Child stunting is associated with weaker human capital among native Amazonians

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Abbreviated Title: Child stunting is associated with weaker human capital among native Amazonians

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Abstract

Objectives. We assessed associations between child stunting, recovery, and faltering with schooling and human capital skills in a native Amazonian society of horticulturalists-foragers (Tsimane').

Methods. We used cross-sectional data (2008) from 1,262 children aged 6 to 16 years in 53 villages to assess contemporaneous associations between three height categories: stunted (height-for-age Z score, HAZ<-2), moderately stunted (-2≤HAZ≤-1), and non-stunted (HAZ>-1), and three categories of human capital: completed grades of schooling, test-based academic skills (math, reading, writing), and local plant knowledge. We used annual longitudinal data (2002-2010) from all children (n=853) in 13 villages to estimate the association between changes in height categories between the first and last years of measure and schooling and academic skills.

Results. Stunting was associated with 0.4 fewer completed grades of schooling (~24% less) and with 13-15% lower probability of showing writing or math skills. Moderate stunting was associated with ~20% lower scores in local plant knowledge and 9% lower probability of showing writing skills, but was not associated with schooling or math and writing skills. Compared with non-stunted children, children who became stunted had 18-21% and 15-21% lower probabilities of showing math and writing skills, and stunted children had 0.4 fewer completed grades of schooling. Stunted children who recovered showed human capital outcomes that were indistinguishable from non-stunted children.

Conclusions. The results confirm adverse associations between child stunting and human capital skills. Predictors of growth recovery and faltering can affect human capital outcomes, even in a remote, economically self-sufficient society.

1   Introduction

Child stunting, the chronic restriction of a child's potential growth, is widespread in low-income nations owing to maternal and child malnutrition (Black et al., 2017; Black et al., 2008; de Onis et al., 2011; Lu et al., 2016; Walker et al., 2015). Several factors contribute to malnutrition, including deprivations from poverty, inadequate nutrients and protein, poor water and sanitation, and high disease burden, resulting in short stature or slow growth in stature (Black et al., 2017; Black et al., 2008; Black et al., 2013; Lu et al., 2016; Victora et al., 2008b). Recent estimates suggest that globally as many as 171 million children (25%) < 5 years of age suffer from stunting (de Onis et al., 2011; United Nations, 2016). While stature is partly determined by genetic potential, nutrition and disease loads during childhood play major roles in shaping world-wide variation in human growth (Martorell and Habicht, 1986). Thus, stunting is amenable to public health interventions (Bhutta et al., 2013; Engle et al., 2007; Hoddinott et al., 2013a).

Predictors of persistent stunting affect brain development and function, risk of illness, energy levels, motor development, and exploratory behaviors and - through some of these paths - erode cognitive and academic skills and educational attainment during early life (Berkman et al., 2002; Casale and Desmond, 2016; Crookston et al., 2013; Fink and Rockers, 2014; Georgiadis et al., 2016; Ghosh, et al., 2015; Sudfeld et al., 2015). Some of these effects may last into adulthood (Alderman, et al., 2006; Hoddinott et al., 2013b; Hoddinott, et al., 2008; Prendergast and Humphrey, 2014; Victora et al., 2008b) and even across generations (Behrman et al., 2009; Victora et al., 2008a; Walker et al., 2015).

Some researchers have defined a window for interventions among children aged <2 years to redress stunting, suggesting that the factors that stunted growth might have irreversible effects after this window (Victora et al., 2008a; Victora et al., 2010). However, recent longitudinal evidence suggests that stunting is reversible after the age of 2 years (Georgiadis et al., 2016; Lundeen et al., 2014; Mani, 2012; Prentice et al., 2013; Schott et al., 2013). In some instances this reversal has been observed even without public health interventions, probably from general improvements in socio-economic conditions (Crookston et al., 2014). Some recent evidence also suggests that children who recover from stunting have better cognitive skills and complete more schooling grades than children who do not recover (Crookston, et al., 2013; Fink and Rockers, 2014), but evidence was not found in at least one other context (Casale and Desmond, 2016).

We contributed to research on child stunting and child human capital by estimating these associations in a unique setting: a remote, economically self-sufficient rural society of native Amazonian horticulturalists-foragers in Bolivia, the Tsimane' (Figure 1). Such a setting contributes to childhood stunting studies in at least three ways. First, with a few possible exceptions (e.g., Hoddinott et al., 2013c), most estimates of the links between child stunting and child human capital are associative, and may be biased by effects of unobserved omitted socioeconomic confounders such as ethnic and racial heterogeneity, access to health care, residential segregation, or differential exposure to pollution (Deaton and Lubotsky, 2003; Prendergast and Humphrey, 2014; Shaw et al., 1999). While Tsimane' households vary in their access to resources (Undurraga et al., 2016b), including food and monetary income, many of these other confounding factors vary much less among the Tsimane' than among many other populations in which associations between stunting and human capital have been studied..

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Tsimane' villages are racially and ethnically homogeneous, with non-Tsimane' accounting for ~5% of the population in their villages, and most Tsimane' have limited access to Western health care (Byron, 2003; Gurven et al., 2007). Second, the setting allowed us to extend the work linking childhood stunting with human capital by examining the association between child stunting and child knowledge of local plants, a culturally-appropriate measure of human capital (Reyes-García et al., 2008). Last, we used longitudinal data to examine whether growth faltering or recovery were associated with changes in human capital over time in a traditional rural society that is increasingly integrated into the market economy.

