimates are larger for the Peruvian sample (in absolute values), but the differences are not statistically significant. In relation to the non-EF measurements, no evidence is found for the pooled sample—in fact, the point estimate for IL is close to zero. In the country-specific estimates, only for LM is a relationship found for Ethiopia (stunting leads to a reduction in this skill by 12.6 %).

[9] The key covariate across all measurements of cognitive skills is the child performance in the baseline trials. These are the variables with the highest contribution to the adjusted R-squared. Looking at household characteristics, which capture aspects related to the socio-economic status of the family, we find that maternal education—in particular, having a mother with tertiary education—predicts better performance in the WM and LTM tasks in the Peruvian sample, but not in the Ethiopian sample. Belonging to the upper quintiles of wealth predicts a better performance in LTM, IC in Ethiopia, and LTM and IL in Peru. Maternal native tongue also explains some heterogeneity in the results, for IL in Peru, and for WM, LTM, and IL in Ethiopia.

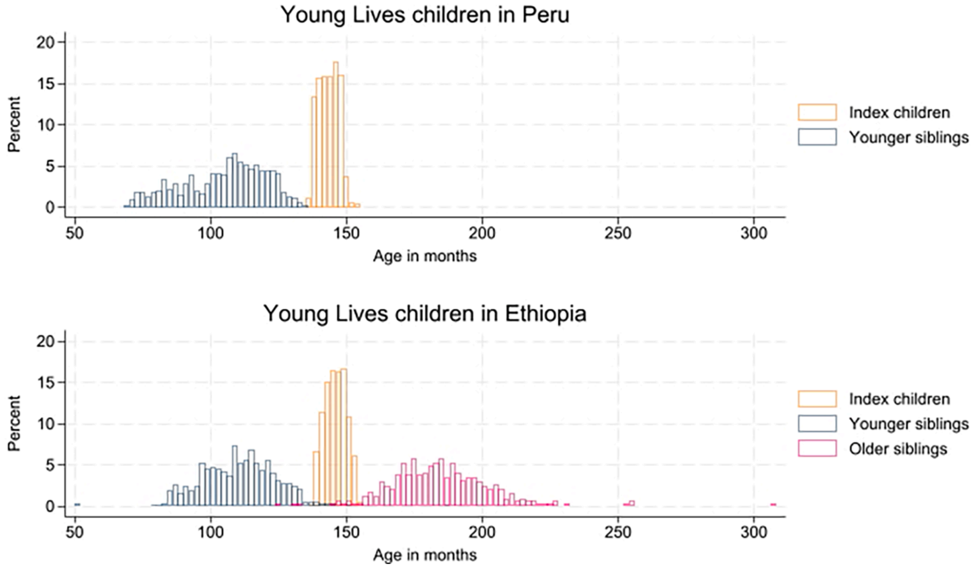

Figure B1. Age distribution by country samples.

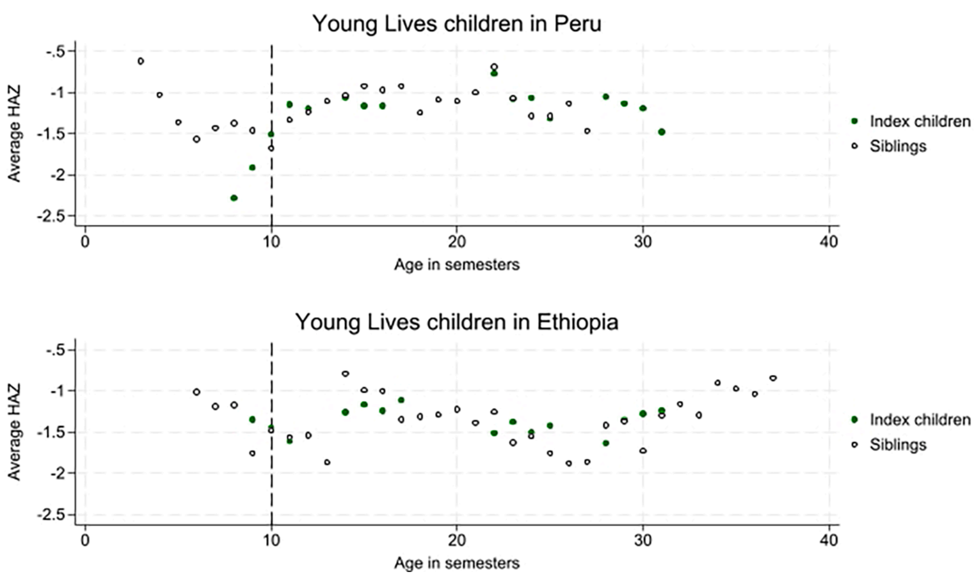

Figure B2. Average height-for-age Z-score (HAZ) by age in semesters.

In Panel B, we present household fixed-effects estimates, as in equation (2). This is our preferred specification, as it purges any remaining heterogeneity in the cognitive skills measured by RACER that could be explained by household unobserved characteristics that simultaneously determine investments in nutrition and skills. Results from this specification confirm that early stunting is associated with EF in later childhood. In the pooled sample, stunting leads to a reduction in WM and IL by 12.6 % and 5.8 % of a standard deviation, respectively. Similar point estimates are obtained for Ethiopia and Peru for WM (between '-10 %' and '-13 %') and IC (between '-6%' and '-5%'), which are statistically significant except for IC for Peru. In fact, the point estimates obtained with the household fixed-effects strategy for stunting tend to be larger (in absolute value) compared to those obtained by OLS. As before, no significant result is found for LM or IL in the pooled sample, and the coefficient linking stunting to LM is no longer statistically significant.

