Changes in anemia and anthropometry during adolescence predict learning outcomes: findings from a 3-year longitudinal study in India

Phuong Nguyen¹, Monika Walia², Anjali Pant², Purnima Menon², and Samuel Scott²

¹Poverty, Health and Nutrition Division, International Food Policy Research Institute (IFPRI), Washington, DC, USA.
²Poverty, Health and Nutrition Division, IFPRI, New Delhi, India

Corresponding author:
Phuong Hong Nguyen, Poverty, Health and Nutrition Division, International Food Policy Research Institute, 1201 I Street, NW, Washington DC, 20005. Phone: 202-826-4088. Email: P.H.Nguyen@cgiar.org

Source of funding: The primary data collection for the UDAYA survey was supported by the Bill and Melinda Gates Foundation and the David and Lucile Packard Foundation through a grant to the Population Council. This secondary analysis was supported by the Bill & Melinda Gates Foundation through POSHAN, led by IFPRI (grant number OPP1150189).

Conflict of interest: The authors have no conflicts of interest. The study sponsor had no role in the study design, data collection, data analysis, data interpretation, report writing, or decision to submit the manuscript for publication.

Data Share Statement: Data described in the manuscript, codebook, and analytic code will be made available upon request.

Running head: Adolescent physical growth/anemia and learning
**Abbreviations:** AOR - Adjusted odds ratio, ASER - Annual Status of Education Report, BMI - Body mass index, BMIZ - Body-mass-index Z-scores, CI - Confidence interval, COVID-19 - Coronavirus disease 2019, HAZ - Height-for-age Z-score, Hb - Haemoglobin, ICDS - Integrated Child Development Services Scheme, Intelligence quotient – IQ, NFHS - National Family Health Surveys, OR - Odds ratio, POSHAN - Prime Minister's Overarching Scheme for Holistic Nourishment, PSU - Primary sampling units, SD - Standard deviation, SES - Socio-economic status, UDAYA - Understanding the Lives of Adolescents and Young Adults, World Health Organization - WHO

**ABSTRACT**

**Background:** Anemia and poor physical growth during adolescence have far-ranging consequences, but limited longitudinal evidence exists on how changes in these factors relate to changes in learning skills as adolescents mature.

**Objectives:** We examined the association between changes in anemia and physical growth during adolescence and learning outcomes.

**Methods:** We used longitudinal data from the Understanding the Lives of Adolescents and Young Adults (UDAYA) project, which surveyed adolescents aged 10-19 years in northern India in 2015-16 and 2018-19 (n=5,963). We used multilevel mixed-effects logistic regression models to examine associations between changes in anemia/thinness/stunting status (four groups: never, improved, new, and persistent) and reading (ability to read a story) and math proficiency (ability to solve division problems) at follow-up.

**Results:** Persistent anemia and stunting were higher among girls than boys (46% vs.8% and 37% vs. 14%, respectively), but persistent thinness was lower (7% vs. 16%). Improvement in anemia, thinness and stunting was 1.4-1.7 times higher among boys than girls. Boys who were anemic in both waves were 74% (adjusted odds ratio [AOR] 0.26, 95% confidence interval [CI]): 0.12,0.59) and 65% (AOR 0.35, 95%CI: 0.16,0.76) less likely to be able to read a story and solve division problems, respectively, compared to boys who were
non-anemic in both waves. Persistent thinness in boys was negatively associated with both reading (AOR 0.37, 95% CI: 0.21,0.66) and math proficiency (AOR 0.27, 95% CI: 0.16,0.46). Persistent stunting contributed to lower reading and math proficiency in boys and girls (AORs: 0.29 to 0.46). Boys whose anemia or thinness status improved and girls whose stunting status improved had similar learning skills at follow-up as those who were never anemic/thin/stunted.

**Conclusions:** Persistent anemia, thinness and short stature during adolescence was associated with poor learning. Programs targeted at adolescents should contribute to nurturing environments that foster healthy growth and learning.

**Keywords:** Adolescent, anemia, thinness, stunting, reading proficiency, math proficiency, India.

**INTRODUCTION**

Globally, there are an estimated 1.8 billion adolescents with 90% residing in low- and middle-income countries and one in five residing in India (1). Poor nutrition during this period is common, with an estimated one in four adolescents (~430 million globally) suffering from anemia and 10% underweight (2). In India, the 2006 and 2016 rounds of the National Family Health Surveys (NFHS) showed no anemia reduction among girls (54%) or boys (29%) adolescents aged 15-19 years (3, 4) and stunting affects one-third of adolescents in this population (5).

Despite the widespread nature of undernutrition during adolescence, investments to promote optimal health and development for this age range have been insufficient (6), with the first 1,000 days taking center stage in the global human development agenda. An estimated 95 percent of child and adolescent health and development research between 2004 and 2017 has focused on children under the age of 5 years (6). However, physical and mental development takes at least two decades—8,000 days beginning with conception—and includes childhood and adolescence, both periods of physical growth, restructuring of
the brain, and socio-behavioral change (6). Addressing the needs of adolescents can contribute to progress toward the United Nations’ Sustainable Development Goals, all of which directly or indirectly relate to adolescent health, development, or well-being.

Poor environments leading to compromised physical growth during adolescence can result in far-ranging and intergenerational consequences. Poor physical growth among adolescent girls adversely impacts their health and development, and is associated with poor birth outcomes such as low birth weight, preterm birth, stillbirth, and an increased risk of neonatal mortality (7). Adolescent physical growth and anemia has also been associated with human capital outcomes, with cross-sectional studies showing negative associations between stunting, underweight, low body mass index, low iron status/anemia and cognitive skills, school attendance, school performance and grade attainment (8-11). Longitudinal evidence reports associations between improved growth during the first few years of life and later development outcomes (12), but less is known about how changes in anthropometry or anemia status during adolescence are related to learning outcomes. The Young Lives studies in Ethiopia, India, Peru, and Vietnam showed that improved physical growth in early and middle childhood was associated with more schooling and higher math, reading and receptive vocabulary scores across countries (13-15), although others have questioned the methods underlying these findings (16). Two studies in India found that iron interventions led to improvements in cognitive abilities (17, 18). A recent study, using UDAYA data, showed that receiving iron and folic acid supplementation was positively associated with learning outcomes, while dietary diversity was positively associated with height-for-age z-score, math proficiency and reduced risk of dropout (19). A better understanding of the association between multiple types of growth failure and learning outcomes is needed as countries make decisions about where to focus their human capital investments.