[Insert Figure 1]

The main form of human capital through history has not been schooling or academic skills, but traditional ecological knowledge, the cumulative body of knowledge of living things, natural resources, and ecosystems that is socially transmitted between generations (Berkes et al., 2000). This type of human capital can be critical to the subsistence, health, and nutritional status of people in small-scale rural societies (Johns, 1996; McDade et al., 2007; Reyes-García et al., 2008; Thomas et al., 2009). Traditional ecological knowledge may improve the use of local natural resources, thus generating benefits such as securing diets of better quality and adequate quantity, using pharmacological properties of plants, or improving farm productivity (Reyes-García, 2015). We used local plant knowledge as a proxy for traditional ecological knowledge. Prior research has found that parental local plant knowledge in rural societies co-varies positively with both parental and child health and may overshadow formal educational

attainment and academic skills in practical importance (McDade et al., 2006; Quave and Pieroni, 2015; Reyes-García et al, 2016b; Reyes-García et al., 2007).

For the analysis, we used cross-sectional and longitudinal data from the Tsimane', a native Amazonian society in the department of Beni, Bolivia (Supplemental Figure 1). At the time of research, the Tsimane' had low levels of monetary income, weak links to the market economy, and mostly primary schools that operated sporadically, with Tsimane' as the primary language of instruction (Godoy et al., 2007b; Undurraga et al, 2013). During 2010, the last year of our nine-year annual longitudinal survey (2002-2010), the mean monetary daily earnings per person reached only US $0.90, about half the global poverty line (US $1.90 Purchasing Power Parity) used by the World Bank (2015). In a worldwide comparative study of 15 small-scale rural societies, the Tsimane' ranked next-to-last in market interactions, with only 7% of total household calories bought in the market (Henrich et al., 2010). Nevertheless, Tsimane' villages vary in the depth and frequency of contact with outsiders. We control for some of these effects in the analysis by using walking distance (in hours) to the nearest town. Last, most Tsimane' self-reported as being monolingual in Tsimane'. For instance, the 2008 survey from the longitudinal study showed that of the 396 children and adults for whom we had data on language skills, 57% self-reported being monolingual in Tsimane', 35% reported having some fluency in Spanish, and 8% reported being fluent in Spanish.

Previous work among the Tsimane' suggests that the share of stunted children is high but declining (Godoy et al., 2010; Zhang et al., 2016). In 2000, 52% of all boys and 43% of all girls aged < 9 years were stunted (Foster et al., 2005a); by 2010 stunting rates for children aged < 9

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years had fallen to 34% for all boys and to 30% for all girls (Zhang et al., 2016). In 2008, the

year we used for much of the analyses, 34% of children aged 6 to 16 years were stunted (height-

for-age Z score, HAZ<-2; girls =31%; boys 36%), 41% were moderately stunted (-2<HAZ<-1;

girls=44%; boys=38%), and 26% were not stunted (HAZ>-1; girls =25%; boys =26%). Based on

a sample of 409 children aged <9 years in 58 villages, Foster et al. (2005b) examined whether

village attributes predicted stunting and found no significant results. McDade et al. (2007) found

no significant predictors of stunting among 330 children 2 to 10 years, but the probability of

severe stunting (HAZ<-3; ~12% of the sample) declined with maternal ethnobotanical

knowledge, village population size, and father's body mass index. Nyberg et al. (2012) found

that acculturation into national society and infection predicted stunting in a sample of 53

Tsimane' children >1.6 years, but Tanner (2014), based on a larger sample of children between 2

and 14 years of age found weak associations between child stunting and helminth infections or

market interactions. Using a sample of 238 children aged <2 years, Gurven (2012) found that the

probability of being stunted decreased with maternal weight and increased with child birth order.

Last, our prior work shows some evidence of catch-up growth (Godoy et al., 2010), but height

deficits persist despite modest year-to-year changes between height categories (Zhang et al.,

2016). None of the prior work has focused on the links between child stunting and human

capital.

We focused on children in primary school (aged 6 to 16 years) to estimate two sets of

associations. First, using cross-sectional data from 2008, we estimated the contemporaneous

association between (i) children's height categories - stunted (HAZ <-2), moderately stunted (-2≤

HAZ $\leq$-1), non-stunted (HAZ >-1) - and (ii) human capital, measured as completed grades of schooling, test-based academic skill (math, reading, writing), and local plant knowledge. We increased our sample size by combining the 2008 survey of the longitudinal study with the baseline survey of a randomized controlled trial (RCT). Second, using a nine-year annual (2002-2010) longitudinal dataset from all children in 13 villages along the Maniqui River, we estimated the association between (a) changes in height category (e.g., from stunted to non-stunted, or vice versa) from the first to the last year in which the child was measured and (b) the schooling and academic skills during the last year of measurement. Supplemental Figure 1 shows visually the overlap between the two datasets, and how each dataset relates to the associations we want to estimate.

2   Study participants and methods

2.1   Data

The data used came from two studies: an annual longitudinal dataset of all Tsimane' living in 13 villages during 2002-2010 (Leonard et al., 2015a) and a cross-sectional dataset collected in 2008 in an additional 40 villages, which was done as part of a baseline survey for an RCT (Undurraga et al., 2016a). We used the same field staff and methods of data collection in the two studies. During the annual survey of 2008 in the 13 villages of the longitudinal study, we also collected data on local plant knowledge from 138 children aged 6 to 16 years (one child per household).

2.2   Stunting

As is standard, we defined stunting as being 2 standard deviations below the median age-sex standardized height Z-score (HAZ) for well-nourished, international populations (UNICEF-WHO-WB, 2012; World Health Organization, 2006). We measured standing height following the protocol of Lohman et al. (1988), using a portable stadiometer. We calculated HAZ scores using the World Health Organization's (WHO) growth standards for children > age 60 months (de Onis et al., 2007). We chose the WHO (2006) standards because they are currently the most widely accepted and preferred standards for evaluating child growth and nutritional status, and more representative of a "global population" than any other existing growth chart. These standards are based on data from well-nourished, healthy children, under optimal environmental conditions, in six very different countries (Brazil, Ghana, India, Norway, Oman, USA). Their ubiquitous use also enhances comparability of our study results. We excluded extreme HAZ values in our regressions following thresholds recommended by WHO (1995).