6.2. Robustness checks

To understand if our conclusions are sensitive to the adjustment made to stunting, in Table 4 results are reported using the child's stunting observation (or unadjusted stunting) closest to the age of 5 measured in the Young Lives Study, without any further adjustment. Since for the older siblings there is no observation close to the age of 5, they are excluded from the sample for this estimation, which is only relevant for the Ethiopian sample. When doing this, our conclusions about the role of stunting on EF remain unchanged—for the pooled sample, changes in the magnitude of the coefficient are negligible, and results remain statistically significant, both in the OLS and in the preferred, household fixed-effects specification.

To assess the sensitivity of our main results to the use of stunting as a nutritional indicator, in Table C2 (Appendix C), alternative results are presented using HAZ instead of stunting as the independent variable of interest. For the pooled OLS model (Panel A), the same patterns are observed: an increase in HAZ by one standard deviation is associated

Table B1
Ages by country sample across rounds (in months).

Cohort	n	Mean	Median	Min	Max	p.5	p.95
<u>Ethiopia</u>							
Index children							
Round 2	1799	61.8	62	52	75	56	68
Round 3	1,795	97.5	98	88	138	91	104
Round 4	1,801	145.5	146	136	156	139	152
Younger siblings							
Round 3	883	61.6	62	0	137	39	83
Round 4	883	110.1	110	50	187	87	131
Older siblings							
Round 3	343	135.7	134	77	258	110	165
Round 4	343	184.2	183	124	307	159	213
<u>Peru</u>							
Index children							
Round 2	1,832	63.5	64	53	75	55	71
Round 3	1,834	94.9	95	85	106	89	100
Round 4	1,852	142.9	143	135	154	137	148
Younger siblings							
Round 3	759	56.4	59	21	87	28	77
Round 4	759	104.5	107	68	135	76	125

Note: data from Round 1 is not used because then index children aged 6 to 18 months, which does not overlap with the age of the younger siblings in round 3.

with subsequent increases in WM and IC by 4.2 % and 2.9 % of a standard deviation, respectively. In this case, the standardized coefficient for LM is statistically significant in the pooled sample (2.3 %). As before, the result is driven by the Ethiopian sample (4.9 % of a standard deviation). Considering the preferred specification (household fixed-effects estimates, reported in Panel B), as before the results linking nutritional status to LM becomes statistically insignificant in this case. Furthermore, using HAZ the results linking early nutrition to IC also become statistically insignificant, only the coefficients linking early nutrition to WM remains significant in this case.

Besides measurement error, a potential concern about this specification is that it might still be afflicted by bias due to differential investments across siblings. Although this possibility is limited in this case because the specification controls for sibling-differences in early life household wealth—this captures, for instance, if the household socioeconomic status has improved over time, benefiting the younger sibling—, there might be differential investments within the household associated with the birth order of the child. For instance, the index child—who is by construction older than the other sibling for all the Peruvian sample and for the majority of the Ethiopian sample— might have benefited for being born earlier (Behrman, 1988), although the effect of the birth order on childś development has an unknown direction a priori (De Haan et al., 2014). To partially alleviate this concern, in Table C3 (Appendix C), we report results from an alternative household fixed-effects specification that controls for birth order (whether the index child was the first-born in the household) and birth-sex order. Our conclusions remain unchanged.

6.3. Additional results

Having established that early nutrition predicts EF and specifically WM and IC, later in childhood, we seek additional evidence that helps us shed light on these results.

First, we investigate whether the predictive role of stunting on EF might have appeared earlier in life, i.e., before age 12 Sheridan et al. (2022) and its implications for answering domain-specific achievement test scores. Second, we test whether our results are indeed underestimating the role of early undernutrition, having a detrimental effect on the childś abilities to answer the computerized tasks (e.g., speed of response) captured by the baseline tasks and included as controls in our specifications. Third, we explore potential heterogenous effects of early nutrition on later EF by age and sex.

To assess the predictive role of undernutrition on early foundational cognitive skills, the scope of our analysis is limited by data availability, as RACER is measured once, at age 12 for the index children while the majority of younger siblings where 8 years old or older at the time RACER was administered. One way to partially circumvent this problem, is to re-estimate our model controlling for earlier measures of a learning outcome that is expected to be a function of EF. Using data from the Young Lives study, Lopez et al. (2022) show that working memory is a relevant ability required to perform well in learning outcomes including vocabulary—measured using PPVT, a test of vocabulary knowledge that can be adjusted according to the age of the child (Cueto et al., 2009). Previous evidence shows that early stunting predicts PPVT scores at ages 4 to 5 (Crookston et al., 2011). Also, importantly from a methodological perspective, PPVT is the only learning outcome measured for both the Young Lives index children and their siblings, since the age of 4–5 years. Building on these facts, we assess whether our results change when controlling for a childś score in the PPVT at ages prior to the measurement of FCS (see Table 5). To facilitate the interpretation of the results, for this part of the analysis we exclude the older siblings and use unadjusted stunting. In columns (1)-(2) we re-estimate the main model without controlling for PPVT but for the sample for which PPVT for younger ages than when RACER was administered is observed. In columns (3)-(4) the estimates control for PPVT measured at the same age that stunting was measured (between ages 4 to 7, early/mid childhood), whereas in columns (5)-(6) PPVT was measured when children were transiting through primary school (between ages 7 to 12 mid/late childhood). Considering the multivariate (OLS) estimates for the pooled sample (Panel A), we observe a slight reduction in the coefficient estimate that links stunting with WM after controlling for PPVT in early/mid childhood (from '-7.0 %' to '-6.3 %'). A similar pattern is observed when considering PPVT in mid/late childhood, when the coefficient further reduces to '-5.6 %'. In contrast, the coefficient estimate that links stunting with IC remains virtually unchanged once