Using longitudinal data on girl and boy adolescents 10-19 years of age in northern India, our study aimed to examine the relationship between physical growth failure (thinness and stunting), anemia and learning skills (reading and math proficiency) during adolescence. We aimed to answer three key research questions: 1) What is the prevalence of growth
failure and anemia in this population and what percentage of adolescents can read a story and solve division problems? 2) Is persistent growth failure or anemia during adolescence related to poorer learning outcomes? and 3) Do adolescents whose physical growth or anemia status improves during adolescence show similar learning abilities at follow-up as their peers who were not short, thin or anemic at either survey wave?

METHODS

Data source and study population

We used longitudinal data from the Understanding the Lives of Adolescents and Young Adults (UDAYA) project which was collected in two Indian states, Uttar Pradesh and Bihar, by the Population Council under the guidance of Ministry of Health and Family Welfare, Government of India (20, 21). The project was designed to provide insights on changes that adolescents undergo as they transition from adolescence to adulthood. Full details on study design, sampling, survey instruments, and data collection can be found elsewhere (20, 21). Briefly, 150 primary sampling units (PSUs)—villages in rural areas and census wards in urban areas were selected, and a multi-stage systematic sampling design was adopted within each residential area. First, villages or wards were selected systematically from the stratified list for an urban or rural area with selection probability proportional to size. This was followed by household selection with equal probability from the household listing and random selection of three respondents maximum within each selected household.

Project UDAYA followed a panel of 16,929 adolescents in 2015-16 (wave 1) when they were 10-19 years old and again in 2018-19 (wave 2) when they were 13-22 years old (20, 21). As per sampling strategy, UDAYA specifically sampled both unmarried and married girls but did not sample married boys separately. From the larger cohort, anthropometric and biomarker data were collected from all adolescents 10-14 years old, and in 24% of randomly selected sample of adolescents 15-19 years old after obtaining appropriate assent and
consent forms. This resulted in a subsample of 7,797 adolescents in 2015-2016. This group was re-assessed in 2018–2019 and had a follow-up rate of 81%, with 3% loss due to migration or parent refusal and 16% loss due to participant refusal or non-availability at home. The final analytical sample for the current paper comprises 5,963 adolescents (2,284 boys and 3,679 girls) who were surveyed in both waves and for which data on either hemoglobin or anthropometric measures were available (Supplemental Figure 1).

**Measures**

**Outcomes**

All variables used in the analysis are defined in Supplemental Table 1. Our key outcomes of interest were reading and math proficiency at wave 2 which were assessed using the Annual Status of Education Report (ASER) tools (22). These tools show high reliability and validity in India (23), have been used in a nationwide survey since 2005, and are widely used in the South-Asian region to assess progress in basic learning skills (24, 25). The ASER tool was administered following standard procedures by trained enumerators who had extensive training including classroom sessions, group activities, field practice, and a quiz. Data collection was carried out in households to ensure that all adolescents (whether enrolled in school or not) are included in the survey. Field supervision, and phone and desk recheck procedures were used for quality control of the assessment. Reading proficiency was measured as the ability to read in the Hindi language on four levels: ability to recognize letters, read words, read a short paragraph, and read a story (standard II level i.e. children age 7-8 years). Math proficiency was also measured on four levels: ability to recognize single-digit numbers, double-digit numbers, solve two-digit subtraction problems, and three-digit division problems. Our outcomes of interest were dummy variables for ability to read a story (reading outcome) and ability to solve a division problem (math outcome).

**Explanatory variables**

Our key explanatory variables were anemia, thinness, and stunting. Hemoglobin (Hb) levels were measured from capillary blood samples by trained health investigators using a portable HemoCue Hb 201+ instrument (20, 21). Anemia was defined as altitude-adjusted
Hb <115 g/L for boys and girls 10–11 years, Hb <120 g/L for boys 12–14 years and girls 12–19 years, and Hb <130 g/L for boys 15–19 years as per the World Health Organization (WHO) guidelines (26).

Adolescent weight and height were measured by trained and standardized field staff using standard methods. Weight was measured using SECA 874 electronic scale with precision to the nearest 100 grams and height was measured using SECA 213 stadiometer with an accuracy level of 0.1 cm. The height and weight measurements are used to calculate height-for-age z-scores (HAZ) and body mass index for-age z-scores (BMIZ) according to the WHO growth reference (27). Stunting and thinness were defined as HAZ and BMI z-score below -2 standard deviations (SD) from the reference, respectively.

We characterized adolescents’ into four groups based on their anemia and physical growth status in waves 1 and 2. For example, never anemic (e.g., not anemic in wave 1 and 2), improved (e.g., anemic in wave 1 but not anemic in wave 2), newly anemic (e.g., not anemic in wave 1 but anemic in wave 2), and persistently anemic (e.g., anemic in both wave 1 and 2). Similar groups categorizing change in physical growth over time were created for thinness, and stunting.

Confounding factors

Variables that could potentially confound the association between anemia/physical growth and learning outcomes included demographic, socio-economic, and environmental factors. Demographic factors included age, religion (Hindu and non-Hindu), caste (scheduled caste/tribe, other backward classes, and others), currently attending school, marital status, mother’s education attainment (highest level of school completed), and household wealth quintile. Data on household assets, ownership of selected durable goods, means of transportation, and access to amenities such as clean cooking fuel and electricity was used to create a wealth index score, which was then divided into five quintiles. Environmental factors included the place of residence (rural/urban), household’s access to an improved toilet facility and improved source of drinking water, type of school where the respondent last received an education (government or private), exposure to mass media (exposed either
every day or at least once a week to the content on three out of five mass media sources – television, radio, newspaper/magazine/books, own mobile, internet) and ever use of any social media platform such as Facebook, Twitter.