2.3   Human capital outcomes: Completed grades of schooling, academic skills, and local plant knowledge

Human capital usually refers to a set of acquired individual traits that affect the person's productivity (Becker, 1994). We use the term *human capital* as an umbrella encompassing completed grades of schooling (hereafter schooling), academic skills, and knowledge of local plants, all measured at the time of the interview.

Schooling and academic skills. We limited the analysis to children age 6 to 16 years, the ages of typical school attendance in Tsimane' villages. Parents reported the grades of completed

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schooling of their dependents. To assess math skills we had children solve four arithmetic

operations that required them to add, subtract, multiple, and divide (in that order) one-digit or

two-digit numbers (Undurraga et al., 2013). The computation for the math questions were written

in numerals on a white card, but they were then read to children in case they could not read.

Scores in the math test ranged from zero to four, with one point for each correct answer. The test

stopped if the child provided an incorrect answer, or could not answer a question. Thus, some

children received only one math problem. For the reading test, we showed children simple

sentences written in Spanish in a white card, the second language of instruction in schools, and

we asked them to read the sentence. For the writing test, we asked children to sign their name

(Godoy et al., 2007a; Saidi et al., 2013). The reading test might have been harder for children

monolingual in Tsimane' and in villages with Tsimane' school teachers who were not completely

bilingual in Tsimane' and Spanish. The reading, writing, and math tests were done outdoors,

under broad daylight. Surveyors coded answers to the reading and writing tests into one of three

categories: cannot, with difficulty, and well. Since 50.2%, 55.7%, and 72.3% of the children

scored zero in the writing, math, and reading tests, we converted the variables into discrete

binary variables, with a value of one for any proficiency and zero otherwise (Table 1). Later we

assessed whether the main results held-up using the original, untransformed scores.

[Insert Table 1]

Local plant knowledge. We used a structured questionnaire to assess children's

knowledge of six common local wild plants (Martinez-Rodriguez, 2009). To select the plants, we

first asked 20 adult Tsimane' in neighboring villages to list all the useful plants they knew (Puri

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and Vogl, 2005). We inputted responses in the free-listing procedure in the Anthropac software to generate a list of the useful plants. We retained plants reported by at least two adults and for which we could obtain a botanical identification. We used Smith's Saliency Index derived from free-listing (Puri and Vogl, 2005) to classify plants into three groups by the number of people who listed the plant and the order in which they list the plant: high, medium, and low saliency. We then randomly selected two plants from each of the three groups to construct the test of plant knowledge.

The knowledge test assessed three domains: (1) whether a child recognized the name of each of the six plants when researchers named it, (2) the child's ability to name the most popular uses of the plants listed, and (3) the child's ability to name at least one animal typically associated with each of the plants listed. We refer to (3) as ecological knowledge. The exact question for task (3) was: "Are there animals, birds, or insects that live on or eat this plant?" For practical reasons, we did not show children a fresh botanical specimen or a picture of the plant. It is possible that some children knew the plant, but did not know it by its common name. If so we would have scored those children as not knowing the plant. Surveyors asked the child the test questions. If a child could not identify the plant (1), surveyors did not ask the child about (2-3). We used responses to construct three scores of individual local plant knowledge regarding (1) plant identification, (2) skills using the plant, and (3) ecological knowledge of the plant. To compute a score for the plant identification task we assigned one point for each plant the child knew, producing a score that ranged from zero to six. To score skills we first calculated the modal response of the full sample (i.e., the most popular use of the plant listed) and then assigned one point if the child's answer matched the modal response (Reyes-García et al., 2016a)

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(range: 0-6). Finally, to obtain a score for ecological knowledge we added a point if the child

mentioned at least one association of the listed plant with another plant or animal (range: 0-6).

We added scores from the three tasks to construct a total score for the three dimensions of local

plant knowledge (range: 0-18).

2.4   Analysis

2.4.1   Height category and human capital (2008 cross-sectional data)

We used the following Ordinary-Least Squares (OLS) regression with household fixed

effects and robust standard errors adjusted for clustering at the village level to analyze the 2008

cross-sectional data:

$$HK_{ihvj} = \alpha + \beta \cdot S_{ihv} + \gamma \cdot MS_{ihv} + \chi \cdot C_{ihv} + \varepsilon_{ihv} \qquad \text{(Eq. 1; OLS)}$$

where the subscripts stand for individual child (i), household (h), and village (v), with (j)

indexing the type of human capital (HK) used as an outcome. HK_{ihv} stands for human capital,

and captures one of the following: grades of completed schooling, score in the tests of math,

reading, writing, or local plant knowledge. S_{ihv} and MS_{ihv} are binary variables for stunted (S) and

for moderately stunted (MS), with non-stunted children serving as a reference category.

Control variables (C) included the child's age in 2008 and the child's sex, a binary

variable for the study (TAPS longitudinal study [2002-2010] = 1; 2008 cross-sectional sample

from RCT =0), and the walking distance (in hours) from the village to the nearest town. We

controlled for the study type because repeated exposure by study participants to the same

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surveyors in the longitudinal study might influence responses (Zwane et al., 2011). Because most households (59%) had only one child who was tested for local plant knowledge, we did not use household fixed effects when using local plant knowledge as an outcome, but we adjusted standard errors for clustering at the village level. For ease of interpretation, we used OLS even for binary outcomes, but later used Tobit, Poisson, and Logistic regressions as robustness checks for our main results. ε_{ihv} is an error term.