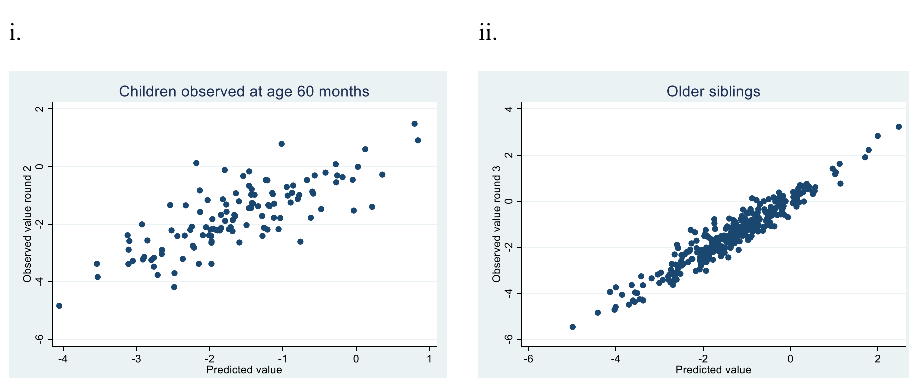

Figure B3. Height-for-age predicted versus observed for children observed at age 60 months (i), and for the older siblings (ii).

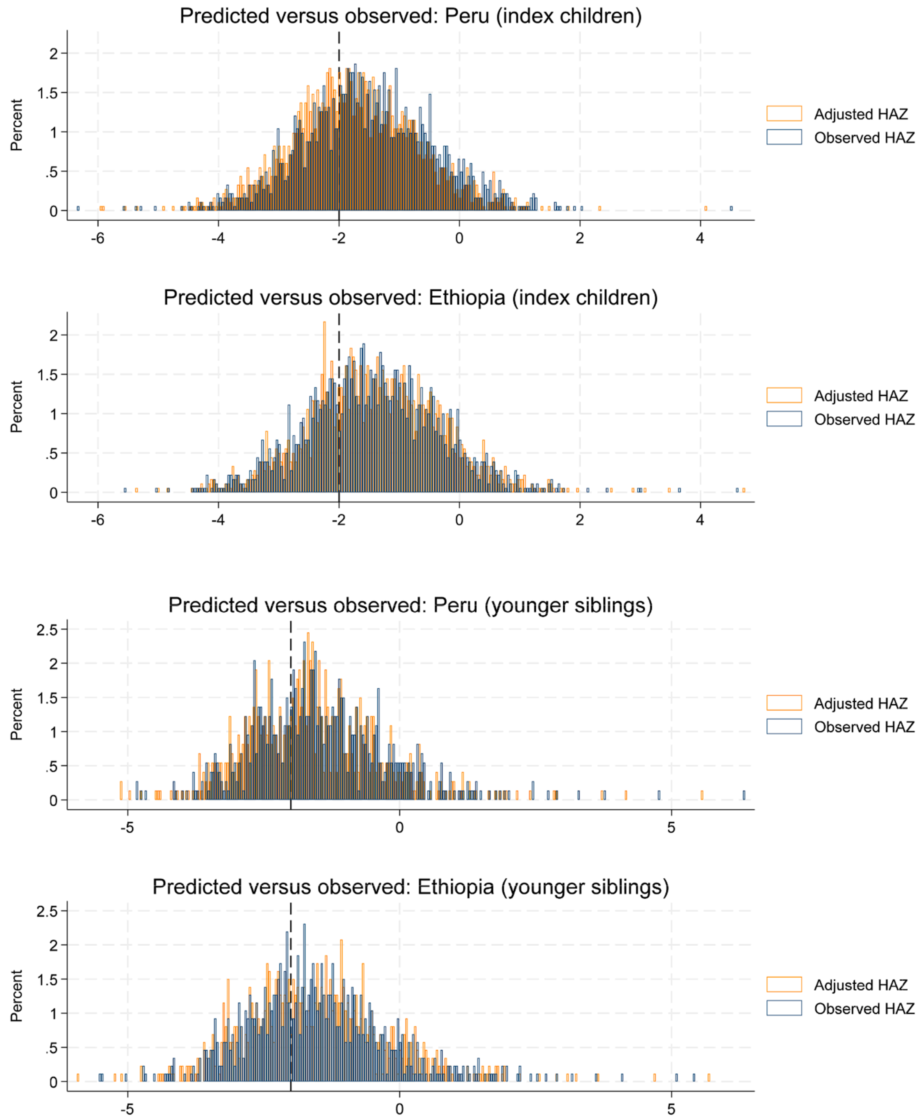

Figure B4. Predicted versus observed: index children and younger siblings.

results control for PPVT. At the country level, the reduction of the coefficient for WM (in absolute value) is driven by the Peruvian sample Results from the household fixed-effects model show the same pattern whereby a slight reduction in the coefficient estimate of interest is observed once results adjust for the earliest measurement available of PPVT.