**Statistical analysis**

We first compared baseline characteristics of study participants in the final analytic sample to those lost to follow-up using Student T-test or Chi-square test. We analysed associations between the predictors and learning outcomes separately for girls and boys. The weighted prevalence of outcomes and physical growth/anemia by age and gender over time were visualized using line charts. Multilevel mixed-effects logistic regression models were used to examine associations between changes in predictors between waves 1 and 2 (predictors) and reading and math proficiency at wave 2. The fitted multilevel models included appropriate sub-sample weights and two levels of variations (level 1 being individual and level 2 being PSU as a random effect to adjust for clustering (28). All models adjusted for demographic, birth history for girls (currently pregnant or ever gave birth) and number of siblings, socio-economic, and environmental factors (which are often associated with anemia/physical growth and learning) to minimize confounding effects. Results from regression were presented in the form of both unadjusted and adjusted odds ratio (OR and AOR respectively) and their 95% confidence intervals (CIs). To offer an example of how to interpret AOR, an AOR of 0.75 would be interpreted as the outcome (in our case, the ability to read a story or solve division problems) being 25% lower odds in the group of interest relative to the reference group, after adjusting for confounding factors. All analyses were conducted in STATA software version 16 (StataCorp LLC, College Station, TX, USA).

**Ethics statement**

This study is based on the secondary data analysis of project UDAYA data, which are publicly available fully anonymized data sets and can be downloaded from [https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/ZPKW5](https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/ZPKW5). Data collection for the primary study was approved by the institutional review board of the
Population Council. For participation in the survey, consent was taken from each individual, and for unmarried adolescents aged 10–17, consent was also taken from a parent or guardian. No additional ethics approval was required for use of the publicly available UDAYA data.

RESULTS

Sample characteristics

Adolescent boys and girls were approximately 13 years and 16 years old respectively during wave 1 of the survey (Table 1). As per UDAYA’s sampling strategy (20, 21), around half of the girls were married. On average, boys and girls completed 8 years of schooling in wave 2 but their mothers had only completed 2 years of schooling. At wave 1, 91% of boys attended school compared to 51% of girls. School attendance dropped by 16-19 percentage points (pp) among both genders between the two survey waves. Compared to boys, fewer girls attended private schools. Most adolescents (>80%) lived in rural, Hindu, backward caste households and almost all (~97%) had access to an improved source of drinking water. Access to an improved toilet facility improved by 20-30 pp between the two survey waves. Exposure to mass media and use of social media increased over time; however, the levels of exposure and use were much low among girls than boys. Among the subsample with anthropometric and/or biomarker data, the analytical sample was similar on baseline characteristics to those with missing data (Supplemental Table 2).

Reading and math proficiency

Overall, reading and math proficiency was low. At wave 1, on average, only 61% of boys and 51% of girls were able to read a story (Figure 1A). Even by 19 years of age, about one-fifth of boys and half of girls could not read a story that children in standard II (7-8 years of age) should be able to read. Overall, reading proficiency improved for both boys (9 pp) and girls (5 pp) at the follow-up survey. Only 47% of boys and 23% of girls were able to solve a division problem in wave 1 (Figure 1B). Math proficiency showed improvement over
time for boys (9 pp), but not for girls. The gender inequality in reading and math proficiency was more pronounced for math than for reading in both survey waves.

**Prevalence of anemia, thinness, and stunting**

Anemia was higher for girls than boys at all ages from 10 to 22 years, with an overall prevalence of 62% for girls versus 32% for boys in wave 1 of the survey (Figure 2A). Anemia decreased with increasing age in boys but remained consistent for girls from ages 12-22 years. Between the two survey waves, anemia reduced by nearly a half for boys (from 32% to 17% for all ages combined), but slightly increased for girls (from 62% to 66%). In contrast, overall thinness was lower among girls compared to boys (14% vs. 27% in wave 1, 20% vs. 23% in wave 2) (Figure 2B). The prevalence of thinness was similar for adolescents of different ages in both waves and increased after the age of 15 years for girls. Stunting was higher among girls than boys (42% vs. 21% in wave 1, 44% vs. 24% in wave 2) and higher among older adolescents in both survey waves (Figure 2C).

Improvement in anemia and anthropometry was 1.4-1.7 times higher among boys than girls. For example, 24% of boys experienced improvements in anemia status vs. 17% of girls, 10% vs. 6% experienced improvements in thinness status, and 7% vs. 5% improved their stunting status (Figure 3). In contrast, persistent anemia was 5.8 times lower in boys than in girls (8% vs. 46%, respectively). New anemia was also more common in girls than boys (20% vs. 9%). The prevalence of persistent thinness was higher in boys than in girls (16% vs. 7%) whereas persistent stunting was 2.6 times higher in girls than boys (37% vs. 14%).

**Association between change in anemia/anthropometry over time and learning outcomes**

Persistently anemic adolescents had statistically significantly lower learning skills than those who were not anemic in both waves, and this remained true after adjusting for confounding factors among boys (AOR: 0.26, 95% CI: 0.12,0.59 for reading proficiency, and
AOR 0.35, 95% CI: 0.16,0.76 for math proficiency), but not among girls (Table 2 and Supplemental Table 3). New anemia also predicted lower odds of reading proficiency among boys (AOR 0.42, 95% CI: 0.19,0.89). Boys whose anemia status improved between waves 1 and 2 had similar learning skills as boys who were not anemic in either wave.

Among boys, persistent thinness was negatively associated with both reading (AOR 0.37, 95% CI: 0.21,0.66) and math proficiency (AOR 0.27, 95% CI: 0.16,0.46) (Table 2 and Supplemental Table 4). Boys who had new thinness or whose thinness status improved showed no difference in reading or math proficiency from those who were not thin in either wave. Girls who experienced new thinness had lower reading and math proficiency compared to those who were never thin in unadjusted models, but these associations did not hold after adjustment for potentially confounding factors.