2.4.2   Change in height category and human capital (2002-2010 longitudinal data)

To estimate what happens to schooling and academic skills when a stunted child became non-stunted (recovery) or when a non-stunted child became stunted (faltering) we used annual data collected during 2002-2010 from ~850 children aged 6 to 16 years from the 13 villages of the longitudinal study. Following Crookston et al. (2010), we created a variable that captured changes in height categories (ΔHAZ), defined as HAZ during the last year a child was measured minus HAZ during the first year the child was measured. The child had to be in the range of 6 to 16 years for both measurements to be included in the analysis. Thus, the first and the last measure did not necessarily refer to the first (2002) and the last (2010) year of the longitudinal study. We decided to consider the first and the last measure to avoid reducing the sample size. Our definition of change in HAZ has the advantage of capturing any change in height category during the maximum length of time we measured a child who was between 6 and 16 years; more transitory changes between height categories were thus swept away in the sample we considered (Cole, 1997; Hermanussen et al., 2002). The mean and median duration between the first and the last measure was four years (SD=2.2; min=1; max=8).

Using ΔHAZ, we created three binary variables for the regression analysis: ΔHAZ$^+$,

ΔHAZ$^-$, and ΔHAZ^0. These variables stand for children whose height improved (recovered) from

stunted to non-stunted (ΔHAZ$^+$=1 recovered, 0 otherwise), children whose height worsened

(faltered) from non-stunted to stunted (ΔHAZ$^-$=1 faltered, 0 otherwise), and children who

remained stunted in both measurement years (ΔHAZ^0=1 stunted, 0 otherwise). Children who

remained non-stunted in both measurement years served as the reference category in the

regressions. We also estimated ΔHAZ between the first and last measurements for all children

without considering the stunted and non-stunted distinction, and then estimated the association

between the total change in HAZ and human capital outcomes.

Because policy questions have focused on what happens to a child's human capital when

a non-stunted child becomes stunted or vice versa, we examined the two-way change from

stunted to non-stunted, without considering the category of moderately stunted. The category of

moderately stunted was useful in the cross-sectional analysis because it permitted a finer-grained

description of how children's human capital varied in relation to height categories. The trade-off

was a smaller sample size in each height category, which may have resulted in less precise

estimates. However, focusing on the two-way change from stunted to non-stunted had the

limitation of defining the boundary between stunted and non-stunted by a single number (HAZ=-

2). A child whose height changed from -2.01 HAZ to -1.99 HAZ would be technically regarded

as someone who had transitioned from stunted to non-stunted even though the size of the height

improvement was trivial. To address this concern, we used the standard definition of stunting,

but then considered a child to have changed height category only if the child passed the threshold

by an additional 0.2 HAZ units. For example, a child with a HAZ of -2.1 would have to improve

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to at least -1.9 HAZ to have been considered as having transitioned from stunted to non-stunted.

Adding 0.2 HAZ units to the threshold reduced the likelihood of counting as meaningful very

small height changes near the boundary.

To estimate the association between changes in height categories and human capital

outcomes we used the following OLS regressions, with one observation per child, and with

household fixed effects and robust standard errors adjusted for clustering at the village level:

$$HK_{ihvjt} = \alpha + \beta \cdot \Delta HAZ^{+}_{ihv} + \gamma \cdot \Delta HAZ^{-}_{ihv} + \delta \cdot \Delta HAZ^{0}_{ihv} + \chi C_{ihvt=first} + \varepsilon_{ihv} \qquad \text{(Eq. 2; OLS)}$$

In equation 2, the outcomes remained the same as in equation 1, but referred to the last

year in which the child was measured. Control variables included the child's age and HAZ

during the first year of measure, the child's sex, baseline measure of the outcome, walking

distance (in hours) from the village to the nearest town, and a variable for the number of years

between the first and the last height measurement.

With both the cross-sectional and longitudinal data we used household fixed effects to

control for well-known confounds linking deprivation, child stunting, and child human capital at

the household level. This was important to ensure we observed the association between child

stunting and child human capital, and not the association between stunting and household

socioeconomic status. By adding household fixed effects, we controlled for all observed and

unobserved, unmeasured fixed household variables. Examples of these confounds include the

height and education of the parents, abilities and preferences of the parents, household

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socioeconomic status (e.g., asset wealth), and household demographics. Elsewhere we showed little change in household socioeconomic status over time among the Tsimane' (Undurraga et al., 2010).

3   Results

3.1   Height category and human capital (2008 cross-sectional data)

Table 1 highlights that, compared with their non-stunted peers, stunted children differed significantly in completed grades of schooling and in math skills. Table 1 and Figure 2 show that stunted children had significantly lower mean (1.5) and median (1) grades of completed schooling than non-stunted children (mean=1.8; median=2) (p=0.01). Almost two-thirds (59.2%) of stunted children scored zero on the math test, compared with 56.1% and 50.8% among moderately stunted and non-stunted children. The mean math score of stunted children (0.9) was significantly lower than the mean math score of non-stunted children (1.1) (p=0.03). We found no statistically significant difference in reading, writing, or local plant knowledge between children of different height categories. In sum, despite low levels of schooling and few opportunities to practice academic skills, descriptive statistics suggested that non-stunted children had more years of completed schooling and more math skills than their age-sex matched stunted peers, but they did not have better reading or writing skills, and they did not know more about local plants than other children.

[Insert Figure 2]

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Table 2 contains the results of the regression analyses (Eq. 1) and shows three findings. (i) Stunting bore a negative association with schooling and with the probability of having any math or writing skills. Compared with their non-stunted age-sex peers, stunted children had 0.38 fewer completed grades of schooling (p=0.05) and were 15% less likely to have any math skills (p=0.04) and 13% less likely to have any writing skills (p=0.07). (ii) Moderate stunting bore no statistically significant association with schooling, or with math and reading ability, but children who were moderately stunted were 9% less likely to have any writing skills compared to non-stunted children (p=0.08). (iii) Children with moderate stunting scored 1.86 fewer points (or ~19% less) in the test of local plant knowledge than non-stunted children (p=0.04), but we found no difference between stunted and non-stunted children in their score of local plant knowledge.