Introducing a learning outcome in the model comes at a cost, as not all children choose to answer these tests, especially in the context of poor families. Behrman et al. (2022) show that PPVT has a higher non-response rate compared to RACER in Ethiopia (12 % versus 3 % for the index children), whereas in Peru the non-response rate is similar, with only a small difference among the siblings (2 % versus 1 %, respectively). It is plausible that children with lower EF might be less likely to answer the PPVT, which would bias downwards our previous results. To assess this possibility, in Table C4 (Appendix C) we measure the drivers of non-response in the PPVT test, including the role of WM and IC and using the same control variables as in Equation (1)—except for stunting. We find that in Ethiopia, children that had a higher level of WM at age 12 were more likely to answer the PPVT test at age 5. This might explain why the coefficient linking stunting to WM in the PPVT-restricted sample in Table 5 became virtually zero for Ethiopia, whereas there were no changes in the Peruvian sample.

Overall, our results suggest that part of the 'impact' of stunting on WM is likely to have occurred early in life, affecting vocabulary test scores in Peru and the likelihood of answering the same test in Ethiopia. Another way to investigate whether the 'impact' of undernutrition on EF might have occurred early in life, is to assess if the relationship early stunting and EF is present among the youngest children. In Table C5 (Appendix C), we split the sample in three groups according to the age children had when RACER was administered in Round 4: 9 years old or less; 10 to 11 years old; and 12 to 13 years old. These results need to be analysed with caution due to sample size considerations. Although the estimates are not always statistically significant, the pooled sample results suggest that the relationship of stunting with WM and IC is already observed among the youngest children. In fact, for WM the relationship appears to be stronger at younger ages and dissipates late childhood.

To assess whether our results might be underestimating the 'impact' of early nutrition on later EF because of effects through the baseline results, we investigate the relationship of early nutrition with the baseline task measures capturing the general abilities required to answer EF-related trials (Table 6). Considering the preferred specification (with household fixed effects), the results show that early stunting is associated with a lower level of these abilities, in the Ethiopian sample, which suggests that our findings represent a lower bound estimate of the impact of early nutrition on later EF.

Finally, we explore potential heterogenous effects of early nutrition

Table C1
Main results, all coefficients.

	Peru				Ethiopia			
	WM **coef/t**	IC **coef/t**	LM **coef/t**	IL **coef/t**	WM **coef/t**	IC **coef/t**	LM **coef/t**	IL **coef/t**
Stunted	−0.102***	−0.051*	0.052	0.001	−0.051	−0.038	−0.126***	0.011
	(0.026)	(0.029)	(0.044)	(0.035)	(0.038)	(0.022)	(0.037)	(0.017)
Age in months, r4	0.012	0.000	0.027**	−0.007	−0.004	0.003	−0.014*	0.003
	(0.014)	(0.007)	(0.011)	(0.009)	(0.008)	(0.006)	(0.008)	(0.005)
Age in months squared, r4	−0.000	0.000	−0.000	0.000	0.000	−0.000	0.000*	−0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Child is female	−0.297***	−0.124***	0.030	−0.158***	−0.210***	−0.066**	−0.087**	−0.065**
	(0.028)	(0.025)	(0.049)	(0.045)	(0.026)	(0.031)	(0.033)	(0.026)
Maternal edu: complete primary	0.061	−0.012	0.056	0.017	0.024	−0.012	−0.004	0.032
	(0.047)	(0.029)	(0.075)	(0.065)	(0.052)	(0.021)	(0.035)	(0.028)
Maternal edu: complete secondary	0.082	0.031	0.201**	0.001	0.027	−0.005	0.067	0.005
	(0.064)	(0.040)	(0.071)	(0.059)	(0.048)	(0.037)	(0.056)	(0.032)
Maternal edu: complete tertiary	0.181**	0.055	0.287***	0.006	−0.070	−0.029	0.119*	−0.004
	(0.077)	(0.049)	(0.098)	(0.066)	(0.058)	(0.038)	(0.067)	(0.050)
Urban area	0.138**	−0.010	0.173*	−0.007	0.022	0.034	0.442**	0.100
	(0.051)	(0.042)	(0.087)	(0.051)	(0.150)	(0.093)	(0.198)	(0.091)
Household size	−0.015**	−0.007	−0.004	0.005	0.006	−0.000	−0.004	−0.001
	(0.007)	(0.008)	(0.010)	(0.006)	(0.009)	(0.006)	(0.008)	(0.004)
Wealth index - quintile 2	0.026	−0.008	0.011	0.035	0.102**	0.009	0.004	0.045
	(0.048)	(0.027)	(0.072)	(0.055)	(0.042)	(0.037)	(0.046)	(0.031)
Wealth index - quintile 3	0.020	0.075**	0.110	0.068	0.074*	0.021	0.036	0.052*
	(0.051)	(0.034)	(0.073)	(0.044)	(0.043)	(0.030)	(0.049)	(0.029)
Wealth index - quintile 4	0.080	0.074	0.213**	0.158**	0.150***	0.053	0.134**	0.069**
	(0.070)	(0.056)	(0.090)	(0.069)	(0.048)	(0.033)	(0.059)	(0.032)
Wealth index - quintile 5 (top)	0.102	0.109*	0.157	0.152**	0.094	0.115*	0.216**	0.080
	(0.067)	(0.060)	(0.115)	(0.062)	(0.065)	(0.060)	(0.087)	(0.047)
Maternal native tongue: spanish	0.076	0.055	0.021	0.198**				
	(0.066)	(0.055)	(0.068)	(0.073)				
Maternal native tongue: oromifah					−0.048	0.013	−0.246***	−0.054
					(0.102)	(0.054)	(0.067)	(0.077)
Maternal native tongue: tigrina					0.127	−0.004	0.175***	0.149**
					(0.185)	(0.098)	(0.058)	(0.071)
Maternal native tongue: other					−0.175**	0.062	−0.110	−0.052
					(0.069)	(0.057)	(0.113)	(0.045)
hr==9 am to 4 pm	−0.028	−0.095	0.003	−0.060	−0.014	0.011	0.037	0.012
	(0.130)	(0.063)	(0.059)	(0.065)	(0.047)	(0.030)	(0.078)	(0.018)
hr==5pm to 12 am	−0.060	−0.061	0.006	−0.035	−0.081	0.015	0.267	0.041
	(0.113)	(0.066)	(0.082)	(0.092)	(0.080)	(0.044)	(0.200)	(0.045)
(mean) wkend	−0.013	−0.002	0.020	0.047	0.006	0.055**	0.032	0.018
	(0.029)	(0.029)	(0.050)	(0.039)	(0.036)	(0.021)	(0.025)	(0.022)
Child is a Younger Sibling	0.270*	0.140*	0.278**	0.218**	0.017	0.035	0.171**	0.002
	(0.137)	(0.079)	(0.111)	(0.090)	(0.090)	(0.058)	(0.065)	(0.055)
Child is an Older Sibling	(dropped)	(dropped)	(dropped)	(dropped)	0.101	0.026	−0.030	0.119*
					(0.085)	(0.076)	(0.064)	(0.057)
Baseline task	0.448***	0.546***	0.195***	0.708***	0.485***	0.548***	0.280***	0.721***
	(0.025)	(0.037)	(0.021)	(0.100)	(0.023)	(0.017)	(0.036)	(0.070)
_cons	−0.914	−0.124	−2.300***	−0.067	0.080	−0.243	0.483	−0.302
	(0.696)	(0.443)	(0.596)	(0.472)	(0.655)	(0.457)	(0.521)	(0.371)
Number of observations	2,497	2,501	2,501	2,491	2,901	2,901	2,901	2,900
Adjusted R2	0.310	0.390	0.080	0.517	0.289	0.353	0.268	0.638