Stunting at any point – either new, improved, or persistent – predicted lower odds of being able to read a story (AOR 0.37 to 0.40) in boys (Table 2 and Supplemental Table 5). Stunting also predicted poorer math ability, with the negative association strengthening from new (AOR 0.52, 95% CI 0.27,0.98) to improved (AOR 0.33, 95% CI 0.15,0.73) to persistent (AOR 0.29, 95% CI 0.16,0.53) stunting. Persistent stunting also predicted poorer reading and math proficiency in girls, but girls whose stunting status improved showed statistically similar reading and math proficiency as girls who were not stunted in both waves.

DISCUSSION

Using panel data following adolescents in northern India for three years, we estimated the association between changes in anthropometry or anemia status and learning outcomes. We found that persistent anemia, thinness, and stunting were associated with lower reading and math proficiency in boys while persistent stunting was associated with poorer learning skills in girls. Boys who became anemic or stunted over this period were also less likely than non-anemic or non-stunted boys at either timepoint to be able to solve division problems. Boys whose anemia or thinness status improved and girls whose linear
growth status improved showed comparable reading and math proficiency to those who
were not anemic, stunted and/or thin at either survey timepoint.

The negative association between anthropometric failure or anemia and learning
outcomes during adolescence in our study is consistent with other studies that have reported
negative associations between early life insults and developmental outcomes in future years
such as the Young Lives (13, 15, 29-32), MAL-ED multinational studies (33), COHORTS
(34) and other studies in low-and-middle income countries (35-45). Children who
experienced stunting in the first 1000 days of life had poorer development of language and
motor skills at 2 years in samples from Burkina Faso, Ghana and Malawi (37); lower
cognitive development at 5 years in multiple countries (33), and lower intelligence quotient at
8-11 years in Peru and the Philippines (35, 36). Weight faltering in the first 9 months of life
was associated with persisting deficits in IQ at 8 years in a cohort from the United Kingdom
(38) and weight gain during the first 2 years of life was strongly associated with schooling in
adulthood in a multi-country analysis (34). Studies have also reported associations between
anemia during infancy and poorer cognition, school achievement, or behavioral problems in
middle childhood (46) and adolescence (47).

We found that boys whose anemia or thinness status improved and girls whose
linear growth improved performed as well on reading and math tests as those with “normal”
indicators at both survey timepoints. Findings from multinational studies show that children
whose stunting status improved at 5, 6 and 8 years performed better in cognitive tests than
those who remained stunted throughout or performed similarly to those who were never
stunted (13, 30, 39). Similarly, weight gain in underweight Japanese children aged 12-13
years had a positive effect on their academic performance, independent of socio-economic
and lifestyle factors (48). A randomized controlled trial in Indian adolescent girls and boys
found that consumption of high iron-biofortified pearl millet during school meals for 6 months
corrected iron deficiency and improved performance on computerized tests of attention and
memory (18). Another iron intervention in Indian girls found that hemoglobin gain following
iron and folic acid supplementation for one year was associated with improved cognitive
ability (17). While anthropometric failure likely reflects failure in a range of factors over time, there is a clearly established mechanism for iron deficiency anemia being a cause of suboptimal brain and behavioral outcomes (49). Taken together, the evidence makes a compelling case for promoting nutrition interventions, or interventions that improve living conditions and lead to improved nutrition, throughout the first two decades of life to achieve optimal learning outcomes.

Associations between change in anthropometry or anemia and learning outcomes differed by gender. Persistent anemia and thinness were negatively associated with learning outcomes in boys but not in girls, apart from persistent anemia showing a negative association with reading ability in girls. We also found that gender inequalities in learning outcomes increased with age, similar to previous studies (50, 51). Lower reading and math proficiency in girls than in boys could be explained by son preference (52) or cultural expectations for girls to drop out of school to perform household chores and marry at a young age (53-55). Another gender difference was that boys whose stunting status improved did not achieve similar learning abilities as their peers who were not stunted during adolescence, whereas girls whose stunting status improved did. As boys are biologically more vulnerable to morbidity during their early years than girls, the interaction of early life stunting and morbidity could have had a significant impact on their cognitive development, preventing them from catching up in their academic performance (56, 57). Further investigation into gender differences in the timing of insults to anthropometry and learning improvement is needed.

The associations identified in this study should be interpreted in a broader learning and living environment. Recent child development literature suggests that growth faltering is a marker of a poor environment and is not always a direct cause of poor cognitive development (58-60). At the same time, being physically smaller limits one’s ability to interact with their environment and acquire knowledge and skills (60). Caregivers or teachers may also knowingly or unknowingly treat smaller children differently and challenge them less
than their peers. Thus, in terms of achieving optimal learning outcomes, interventions must address environmental and social barriers. A systematic review and meta-analysis of 75 intervention studies involving children aged 0-5 years found smaller effects of nutritional supplementation interventions on learning compared to nurturing and stimulation interventions (58). Further research in different contexts is needed to assess the relative benefit of nutritional and non-nutritional interventions on learning outcomes in adolescents.