[Insert Table 2]

We used OLS regressions with household fixed effects and robust standard errors in our main results for ease of interpretation. But alternative regression specifications may be more adequate in some cases. For example, a large proportion of children in the sample never attended school, which may result in a violation of the assumption that error terms have to be normally distributed for a linear regression. We addressed this by using a lowered-censored Tobit regression for schooling. Table 3 and Supplemental Table 1 contain robustness analyses. Table 3 shows a summary of results using different regressions than those used in Table 2. Some of the changes included the use of a lower-censored Tobit regression for schooling because schooling was censored at zero, with 23.6% of children having no schooling; the use of a Poisson

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regression for raw scores of academic skills and local plan knowledge; logit regressions for

binary academic skills; and the use of OLS regressions with random effects for all outcomes.

[Insert Table 3]

The results from Table 3 buttress the results from Table 2. The Tobit regression (Table 3,

Panel A) showed that stunting and moderate stunting were associated with 0.6 and 0.3 fewer

completed grades of schooling (p<0.001). The Poisson regressions (panel A), showed that

stunting and moderate stunting bore a statistically significant negative association with math

(p<0.001) and writing skills (p=0.03; p=0.04), and that moderate stunting was associated with a

lower score in local plant knowledge (p=0.004). Eliminating moderate stunting as a height

category (Table 3, panel B), reduced the magnitude of the coefficients for the stunting variable,

but still showed that stunting was associated with 0.3 fewer completed grades of schooling

(p=0.06) and with a 9% lower probability of having any math skills (p=0.06), compared with

non-stunted children. Using HAZ as a continuous variable (Table 3, panel C) showed that a unit

increase in HAZ was associated with 0.2 more completed grades of schooling (p=0.02), a 6%

higher probability of knowing any math (p=0.08) and a 4% higher probability of having any

writing skills (p=0.09). This is consistent with previous results, indicating that higher HAZ was

associated with an increase in human capital outcomes. We also included an indicator variable

for severe stunting (HAZ < -3; Table 3, panel D), which showed no significant results, possibly

due to a small sample of children in the severely stunted category (n=73). The coefficients for

stunted and moderately stunted remained largely unchanged. In Table 3, panel E, we used a

Logit regression for academic skills, and found statistically stronger results than when using

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OLS, with previously statistically insignificant coefficients becoming significant. For example, moderate stunting was negatively associated with math skills (p=0.03) and stunting was negatively associated with reading skills (p=0.03).

Last, we examined the robustness of our results using household random effect models, which are also robust to serial correlation in the error terms. Much of the bias from important confounds, such as household socioeconomic status and parental attributes, is eliminated using household fixed-effects. While regressions with random effects result in smaller standard errors, the coefficients may be biased if the error terms were correlated with the explanatory variables, which was likely in our data. A Hausman specification test, however, suggested that we could not reject the random-effect specification in favor of the fixed-effect specification (Table 3, Section F). The use of a household random-effect model (Section D) showed slightly larger negative coefficients for the stunting variable and that, compared with non-stunted children, stunted children were six percentage points less likely to have any reading skills (p=0.09). Moderately stunted children had less schooling (p=0.04), and lower scores in tests of math (p=0.01), writing (p=0.004), and local plant knowledge (p=0.02), but not in reading (p=0.24).

Supplemental Table 1 shows that stunting and moderately stunted generally bore no significant interaction effects (p <10%) with the following: (i) child's sex, (ii) child's age, (iii) village road access, and (iv) household socioeconomic status. Stunting and moderate stunting also bore no significant interaction effects with schooling in the regressions with academic skills as outcomes.

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3.2 Change in height category and human capital (2002-2010 longitudinal data)

Panels A-B of Table 4 show four findings that hold up irrespective of the HAZ threshold used to define stunting or moderate stunting: -2 HAZ or -2 HAZ ± 0.2 HAZ. First, compared with a child who was not stunted during the first and the last year of measurement, a child who was not stunted but became stunted (faltered) had an 18% lower probability of knowing any math (p=0.06) and a 15% lower probability of knowing how to write (p=0.04) for a threshold of -2 HAZ. Similarly, a child who was not stunted but became stunted, based on a threshold of -2 HAZ ± 0.2 HAZ, had a 21% lower probability of knowing any math (p=0.02) or knowing how to write (p=0.04) than a child who was not stunted during the first and the last year of measurement. Second, children who remained stunted in both the first and the last year of measurement had 0.4 fewer completed grades of schooling than their age-sex peers who were not stunted in both periods (p<0.05). Third, we found no evidence suggesting that children who improved their height by transitioning from stunted to non-stunted were any different in the completed grades of schooling or in math, reading, or writing skills than children who were not stunted in both periods (panel A and panel B, Table 4). Fourth, we found no statistically significant association between the total change in HAZ between the last and first year that a child was measured and human capital, conditioning on the child's initial (Table 4, Panel C) or final value (not shown) of HAZ. In sum, faltering and persistent stunting were associated with an erosion in human capital outcomes, and we found no difference in human capital between children who were never stunted and those who experienced growth recovery.

[Insert Table 4]

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4   Discussion and conclusions

The study yielded two main findings and two puzzles. First, the ubiquitous cross-sectional association between child stunting and child human capital found in previous studies extended to remote societies without well-established educational systems. The magnitude of these associations was meaningful. For example, Table 2 suggested that stunted children had 0.4 fewer completed grades of schooling than their non-stunted age-sex peers. Since the average number of completed grades of schooling was 1.7, a 0.4 deficit amounted to ~24% fewer completed grades of schooling in the area studied.