Note: These results correspond to those reported in Table 5 for Ethiopia and Peru. Standard errors (reported in parentheses) are clustered at cluster level. * $p < 0.1$ ** $p < 0.05$ *** $p < 0.01$.

on EF by age and sex. We expect that the relationship of early nutrition on cognitive skills might decline as children age, and other factors become equally or more important for the development of skills, such as access to school, school quality, access to social programmes, changes in the family socio-economic status and/or in the community environment. It is also possible that children recover from early stunting, which in turn might lead to cognitive recovery (Crookston et al., 2013). To test this hypothesis, in Table 7 , Panel A, we interact age in months with all the variables in the model, and report specifically the coefficients linked to stunting. For the EF measurements, we do not find evidence supporting the hypothesis that the association of stunting with skills declines with age for WM, though the point estimates go in the expected direction in the pooled sample and in the country samples. For IC, in the pooled sample the interaction with age is virtually zero, and the point estimates for each country sample go in different directions and are statistically insignificant.

We also test whether the relationship of stunting with EF differ by gender. While there is evidence of gender gaps in learning outcomes in LMICs, the directions of the estimated gaps are mixed. In the Young Lives Study countries, there is little evidence of gender gaps (in vocabulary) prior to school, but gaps appear during mid childhood and adolescence, widening between ages 12 to 15, favouring males in Ethiopia, India and Peru (in math and vocabulary), and favouring females in Vietnam; conversely, evidence that females slightly outperform males at age 12 in reading comprehension (Krutikova and Singh, 2017).

Behrman et al. (2022) show that in the RACER tasks administered in Ethiopia and Peru, males typically outperform females at age 12—males answer WM and IC challenge trials with more precision, and the IC trial faster compared to females. Based on the available evidence, if we were to find differences by sex in the (negative) associations of stunting with

Table C2
Predictions of early life nutritional status on later foundational cognitive skills – using HAZ as the nutritional indicator.

		Working memory (WM) **(1)**	Inhibitory control (IC) **(2)**	Long-term memory (LM) **(3)**	Implicit learning (IL) **(4)**
Panel A: multivariate OLS					
Pooled sample	Coef.	0.042***	0.029***	0.023**	0.012
	Std. Error	(0.012)	(0.008)	(0.011)	(0.008)
	Adjusted R2	*0.316*	*0.389*	*0.185*	*0.572*
Peru	Coef.	0.052***	0.039***	−0.004	0.013
	Std. Error	(0.014)	(0.013)	(0.017)	(0.015)
	Adjusted R2	*0.310*	*0.391*	*0.079*	*0.517*
Ethiopia	Coef.	0.031	0.021**	0.049***	0.013*
	Std. Error	(0.018)	(0.010)	(0.012)	(0.007)
	Adjusted R2	*0.290*	*0.353*	*0.268*	*0.639*
Panel B: household fixed effects					
Pooled sample	Coef.	0.044**	0.013	−0.002	0.011
	Std. Error	(0.019)	(0.013)	(0.021)	(0.015)
Peru	Coef.	0.005	−0.005	−0.004	0.003
	Std. Error	(0.030)	(0.024)	(0.040)	(0.030)
Ethiopia	Coef.	0.054**	0.022	0.014	0.021
	Std. Error	(0.025)	(0.016)	(0.024)	(0.016)
Sample size					
Peru		2,497	2,501	2,501	2,491
Ethiopia		2,901	2,901	2,901	2,900

Note: All coefficients are standardized. Each coefficient comes from a different estimation linking height-for-age Z-score (HAZ) to a given FCS. Results from panel A correspond to equation (1) (pooled OLS). Controls included: childś age (in months) and sex; native tongue of the mother and maternal education; wealth index (in quintiles) at age 1, area of location at age 1, household size at age 1; community fixed effects at age 1 (specific to the index child); performance in the baseline tasks, whether the task was administered during the weekend, and the time of the day when the tasks were administered. Results from panel B correspond to a household fixed effects specification (equation (2)). Standard errors (reported in parentheses) are clustered at cluster level. * p < 0.1 ** p < 0.05 *** p < 0.01.