Strengths of our analysis include the large and representative longitudinal data on adolescents from two populous Indian states. This unique data provides rich information on multiple facets of adolescent transition to adulthood, including learning outcomes, nutritional status, and various socio-economic, demographic, and environmental factors. Using multilevel mixed-effects logistic regression models, we were able to track changes in physical growth/anemia status and examine how these changes relate to reading and math proficiency 3 years later. By analysing boys and girls separately, we have identified gender gaps in the prevalence of poor physical growth or anemia and poor learning skills. However, some data limitations must be noted. First, information on the quality of teaching was not available and information on the quality of schools could not be used. Given our interest in considering both in-school and out-of-school adolescents, we could not control for variables only available for in-school adolescent such as school-based programs and school infrastructure. Second, data on physical growth and anemia before adolescence was not available. Although it may be reasonable to assume a correlation between pre-adolescent and adolescent growth and anemia status in this high poverty population with limited opportunities for upward mobility (61) we are not able to confirm this hypothesis with the available data. Third, studying changes in linear growth during adolescence is complicated by growth spurts, which may occur at different times for the studied population and the “healthy” reference population used to generate HAZ scores (62). Our findings that relate changes in height-for-age to learning outcomes should therefore be interpreted with caution.
Given the demonstrated associations between physical growth, anemia and learning outcomes during adolescence, investments in nutrition and human capital should cover late childhood and adolescence in addition to the first 1,000 days. The recent Lancet series on adolescent health highlights the roles of nutrition in late childhood and early adolescence on the timing and pattern of puberty, physical growth, neurodevelopment, immunity and risk of non-communicable diseases in later life (63). The series also calls for multifaceted actions at local and national levels across sectors (education, health, food systems, social protection, and digital media) and tailoring of nutrition interventions to local contexts (64). To address adolescent wellbeing in India, several programs have been implemented under various ministries (65). Examples include: the Adolescent Girls Scheme or “Kishori Shakti Yojana”, the Rajiv Gandhi Scheme for Empowerment of Adolescent Girls, the Balika Samriddhi Yojana and the Rashtriya Kishor Swasthya Karyakram. In 2018, adolescent nutrition in India received renewed political and programme focus under Prime Minister’s Overarching Scheme for Holistic Nourishment (POSHAN) Abhiyaan and the Anaemia Free India.

Collectively, the findings to date underscore the importance of continued investment in adolescent-focused programs and research to better understand how to optimize program impacts for both girls and boys.

With fewer than ten years remaining to achieve the Sustainable Development Goals of ending all forms of malnutrition and achieving universal literacy and numeracy, targeted and integrated health-nutrition-cognition interventions covering the first 8,000 days of life are needed. Our study found that anemia and anthropometric failure were associated with poor learning outcomes and these effects were more pronounced among boys than girls. Adolescents whose anthropometry or anemia status improved in the 3-year period between the two surveys showed similar learning abilities as their peers who were not undernourished at either survey. Beyond interventions directly targeting learning, efforts to provide equal and adequate learning opportunities to both boys and girls as well as
interventions that enhance standards of living and contribute to improvements in anthropometry and anemia, could help to support learning outcomes in adolescents.

AUTHOR CONTRIBUTIONS

P.H.N. conceived the idea for the manuscript and led the overall synthesis of the manuscript, conducted the statistical analysis, and wrote significant sections of the manuscript.

S.S. conceived the idea for the manuscript, reviewed the statistical analyses, wrote significant sections of the manuscript, reviewed, and edited the manuscript.

MW and AP conducted literature review, conducted the statistical analysis, prepared tables and figures for the manuscript and drafted some sections of the manuscript.

P.M. reviewed the statistical analyses, supported data interpretation, reviewed, and edited the manuscript.

All authors read and approved the final submitted manuscript.