The second main finding related to the longitudinal relation between changes in stunting and human capital over time. We found that persistent stunting was associated with 0.4 fewer completed grades of schooling, but that it was not consistently associated with weaker academic skills. Faltering was associated with a 15-21% lower probability of having any math or writing skills. Because the datasets we used were part of larger studies that examined several different aspects of the transition of the Tsimane' from a largely autarkic to a market economy (Leonard et al., 2015b; Undurraga et al., 2016a), we had to limit the length of the education module to lower respondent burden. The ability to sign one's name, to read simple sentences, or to solve basic math operations resemble the type of questions used to measure child human capital in the Young Lives Study, the largest international comparative longitudinal study of child growth (n~12,000, in four nations: India, Ethiopia, Peru, and Vietnam) (Barnett et al., 2013; Crookston et al., 2013). On the other hand, we found recovery from earlier stunting leads to estimates for

schooling attainment that are no different from those for children who were never stunted. However, we could not fully discard the possibility that our measures of human capital were not sensitive enough to capture small differences between children who recovered and those who were never stunted.

Our results in some respects agreed with – but also differed in other respects from – the results of the Young Lives Study. Crookston et al. (2013) measured changes in HAZ categories of children between about 1 and 8 year of age and, depending on the nation, found that 18-32% of children changed their height status from stunting to non-stunting or vice versa. Children in the four nations who remained stunted were more likely to be overage for their grade, a result consistent with our finding that persistent stunting was associated with less completed grades. As in this study, Crookston and colleagues found no consistent association between schooling and recovery; in Peru and Vietnam recovery was associated with an increase in the age of the child for their school grade, but in Ethiopia and India recovery bore no significant association with appropriate school age. In academic skills, we found only one consistent association: an inverse association between faltering and math and writing skills. In contrast, Crookston et al. only found a consistent negative association between persistent stunting and math scores, reading comprehension, and receptive vocabulary. Children aged 5 to 8 years who recovered improved their math, reading, and receptive vocabulary compared with children who remained stunted, but did not fully catch up with children who were never stunted (Crookston et al., 2013). However, in a study restricted to Peru, children age ~5y who recovered scored as well in verbal vocabulary and in quantitative tests as children who were never stunted (Crookston et al., 2010). This finding was consistent with our study; we found that children who recovered were statistically

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indistinguishable from those who were never stunted, suggesting an improvement in human capital outcomes. These and other studies (Berkman et al., 2002; Casale and Desmond, 2016; Fink and Rockers, 2014) suggested that, compared with children who remained non-stunted, children who faltered, or who remained stunted, did not tend to fully catch up in academic or cognitive skills.

We found two puzzling results. First, it is not clear why moderate stunting, but not stunting, was associated with lower scores in local plant knowledge. The statistical significance of this finding could be spurious and attributed to a small sample size of children in these categories. Nevertheless, the negative association between moderate stunting and local plant knowledge was consistent with our other findings showing negative associations between stunting and other indicators of human capital. Taken together, the evidence suggested that the factors that stunted growth, such as malnutrition or disease burden, may also have decreased the efficiency of cultural transmission of traditional ecological knowledge.

The second puzzling result was that stunting or moderate stunting almost never bore a significant association with reading skills. Our measure of reading skills may have been hampered by the fact that the sentences were written in Spanish, the second language of instruction in schools, which only some Tsimane' can speak. One possible explanation for the lack of results in reading, compared with other academic skills, is that the tests of math and writing did not hinge as much on understanding Spanish.

The study had at least three limitations. First, measurement errors with reported age, height, and perhaps years of schooling may have occurred in our data (Godoy et al., 2008; Gurven et al., 2007). This was largely due to parental report of a child's age and grades of schooling instead of relying on vital and school records, which were many times non-existent.

Second, we could not control for unobserved abilities, such as drive, attention, or patience. If these traits were fixed and covaried positively with child human capital and negatively with stunting, then our estimated negative coefficients of stunting would be more pronounced than the true values. Likewise, if stunting covaries negatively with factors such as task comfort, that may increase performance (Gibson et al., submitted). Unfortunately, it was difficult to quantify these effects with the available data.

Third, we did not have information to capture the pathways that would allow stunting to influence human capital outcomes. For example, the early life stressors that led to stunting may have impaired attention, motivation, memory, or a combination of these factors (Aburto et al., 2009; Baker-Henningham et al., 2009; Chang et al., 2002; Fernald and Grantham-McGregor, 1998; Gardner et al., 1999). We also lacked information on vision and hearing loss in our cohorts, which would have hampered children's ability to accumulate human capital (Chua and Mitchell, 2004; Davis and Hind, 1999; Emmett et al., 2014; Lim et al., 2010; Sharma et al., 2010; Steward-Brown et al., 1985; Teasdale and Sorensen, 2007). This did not bias our estimates of the associations between stunting and the outcomes that we considered, but understanding the pathways would be useful for directly addressing the underlying human capital deficits.

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We did not measure the social and household context in which stunting occurred. In an earlier study, we found that adult Tsimane' attributed more positive traits to taller children, but not to taller adults (Undurraga et al., 2012). Some of the adverse associations between stunting and child human capital might have taken place because parents invested less in stunted than in non-stunted children, for example, reinforcing a child's endowments. Parental investment has been shown to affect the number of years of schooling of a child, and family environment is a key determinant of cognitive abilities (Alderman and King, 1998; Heckman, 2006; Knudsen et al., 2006; Luby et al., 2013; Wilder, 2014). Stunting could also have elicited compensatory behaviors from parents through extra stimulation to redress the adverse association with stunting or faltering (Engle and Fernández, 2010; Pollitt et al., 1993; Prado and Dewey, 2014; Wachs, 2009; Wachs et al., 1992). We did not have data on parental attitudes or behaviors toward stunted children or on caretakers' behavior, though we controlled for some of these attitudes and behaviors by using regressions with household fixed effects.