EF, we would expect these effects to be larger (in absolute value) for females. We test this hypothesis by including interactions between a dummy that takes the value of 1 if the childś sex is female (and 0 otherwise) and all the other variables in the model. The interaction of the female dummy with the RACER outcomes is reported in Table 7, Panel B. Although the point estimates for WM and IC suggest that the (negative) effects of stunting are larger for females in the pooled sample and in the Peruvian sample, we find no evidence of statistically significant differential effects by gender.

7. Discussion

The existing evidence shows that early stunting predicts learning outcomes in developing countries (Glewwe et al., 2001; Alderman et al., 2006; Maluccio et al., 2009; Crookston et al., 2011; among others). However, this does not necessarily mean that there are underlying differences in cognitive skills as differences in learning outcomes can also be due in part to behavioural mechanisms that lead parents of stunted

Table C3
Predictions of early life nutritional status on later foundational cognitive skills –household fixed effects model controlling for birth order and birth-sex order.

		Working memory (WM) **(1)**	Inhibitory control (IC) **(2)**	Long-term memory (LM) **(3)**	Implicit learning (IL) **(4)**
Pooled sample	Coef.	−0.130***	−0.062**	0.006	−0.000
	Std. Error	(0.043)	(0.029)	(0.048)	(0.035)
Peru	Coef.	−0.149**	−0.049	0.024	0.016
	Std. Error	(0.068)	(0.052)	(0.085)	(0.065)
Ethiopia	Coef.	−0.094	−0.067*	−0.028	−0.004
	Std. Error	(0.057)	(0.035)	(0.057)	(0.040)
Peru		716	716	716	716
Ethiopia		1,158	1,158	1,158	1,158

Note: All coefficients are standardized. Each coefficient comes from a different estimation linking stunting to a given FCS. Results come from an OLS specification that regresses siblings-difference in a given FCS on siblings-difference in stunting, controlling for: (i) sibling-differences in age; (ii) sibling-differences in: early-life wealth index, early-life area of location, and early-life household size; (iii) sibling-differences in performance in: baseline tasks, whether the task was administered during the weekend, and the time of the day when the tasks were administered; (iv) whether the index child was the first born; (v) birth-sex order dummies. * p < 0.1 ** p < 0.05 *** p < 0.01.

children to invest less in schooling (e.g., Glewwe and Jacoby, 1995; Alderman et al., 2001). This paper investigates the potential predictive role of early undernutrition (proxied by stunting at the age of 5) on a set of later foundational cognitive skills in two large samples of children in Ethiopia and Peru. Overall, we found that early stunting is associated with the development of later EF—WM and IC. This conclusion is robust to the inclusion of household fixed effects, and no statistically significant differences are found when comparing the Ethiopian and Peruvian samples. We used predicted stunting at age 5 as not all children were observed at that age, but results are similar using observed stunting and considering only those children observed around that age. Results are also similar when using height-for-age instead of stunting as a nutritional indicator, although in this case the result for IC loses statistical significance when household fixed effects are used.

Other findings from the literature (Crookston et al., 2011; Lopez, Behrman, Cueto, Favara, & Sánchez, 2022) paired with our auxiliary estimations suggest that part of the impact of stunting on EF—specifically, on WM—might have already occurred as early as when the children were 5 years old, through a childś vocabulary development. Overall, our findings contribute to existing literature on the linkage between early nutrition and schooling achievement, by showing one way in which this relationship is mediated.

In contrast, no evidence of a linkage between early nutrition and later IL is found. Some evidence about the importance of nutritional investments for the development of LM is found in the Ethiopian sample; however these results are not robust. The absence of evidence of an association of nutrition with later IL is not necessarily surprising. A priori, it is expected to vary less across population subgroups than our other measures (Hamoudi & Sheridan, 2015). However, to our knowledge there are few instances in which this relationship has been tested in large, population-based samples.

Finally, there is no strong evidence of heterogenous effects by gender. However, results suggest a larger impact of stunting on WM for females. This result, which might be informative of differential cognitive investments in females compared to males, is aligned with the fact that in both the Young Lives Ethiopian and Peruvian samples males outperform females in the tasks used to measure EF (Behrman et al., 2022) as well as in math and vocabulary development (Krutikova and Singh, 2017), and requires further investigation.

Table C4
The predictive role of working memory and inhibitory control on the PPVT response rate.

	Independent variable:	Dependent variable: PPVT response rate (PPVT measured at the age RACER was measured, all children)		Dependent variable: PPVT response rate (PPVT measured at the age of 5, index children)	
		Working memory (WM) **(1)**	Inhibitory control (IC) **(2)**	Working memory (WM) **(5)**	Inhibitory control (IC) **(6)**
Pooled sample	Coef.	0.003**	0.007*	0.004	−0.002
	Std. Error	(0.002)	(0.004)	(0.003)	(0.004)
	Adjusted R2	0.829	0.829	0.021	0.019
Peru	Coef.	0.004*	0.004	−0.001	−0.006
	Std. Error	(0.002)	(0.003)	(0.004)	(0.005)
	Adjusted R2	0.007	0.006	0.016	0.016
Ethiopia	Coef.	0.002	0.010	0.008**	0.006
	Std. Error	(0.002)	(0.007)	(0.003)	(0.007)
	Adjusted R2	0.860	0.860	0.027	0.022
Sample size					
Peru		2,500	2,505	1,780	1,783
Ethiopia		2,917	2,923	1,731	1,736