REFERENCES

1. United Nations. “World Population Prospects: The 2017 Revision, DVD Edition”. 2017.
2. Azzopardi PS, Hearps SJC, Francis KL, Kennedy EC, Mokdad AH, Kassebaum NJ, Lim S, Irvine CMS, Vos T, Brown AD, et al. Progress in adolescent health and wellbeing: tracking 12 headline indicators for 195 countries and territories, 1990-2016. Lancet 2019; 393:1101-1118.
3. IIPS: International Institute for Population Sciences and Macro International. National Family Health Survey (NFHS-3), 2005–06. In. Mumbai, India: IIPS; 2007.
4. IIPS: International Institute for Population Sciences and Macro International. National Family Health Survey (NFHS-4), 2015–16. In. Mumbai, India: IIPS; 2017.
5. Bhargava M, Bhargava A, Ghatge SD, Rao RSP. Nutritional status of Indian adolescents (15-19 years) from National Family Health Surveys 3 and 4: Revised estimates using WHO 2007 Growth reference. PLoS One 2020; 15:e0234570.
6. Bundy DAP, Silva Nd, Horton S, Jamison DT, Patton GC. Child and adolescent health and development: Realizing neglected potential. Washington, DC: International Bank for Reconstruction and Development/ The World Bank; 2017.
7. ACC/SCN: Fourth Report on the World Nutrition Situation – Nutrition throughout the life cycle. In. Geneva, Switzerland: ACC/SCN in collaboration with IFPRI; 2000.
8. Teni M, Shiferaw S, Asefa F. Anemia and its relationship with academic performance among adolescent school girls in Kebena District, Southwest Ethiopia. Biotech Health Sci 2017:e43458.
9. Acham H, Kikafunda JK, Oluka S, Malde MK, Tylleskar T. Height, weight, body mass index and learning achievement in Kumi district, east of Uganda. Sci Res Essays 2008:1-8.
10. Perignon M, Fiorentino M, Kuong K, Burja K, Parker M, Sisokhom S, Chamnan C, Berger J, Wieringa FT. Stunting, poor iron status and parasite infection are significant risk factors for lower cognitive performance in Cambodian school-aged children. PLoS One 2014; 9:e112605.
11. Mukidi E. Nutrition status, education participation, and school achievement among Kenyan middle-school children. Nutrition 2003; 19:612-616.
12. Richter LM, Daelmans B, Lombardi J, Heymann J, Boo FL, Behrman JR, Lu C, Lucas JE, Perez-Escamilla R, Dua T, et al. Investing in the foundation of sustainable development: pathways to scale up for early childhood development. Lancet 2017; 389:103-118.
13. Crookston BT, Schott W, Cuetol, Dearden KA, Engle P, Georgiadis A, Lundeen EA, Penny ME, Stein AD, Behrman JR. Postinfancy growth, schooling, and cognitive achievement: Young Lives. Am J Clin Nutr 2013; 98:1555-1563.
14. Fink G, Rockers PC. Childhood growth, schooling, and cognitive development: further evidence from the Young Lives study. Am J Clin Nutr 2014; 100:182-188.
15. Georgiadis A, Benny L, Duc LT, Galab S, Reddy P, Woldehanna T. Growth recovery and faltering through early adolescence in low- and middle-income countries: Determinants and implications for cognitive development. Soc Sci Med 2017; 179:81-90.
16. Leroy JL, Ruel M, Habicht JP, Frongillo EA. Using height-for-age differences (HAD) instead of height-for-age z-scores (HAZ) for the meaningful measurement of population-level catch-up in linear growth in children less than 5 years of age. BMC Pediatr 2015; 15:145.
17. Sen A, Kanani SJ. Impact of iron-folic acid supplementation on cognitive abilities of school girls in Vadodara. Indian Pediatr 2009; 46:137-143.
18. Scott SP, Murray-Kolb LE, Wenger MJ, Udipi SA, Ghugre PS, Boy E, Haas JD. Cognitive Performance in Indian School-Going Adolescents Is Positively Affected by Consumption of Iron-Biofortified Pearl Millet: A 6-Month Randomized Controlled Efficacy Trial. J Nutr 2018; 148:1462-1471.
19. Shinde S, Madzorera I, Fawzi WW. Association of iron supplementation and dietary diversity with nutritional status and learning outcomes among adolescents: Results from a longitudinal study in Uttar Pradesh and Bihar, India. J Glob Health 2021; 11:04037.
20. Santhya K, Acharya R, Pandey N, Gupta AK, Rampal S, Singh SK, Zavier A: Understanding the lives of adolescents and young adults (UDAYA) in Uttar Pradesh, India. In. New Delhi: Population Council; 2017.
21. Santhya K, Acharya R, Pandey N, Singh SK, Rampal S, Zavier A, Gupta AK: Understanding the lives of adolescents and young adults (UDAYA) in Bihar, India. In. New Delhi: Population Council; 2017.
22. Ramaswami B, Wadhwa W. Survey Design and Precision of ASER Estimates. New Delhi: ASER Centre Retrieved November 21, 2021, from http://imagerasercentreorg/docs/Aser20survey/Technical20Papers/precisionofaserestimates_20ramaswami_20wadhwapdf 2010.
23. Vagh SB. Validating the ASER testing tools: Comparisons with reading fluency measures and the Read India measures. Retrieved November 21, 2021, from http://imagerasercentreorg/docs/Aser20survey/Tools20validating_the_aser_testing_tools_oct_2012__3.pdf 2012.
24. Alcott B, Rose P. Schools and learning in rural India and Pakistan: Who goes where, and how much are they learning? Prospects 2015; 45:345-363.
25. Scott S, Pant A, Nguyen PH, Shinde S, Menon P. Demographic, nutritional, social and environmental predictors of learning skills and depression in 20,000 Indian adolescents: Findings from the UDAYA survey. PLOS ONE 2020; 15:e0240843.
26. WHO. Haemoglobin concentrations for the diagnosis of anaemia and assessment of severity. Vitamin and Mineral Nutrition Information System. Geneva, World Health Organization (WHO/NMH/NHD/MNM/11.1), 2011.
27. de Onis M, Onyango AW, Borghi E, Siyam A, Nishida C, Siekmann J. Development of a WHO growth reference for school-aged children and adolescents. Bull World Health Organ 2007; 85:660-667.
28. Verbeke G, Molenberghs G. Rizopoulos D. Random Effects Models for Longitudinal Data. In: Longitudinal Research with Latent Variables. Montfort Kv, Oud JHL, Satorra A(s); Verbeke G, Molenberghs G, Rizopoulos D. Berlin, Heidelberg: Springer, 2010; 37-96.
29. Aurino E, Schott W, Behrman JR, Penny M. Nutritional Status from 1 to 15 Years and Adolescent Learning for Boys and Girls in Ethiopia, India, Peru, and Vietnam. Population Research and Policy Review 2019; 38:899-931.
30. Crookston BT, Penny ME, Alder SC, Dickerson TT, Merrill RM, Stanford JB, Porucznik CA, Dearden KA. Children who recover from early stunting and children who are not stunted demonstrate similar levels of cognition. J Nutr 2010; 140:1996-2001.
31. Georgiades A, Benny L, Crookston BT, Duc LT, Hermida P, Mani S, Woldehanna T, Stein AD, Behrman JR. Growth trajectories from conception through middle childhood and cognitive achievement at age 8 years: Evidence from four low- and middle-income countries. SSM Popul Health 2016; 2:43-54.

32. Kumar K, Kumar S, Singh A, Ram F, Singh A. Heterogeneity in the effect of mid-childhood height and weight gain on human capital at age 14-15 years: Evidence from Ethiopia, India, Peru, and Vietnam. PLoS One 2019; 14:e0212783.

33. Alam MA, Richard SA, Fahim SM, Mahfuz M, Nahar B, Das S, Shrestha B, Koshy B, Mduma E, Seidman JC, et al. Impact of early-onset persistent stunting on cognitive development at 5 years of age: Results from a multi-country cohort study. PLoS One 2020; 15:e0227839.

34. Martorell R, Horta BL, Adair LS, Stein AD, Richter L, Fall CH, Bhargava SK, Biswas SK, Perez L, Barros FC, et al. Weight gain in the first two years of life is an important predictor of school outcomes in pooled analyses from five birth cohorts from low- and middle-income countries. J Nutr 2010; 140:348-354.

35. Berkman DS, Lescano AG, Gilman RH, Lopez SL, Black MM. Effects of stunting, diarrhoeal disease, and parasitic infection during infancy on cognition in late childhood: a follow-up study. Lancet 2002; 359:564-571.

36. Mendez MA, Adair LS. Severity and timing of stunting in the first two years of life affect performance on cognitive tests in late childhood. J Nutr 1999; 129:1555-1562.

37. Prado EL, Abbedou S, Adu-Afarwuah S, Arimond M, Ashorn P, Ashorn U, Brown KH, Hess SY, Laird T, Maleta K, et al. Linear Growth and Child Development in Burkina Faso, Ghana, and Malawi. Pediatrics 2016; 138.