Further, several studies have documented the impact of school quality, and particularly teacher quality (Rivkin et al., 2005; Rockoff, 2004), in children's academic skills and years of schooling. It is theoretically possible that non-stunted children attended better quality schools because more motivated parents were willing to migrate to villages with better schools.

One final potential limitation deserves mention related to our reference sample. We used the WHO (2006) standards in our analysis because they are currently the most widely accepted and preferred standards for evaluating child growth and nutritional status. However, it is possible that they do not closely represent the growth of healthy local populations, including native

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Amazonian children, even though there are no significant differences among the six diverse populations that WHO used to produce its standards (Blackwell et al., 2016; Urlacher et al., 2016). Further, the results may not necessarily be affected or biased even if local growth standards, such as those for Amazonian populations, differed from WHO standards. This would be true if, for example, local and international standards were correlated except for random differences.

Prior studies have documented the ubiquity of child stunting in remote native Amazonian societies (Benefice et al., 2006; Blackwell et al., 2009; Cobayashi et al., 2006; Godoy et al., 2005; Pedraza et al., 2014; Roche et al., 2011). Our results suggested that some of these remote societies might not be able to offer their children enough protection to foster normal growth, leaving open the question of how best to redress faltering and avoid losses in the human capital of these children.

5   Acknowledgments

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Table 1. Summary statistics of outcomes and explanatory variables by height categories of Tsimane' children 6y ≤ age ≤ 16y, 2008.

Human-capital outcome	Statistic	Height category			Total
		Not stunted (HAZ >-1)	Moderately stunted (-2≤ HAZ ≤-1)	Stunted (HAZ <-2)	
Schooling[a]	N	328	516	418	1,262
	Mean	1.86	1.78	1.57**	1.73
	SD	1.65	1.77	1.54	1.67
	% zero	19.21	24.22	26.56	23.69
Academic skills					
Math: Test score (0-4)[b]	N	289	420	351	1,060
	Mean	1.12	1.04	0.89**	1.01
	SD	1.36	1.37	1.28	1.34
	% zero	50.87	56.19	59.26	55.75
Reading:[c]	N	256	382	315	953
Cannot	%	71.48	71.20	74.29	72.30
With difficulty	%	19.53	19.11	19.05	19.20
Well	%	8.98	9.69	6.67	8.50
Writing:	N	288	410	347	1,045
Cannot	%	46.53	49.76	53.89	50.24
With difficulty	%	30.56	27.07	25.65	27.56
Well	%	22.92	23.17	20.46	22.20
Local plant knowledge[e] (0-18)	N	49	52	37	138
	Mean	9.93	8.76	9.94	9.50
	SD	3.78	3.92	3.71	3.83
	% zero	4.08	7.69	5.41	4.35
Explanatory variables					
HAZ	N	335	535	439	1,309
	Mean	-0.18	-1.54	-2.63	-1.56
	SD	0.87	0.27	0.63	1.10
Child's age (6-16)[f]	N	335	535	439	1,309
	Mean	9.71	9.89	9.87	9.84
	SD	2.60	3.02	2.94	2.89
Child's sex	N	335	535	439	1,309
Female children	%	48	53	44	49
Male children	%	52	47	56	51

Notes: *, **, and *** significant at ≤ 10%, ≤ 5%, and ≤ 1% in OLS regression with schooling, math, or local plant knowledge as outcomes, against stunted and moderate stunted binary variables as covariates, with non-stunted children as the excluded category. For reading and writing we used a chi-squared test between reading or writing and the three height categories, and found no significant differences at $p<0.10$ between the three height categories.

[a] Schooling = completed grades of schooling as reported by parent at the time of the survey.

[b] Math = score in a test with four questions, each of which asked the child to either add, subtract, multiply, or divide one-digit or two- digit numbers, with one point assigned for each correct answer. The test stopped if the child provided an incorrect answer, or could not answer.

[c] Reading = a child was asked to read a simple sentence in Spanish and surveyor judged whether the child could read well or with difficulty, or could not read. The text was written in a large white piece of paper and children were shown the paper outdoors, in broad daylight.

[d] Writing = a child was asked to sign her/his name and surveyors coded whether the child could sign the name easily, with difficulty, or could not sign her/his name. In the regressions, the variables for math, reading, and writing have been converted into binary variables, with the value of one for a child who displayed any skill, and zero otherwise.

[e] Definition of local plant knowledge and further details on the measure of academic skills can be found in the main text.

[f] Child age is reported by parents.

Table 2. Association between (i) height categories and (ii) schooling and academic skills among Tsimane' children 6y ≤ age ≤ 16y, 2008

Explanatory variables:	Schooling	Academic skills			Local plant knowledge
		Math	Reading	Writing	
Stunted[a]	-0.38**	-0.15**	-0.03	-0.13*	-0.52
	(0.19)	(0.07)	(0.06)	(0.07)	(1.00)
Moderately stunted[a]	-0.18	-0.09	-0.03	-0.09*	-1.86**
	(0.16)	(0.06)	(0.04)	(0.05)	(0.80)
Male	0.31***	0.13***	0.06**	0.10***	0.44
	(0.11)	(0.04)	(0.03)	(0.04)	(0.56)
Age	0.35***	0.09***	0.07***	0.08***	0.76***
	(0.03)	(0.01)	(0.01)	(0.009)	(0.16)
Distance[b]	-0.11***	-0.02***	0.003	-0.03***	-0.04*
	(0.01)	(0.004)	(0.003)	(0.002)	(0.02)
TAPS[c]	0.15	0.23***	0.74***	0.44***	Not applicable
	(0.11)	(0.03)	(0.04)	(0.04)	
Constant	-1.16***	-0.41***	-0.50***	-0.29***	1.15
	(0.29)	(0.08)	(0.08)	(0.08)	(2.50)
R^2	0.76	0.72	0.76	0.76	0.16
N	1,246	1,045	940	1,030	129
Household fixed effects		Yes			No