Note: Each coefficient comes from a different estimation linking working memory or inhibitory control to the probability of answering the PPVT. The dependent variable takes the value of 1 if the child answered the PPVT, 0 otherwise. Results come from an OLS specification. Controls included: childś sex and age (in months) at the age PPVT was offered; native tongue of the mother and maternal education; wealth index (in quintiles) at age 1, area of location at age 1, household size at age 1; community fixed effects at age 1 (specific to the index child); performance in the baseline tasks, whether the task was administered during the weekend, and the time of the day when the tasks were administered. Standard errors (reported in parentheses) are clustered at cluster level. * $p < 0.1$ ** $p < 0.05$ *** $p < 0.01$.

Table C5
Predictions of nutritional status on later foundational cognitive skills –Multivariate (OLS model), sample split by age groups.

		Working memory (WM)				Inhibitory control (IC)			
		All children **(1)**	Less than 9 years of age **(2)**	10 to 11 years of age **(3)**	12 to 13 years of age **(4)**	All children **(5)**	Less than 9 years of age **(6)**	10 to 11 years of age **(7)**	12 to 13 years of age **(8)**
Pooled sample	Coef.	−0.084***	−0.121	−0.121*	−0.050	−0.053***	−0.039	−0.083	−0.044*
	Std. Error	(0.026)	(0.083)	(0.061)	(0.032)	(0.018)	(0.040)	(0.050)	(0.022)
	Adjusted R2	0.315	0.354	0.388	0.296	0.392	0.401	0.361	0.403
Peru	Coef.	−0.140***	−0.184	−0.179*	−0.105**	−0.068**	−0.002	−0.201*	−0.040
	Std. Error	(0.031)	(0.114)	(0.093)	(0.046)	(0.028)	(0.066)	(0.108)	(0.036)
	Adjusted R2	0.309	0.293	0.330	0.308	0.388	0.415	0.317	0.404
Ethiopia	Coef.	−0.025	−0.064	−0.092	0.005	−0.036	−0.065	−0.006	−0.041
	Std. Error	(0.037)	(0.131)	(0.084)	(0.041)	(0.022)	(0.054)	(0.035)	(0.027)
	Adjusted R2	0.285	0.334	0.396	0.251	0.357	0.392	0.384	0.349
Sample size									
Peru		2,497	361	354	1,781	2,501	362	355	1,784
Ethiopia		2,587	338	478	1,770	2,587	338	479	1,775

Note: All coefficients are standardized. Each coefficient comes from a different estimation linking stunting (as observed in the dataset, using the observation closest to age of five) to a given FCS. This sample excludes the older siblings from Ethiopia. Results correspond to equation (1) (pooled OLS). Controls included: childś age (in months) and sex; native tongue of the mother and maternal education; wealth index (in quintiles) at age 1, area of location at age 1, household size at age 1; community fixed effects at age 1 (specific to the index child); performance in the baseline tasks, whether the task was administered during the weekend, and the time of the day when the tasks were administered. Standard errors (reported in parentheses) are clustered at cluster level. * $p < 0.1$ ** $p < 0.05$ *** $p < 0.0$.

Our results are aligned with evidence that shows that EF in mid and late childhood is sensitive to experiences in the early years. Sheridan et al. (2022) show that early experiences change the structure of the brain which supports EF at 16 years of age. Although the exact mechanism linking stunting to EF is unknown, recent evidence shows that exploratory behaviour is linked with improvements in EF (McLaughlin et al., 2017; Rosen et al., 2020; Miller et al., 2021). Similarly, it is known that undernutrition has an impact on motor maturation and exploratory behaviour (Pollitt et al., 1993; Black et al., 2004). Thus, it could be that the impact of stunting on EF is mediated by exploratory behaviour.

We identify two areas for which our results are of interest for policy makers. First, given that EF in mid-and-late childhood is both sensitive to investments in the early years (Sheridan et al., 2022) and a well-known predictor of educational attainment (Lopez et al., 2022), our results provide another reason to justify the promotion of investments in early nutrition in developing countries, as part of the strategies implemented by countries to promote equity in learning outcomes, one of the Sustainable Development Goals. Second, in the past it has been difficult and expensive to measure foundational cognitive skills in population studies. Using assessment tools such as RACER is relatively inexpensive and could be used to monitor progress towards these goals over time. In fact, our evidence suggests that previous evidence focused on learning outcomes might be biased, as children with lower EF are more likely to choose not to respond to such tests—possibly due to a lower literacy.

CRediT authorship contribution statement

Alan Sánchez: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Software, Writing – original draft. **Marta Favara:** Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Validation, Writing – review & editing. **Margaret Sheridan:** Investigation, Resources, Writing – review & editing. **Jere Behrman:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Writing –

review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data from the Young Lives study is accessible via the UK data service. Replication files available here: https://doi.org/10.7910/DVN/MEM7HF.

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Ethical approval

The Institutional Review Board of the University of Pennsylvania approved this project (protocol #834313).

Appendix A

Appendix B

Adjustment of height-for-age around the age of 5 years

This note explains how HAZ at age 60 months (five years) is predicted for YLS children in the Peruvian and Ethiopian samples, using data from rounds 2, 3 and 4. We use two different prediction models, one for the older siblings and one for the group of index children and younger siblings.