38. Emond AM, Blair PS, Emmett PM, Drewett RF. Weight faltering in infancy and IQ levels at 8 years in the Avon Longitudinal Study of Parents and Children. Pediatrics 2007; 120:e1051-1058.

39. Casale D, Desmond C. Recovery from stunting and cognitive outcomes in young children: evidence from the South African Birth to Twenty Cohort Study. J Dev Ontog Health Dis 2016; 7:163-171.

40. Gandhi M, Ashorn P, Maleta K, Teivaanmaki T, Duan X, Cheung YB. Height gain during early childhood is an important predictor of schooling and mathematics ability outcomes. Acta Paediatr 2011; 100:1113-1118.

41. Yang S, Tilling K, Martin R, Davies N, Ben-Shlomo Y, Kramer MS. Pre-natal and post-natal growth trajectories and childhood cognitive ability and mental health. Int J Epidemiol 2011; 40:1215-1226.

42. Cheung YB, Ashorn P. Continuation of linear growth failure and its association with cognitive ability are not dependent on initial length-for-age: a longitudinal study from 6 months to 11 years of age. Acta Paediatr 2010; 99:1719-1723.

43. Huang C, Martorell R, Ren A, Li Z. Cognition and behavioural development in early childhood: the role of birth weight and postnatal growth. Int J Epidemiol 2011; 42:160-171.

44. Li H, DiGirolamo AM, Barnhart HK, Stein AD, Martorell R. Relative importance of birth size and postnatal growth for women's educational achievement. Early Hum Dev 2004; 76:1-16.

45. Pongcharoen T, Ramakrishnan U, DiGirolamo AM, Winichagoon P, Flores R, Singhkornard J, Martorell R. Influence of prenatal and postnatal growth on intellectual functioning in school-aged children. Arch Pediatr Adolesc Med 2012; 166:411-416.

46. Grantham-McGregor S, Ani C. A review of studies on the effect of iron deficiency on cognitive development in children. J Nutr 2001; 131:649S-666S; discussion 666S-668S.

47. Lukowski AF, Koss M, Burden MJ, Jonides J, Nelson CA, Kaciroti N, Jimenez E, Lozoff B. Iron deficiency in infancy and neurocognitive functioning at 19 years: evidence of long-term deficits in executive function and recognition memory. Nutr Neurosci 2010; 13:54-70.

48. Ishihara T, Nakajima T, Yamatsu K, Okita K, Sagawa M, Morita N. Longitudinal relationship of favorable weight change in childhood is an important predictor of schooling outcomes in pooled analyses from five birth cohorts from low- and middle-income countries. J Nutr 2010; 140:348-354.

49. Murray-Kolb LE. Iron and brain functions. Curr Opin Clin Nutr Metab Care 2013; 16:703-707.

50. Singh A, Krutikova S. Starting together, growing apart: Gender gaps in learning from preschool to adulthood in four developing countries (Working Paper Series No. 174). Oxford. 2017.

51. Dercon S, Singh A. From nutrition to aspirations and self-efficacy: Gender bias over time among children in four countries. World Development 2013; 45:31-50.

52. Kugler AD, Kumar S. Preference for Boys, Family Size, and Educational Attainment in India. Demography 2017; 54:835-859.
53. Prakash R, Beattie T, Javalkar P, Bhattacharjee P, Ramaanaik S, Thalinja R, Murthy S, Davey C, Blanchard J, Watts C, et al. Correlates of school dropout and absenteeism among adolescent girls from marginalized community in north Karnataka, south India. J Adolesc 2017; 61:64-76.

54. Maertens A. Social Norms and Aspirations: Age of Marriage and Education in Rural India. World Development 2013; 47:1-15.

55. Rao N. Aspiring for distinction: gendered educational choices in an Indian village. Compare: A Journal of Comparative and International Education 2010; 40:167-183.

56. Hawkes S, Buse K. Gender and global health: evidence, policy, and inconvenient truths. The Lancet 2013; 381:1783-1787.

57. Khalid Ijaz M, R Rubino J. Impact of infectious diseases on cognitive development in childhood and beyond: potential mitigational role of hygiene. The Open Infectious Diseases Journal 2012; 6.

58. Prado EL, Larson LM, Cox K, Bettencourt K, Kubes JN, Shankar AH. Do effects of early life interventions on linear growth correspond to effects on neurobehavioural development? A systematic review and meta-analysis. Lancet Glob Health 2019; 7:e1398-e1413.

59. Leroy JL, Frongillo EA. Perspective: What Does Stunting Really Mean? A Critical Review of the Evidence. Adv Nutr 2019; 10:196-204.

60. Martorell R, Nguyen P. Interrelationship between growth and development in middle and low income countries. In: Importance of Growth for Health and Development Nestlé Nutr Inst Workshop Ser Pediatr Program, vol 65, pp 99–121, Nestec Ltd, Vevey/S Karger AG, Basel © 2010. Lucas A, Makrides M, Ziegler E(s):Martorell R, Nguyen P. 2009.

61. Choudhary A, Singh A. Are Daughters Like Mothers: Evidence on Intergenerational Educational Mobility Among Young Females in India. Social Indicators Research 2017; 133:601-621.

62. Collaboration NCDRF. Height and body-mass index trajectories of school-aged children and adolescents from 1985 to 2019 in 200 countries and territories: a pooled analysis of 2181 population-based studies with 65 million participants. Lancet 2020; 396:1511-1524.

63. Norris SA, Frongillo EA, Black MM, Dong Y, Fall C, Lampl M, Liese AD, Naguib M, Prentice A, Rochat T, et al. Nutrition in adolescent growth and development. Lancet 2021.

64. Hargreaves D, Mates E, Menon P, Alderman H, Devakumar D, Fawzi W, Greenfield G, Hammoudeh W, He S, Lahiri A, et al. Strategies and interventions for healthy adolescent growth, nutrition, and development. Lancet 2021.

65. Maliye C, Garg BS. Adolescent Health and Adolescent Health Programs in India. Journal of Mahatma Gandhi Institute of Medical Sciences.78-82.
## Table 1: Demographic, health, social and environmental characteristics of Indian adolescents over time, UDAYA data 2015-2016 and 2018-2019

|                       | Wave 1: 2015-2016 | Wave 2: 2018-2019 |
|-----------------------|-------------------|-------------------|
|                       | Boys (N = 2,284)  | Girls (N = 3,679) |
|                       | Boys (N = 2,284)  | Girls (N = 3,679) |
| **Demographic**        |                   |                   |
| Age, y                | 12.9 ± 2.4        | 15.8 ± 2.9        |
| Currently married, %  | 0.0               | 45.9              |
| Currently pregnant, % | 0.0               | 21.0              |
| Belongs to Hindu religion, % | 85.8        | 80.2              |
| Belongs to a backward caste, % | 82.4        | 83.4              |
| Wealth index: poorest, % | 14.0            | 14.7              |
| Lives in urban area, % | 15.3           | 13.0              |
| Education, y          | 5.9 ± 2.7         | 6.6 ± 3.8         |
| Currently attending school, % | 91.1        | 51.2              |
| Mother’s education, y | 2.4 ± 4.2         | 1.8 ± 3.6         |
| **Environmental**     |                   |                   |
| Improved source of drinking water, % | 96.8        | 97.8              |
| Improved latrine facility at home, % | 30.1        | 30.3              |
| In government school¹, % | 54.9           | 67.0              |
| In private school¹, % | 45.1             | 32.7              |
| Exposure to mass media, % | 35.5        | 20.1              |
| Ever used social media, % | 8.9           | 2.6               |

Values are means ± SD for continuous variables or percentages for categorical variables.

¹Percentages for type of school are among the subsample currently attending school.
Table 2: Association between changes in anemia, thinness or stunting status on learning outcomes among adolescent boys and girls, UDAYA data 2015-2019

| Change in anemia prevalence over time | Boys Reading proficiency | Girls Reading proficiency | Boys Math proficiency | Girls Math proficiency |
|--------------------------------------|--------------------------|--------------------------|----------------------|-----------------------|
|                                      | Unadjusted model OR [95% CI] | Adjusted model AOR [95% CI] | Unadjusted model OR [95% CI] | Adjusted model AOR [95% CI] |
| New (reference)                      | 1                         | 1                         | 1                    | 1                     |
| New                                  | 0.15***                   | 0.42                       | 0.69                  | 0.92                  |
| [0.07,0.36]                          | [0.19,0.89]               | [0.39,1.21]                | [0.53,1.60]           | [0.25,1.05]           |
| Improved                             | 0.56*                     | 0.87                       | 0.70                  | 1.00                  |
| [0.33,0.94]                          | [0.52,1.44]               | [0.38,1.29]                | [0.55,1.82]           | [0.48,1.25]           |
| Persistent                           | 0.04**                    | 0.26                       | 0.54*                 | 0.95                  |
| [0.02,0.12]                          | [0.12,0.59]               | [0.33,0.88]                | [0.59,1.54]           | [0.08,0.39]           |
| Stable stunting prevalence over time | Boys Reading proficiency | Girls Reading proficiency | Boys Math proficiency | Girls Math proficiency |
|                                      | Unadjusted model OR [95% CI] | Adjusted model AOR [95% CI] | Unadjusted model OR [95% CI] | Adjusted model AOR [95% CI] |
| Never (reference)                    | 1                         | 1                         | 1                    | 1                     |
| New                                  | 0.83                      | 0.76                       | 0.51*                 | 1.12                  |
| [0.36,1.94]                          | [0.33,1.78]               | [0.28,0.94]                | [0.60,2.10]           | [0.23,1.06]           |
| Improved                             | 0.31**                    | 0.77                       | 0.60                  | 0.92                  |
| Persistent                           | 0.16***                   | 0.37                       | 1.80                  | 1.30                  |
| Improved                             | 0.08,0.30                 | 0.21,0.66                  | 0.86,3.79             | 0.63,2.67             |
| Persistent                           | 0.10,0.33                 | 0.11,0.33                  | 0.16,0.46             | 0.48,1.74             |
| Persistent                           | 0.08,0.30                 | 0.21,0.66                  | 0.86,3.79             | 0.63,2.67             |
| Persistent                           | 0.10,0.33                 | 0.11,0.33                  | 0.16,0.46             | 0.48,1.74             |

*p < 0.05,  **p < 0.01,  ***p < 0.001

1 The categories were defined as follows: never (non-anemic in both waves), new (anemic only in wave 2), improved (anemic only in wave 1), persistent (anemic in both waves). Similar categories were created for thinness and stunting.

Values are odds ratio or adjusted odds ratio and 95% confidence intervals. OR: Odds ratio; AOR: Adjusted odds ratio; 95% confidence intervals. Estimated using multilevel
multivariate mixed-effect models adjusted for survey wave, respondent’s age, marital status, birth history for girls (currently pregnant or ever gave birth), number of siblings, whether attending school, type of school studied in, exposure to mass media, use of any social media platform; mother’s education attainment; and household’s place of residence (urban/rural), wealth status, religion, caste, access to improved toilet facility, and their use of improved source of drinking water.
Figure 1: Reading and math proficiency\(^1\) in Indian adolescents by age, gender, and survey waves, UDAYA data 2015-2016 and 2018-2019

\(^1\)Reading proficiency: Ability to read a story in Hindi language; Math proficiency: Ability to solve a three-digit division problem
Figure 2: Prevalence of anemia, thinness and stunting in Indian adolescents by age, gender, and survey waves, UDAYA data 2015-2016 and 2018-2019
Figure 3: Status of anemia, thinness, and stunting\textsuperscript{1} among adolescents over time, UDAYA data 2015-2019

\textsuperscript{1}The categories were defined as follows: never (non-anemic in both waves), new (anemic only in wave 2), improved (anemic only in wave 1), persistent (anemic in both waves). Similar categories were created for thinness and stunting.