1. For the older siblings, we estimate a model that assumes that two measurements of height-for-age can be observed, one at around the age of 60 months, and one at a later age. This model is calibrated using data from the index children and younger siblings, and the predicted coefficients are used to extrapolate the prediction of the HAZ that older siblings would have had if they had been observed at the age of 60 months.
2. For the younger siblings and index children, HAZ is observed closer to the age of 60 months. For this reason in this case we simply adjust HAZ taking into account average differences in HAZ observed by age in months in each country.

Data

Table B1 shows the mean age and age range for each group of children in each round. Information centered around the age of 60 months is observed for the Index Children in Round 2 and for Younger Siblings in Round 3. In contrast, for the Older Siblings there is no information available close to that age. The earliest information for the Older Siblings was obtained in Round 3, when average age was 136 months, with a range between 110 and 165 months. This range partially overlaps with the Index Children as observed in Round 4 (ages between 139 and 152 months) and the Younger Siblings in Round 4 (ages between 87 and 131).

Older siblings in Ethiopia

The age structure presented above suggests that to predict HAZ at 60 months for the Older Siblings, the following steps can be taken:

1. Use data from the Index Children and Younger Siblings.
2. Estimate a model linking HAZ centered at 60 months as a function of HAZ observed at a later age, and other child and household characteristics.
3. Use these coefficients to predict HAZ at 60 months for the Older Siblings (out of sample prediction).

To further increase precision, it is important to recognize that in some households, both Index Children and Younger Siblings are observed. For this reason, to predict HAZ, we consider the following model:

$$haz_{i,r} = a_1 age_{i,r} + a_2 age_{i,r}^2 + a_3 hazref_{i,r^*} + a_4 ageref_{i,r^*} + a_5 ageref_{i,r^*}^2 + a_6 Ind_i + a_7 HH_i + a_8 hazref_{j,r^*} + a_9 ageref_{j,r^*} + a_{10} ageref_{j,r^*}^2 + u_i \quad (1)$$

where $haz_{i,r}$ is the HAZ of child i observed in round r; $age_{i,r}$ is the age of the child i in round r, expressed in months; $hazref_{i,r^*}$ corresponds to another measure for HAZ for child i observed in round r* such that r*>r (as defined below); $ageref_{i,r^*}$ is the age at which this alternative measure of HAZ is observed; Ind_i is a vector that contains sex and other individual characteristics of child i; $hazref_{j,r^*}$, is the HAZ of sibling j observed in round r; HH_i includes household characteristics common to both siblings; and u_i is measurement error. In practice, Model (1) is expanded by interacting all coefficients with age_i and age_i^2, denominated as model (1′), and this is the model of interest to us.

We estimate model (1′) for the following combinations of $(haz_{i,r}, hazref_{i,r^*}, hazref_{j,r^*})$:

Cohort	$haz_{i,r}$	$hazref_{i,r^*}$	$hazref_{j,r^*}$
(i = index; j = younger sib)	r = 2	r = 4	r = 4
(i = younger sib; j = index)	r = 3	r = 4	r = 4

Once the coefficients of this model are obtained, these are used to predict HAZ at age 60 months for the Older Siblings. For this purpose, we consider the following steps:

1. $age_{i,r}$ and $age^2_{i,r}$ are set to 60 and 3600.
2. For Older Siblings, child i defined as the Older Sibling, and j as the Index Child.
3. For Older Siblings, $hazref_{i,r^*}$ refers to HAZ measured in round 3.

The resulting model has an adjusted R squared of 0.50. A true assessment of the model can only be obtained for a group of 157 children that aged exactly 60 months when observed. This is reported in Figure B3**.i**. Finally, the predicted value of HAZ at the age of 60 months obtained for the older siblings—which is the 'out of sample' group– is reported in Figure B3**.ii**. Following model (1′), through LASSO it is possible to identify the set of coefficients that minimizes prediction error. The model selected by LASSO is the one finally used.

Index children and younger siblings

For the index children and younger siblings, in theory it is possible to use the model reported above, however in doing so we would lose useful information about the HAZ observation that is already close to the age of 60 months. Therefore, in this case we use an approach inspired by Crookston et al. (2013, Am J Clin Nut. r). Consider the following linear in parameters model: $haz_i = a_0 + a_1 age_i + a_2 age_i^2 + \cdots + a_p age_i^p + u_i$, where haz_i is HAZ, age_i is age in months, and p is the degree of the polynomial. Once the coefficients are estimated, we have that,

$$haz_i = \widehat{a}_0 + \widehat{a}_1 age_i + \widehat{a}_2 age_i^2 + \cdots + \widehat{a}_p age_i^p + \widehat{u}_i \quad \text{(a)}$$

suppose the child is more than 60 months of age at the time he/she is observed. Assuming that HAZ is only a function of age, then haz_i^* predicted can be obtained as:

$$haz_i^* = \widehat{a}_0 + \widehat{a}_1 60 + \widehat{a}_2 60^2 + \cdots + \widehat{a}_p 60^p + \widehat{u}_i \quad \text{(b)}$$

replacing $\widehat{u}_i$ according to equation (b), we have that:

$$haz_i^* = haz_i + \widehat{a}_1 (60 - age_i) + \widehat{a}_2 \left(60^2 - age_i^2\right) + \cdots + \widehat{a}_2 (60^p - age_i^p) \quad \text{(b')}$$

Expression (b') can be used to adjust HAZ to a value that is closer to what would have been observed by a given child at the age of 60 months. We estimate this relationship by country and by group (index children and younger siblings separately). The latter is because the nature of the non-linear relationship between HAZ differs by group. We select a model with a polynomial of second degree. The predicted values are reported in Figure B4.

Appendix C

References

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