Notes: *, **, and *** significant at ≤10%, ≤5%, and ≤1%. OLS regressions; robust standard errors (in parentheses) were adjusted for clustering at the village level. See Table 1 for a definition and description of the variables. [a] Non-stunted children are the excluded category. [b] Walking distance (hours) of the village to the nearest town. [c] TAPS = Tsimane' Amazonian Panel Study; longitudinal study with 13 villages. The variable TAPS=1 if the village is in the TAPS sample, and 0 if the village was part of the baseline survey for the randomized controlled trial.

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Table 3. Robustness analysis of Table 2, using different regression specifications and household fixed effects: Summary of coefficients for stunted and moderately stunted children

Height category:	Schooling	Academic skills			Local plant knowledge
		Math	Reading	Writing	
[A] Tobit (schooling) and censored Poisson regressions (skills and plant knowledge)[a]					
Stunted	-0.55***	-0.45***	-0.28	-0.33**	-0.05
	(0.04)	(0.13)	(0.24)	(0.15)	(0.06)
Moderately stunted	-0.27***	-0.31***	-0.28	-0.26**	-0.20***
	(0.03)	(0.11)	(0.20)	(0.13)	(0.07)
[B] Eliminating moderate stunting as a category; non-stunted is used as the reference					
Stunted	-0.25*	-0.09*	-0.01	-0.07	0.49
	(0.13)	(0.05)	(0.05)	(0.05)	(0.72)
[C] OLS using HAZ as a continuous variable[b]					
HAZ	0.19**	0.06*	0.01	0.04*	0.22
	(0.08)	(0.03)	(0.03)	(0.02)	(0.32)
[D] Including severe stunting[c]					
Severely stunted	-0.42	-0.06	0.07	-0.04	1.83
	(0.29)	(0.13)	(0.10)	(0.09)	(1.04)
Stunted	-0.37*	-0.17**	-0.05	-0.15**	-0.83
	(0.20)	(0.07)	(0.05)	(0.07)	(1.06)
Moderately stunted	-0.18	-0.09	-0.04	-0.10*	-1.86**
	(0.16)	(0.06)	(0.06)	(0.05)	(0.84)
[E] Logit regressions for academic skills with odds ratio & 95% CI also reported					
Stunted		-0.86***	-0.63**	-0.74**	
		(0.32)	(0.29)	(0.32)	
Odds ratio		0.42***	0.53**	0.48**	
95% CI	NA	(0.23-0.79)	(0.30-0.94)	(0.25-0.89)	NA
Moderately stunted		-0.56**	-0.22	-0.38	
		(0.26)	(0.22)	(0.27)	
Odds ratio		0.57**	0.80	0.68	
95% CI		(0.34-0.95)	(0.52-1.24)	(0.40-1.15)	
[F] Using household random-effects					
Stunted	-0.38***	-0.15***	-0.06*	-0.13***	-0.47
	(0.10)	(0.03)	(0.04)	(0.03)	(0.81)
Moderately stunted	-0.18**	-0.09**	-0.03	-0.09***	-1.76**
	(0.09)	(0.03)	(0.03)	(0.03)	(0.74)
Hausman test $[\chi^2, (p)]$	6.39 (0.17)	3.30 (0.51)	1.70 (0.79)	2.70 (0.61)	0.80 (0.94)

Notes: Same notes as in Table 1 and same regressions as in Table 2 (main manuscript), except where noted. [a] Lower-censored Tobit for schooling and lower-censored Poisson regressions for math, reading, writing, and local plant knowledge with raw scores of academic skills used as outcome variables (see Table 1 for raw scores). CI = confidence interval. [b] HAZ was used as a continuous variable. [c] Severe stunting was defined as HAZ< -3. NA=not applicable.

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Table 4. OLS regressions for Eq. 2 showing association between (i) changes in height category (from stunted to non-stunted or vice versa) from year of first measure to year of last measure and (ii) schooling and academic skills in last year of measure for Tsimane' children 6y ≤ age ≤ 16y during 2002-2010

Change in HAZ (HAZ in last year of measure minus HAZ in first year of measure)	Outcome during last measurement year			
	Schooling	Math	Reading	Writing
A. Change from stunted to non-stunted or vice versa: Child crosses threshold of -2 HAZ				
Δ HAZ⁻ [worsened (faltered); from non-stunted to stunted]	-0.21	-0.18*	-0.001	-0.15**
	(0.24)	(0.08)	(0.06)	(0.06)
Δ HAZ⁺ [improved (recovered); from stunted to non-stunted]	-0.11	-0.04	0.04	0.05
	(0.20)	(0.08)	(0.08)	(0.08)
Δ HAZ⁰ [stunted in both periods (persistent stunting)]	-0.44**	-0.12	-0.08	-0.009
	(0.19)	(0.09)	(0.07)	(0.07)
Number of observations (children)	842	839	839	839
R^2	0.73	0.62	0.58	0.63
B. Change from stunted to non-stunted or vice versa: Child crosses threshold of -2 HAZ ± 0.20HAZ				
Δ HAZ⁻ [worsened (faltered); from non-stunted to stunted]	-0.43	-0.21**	-0.02	-0.21**
	(0.28)	(0.07)	(0.08)	(0.09)
Δ HAZ⁺ [improved (recovered); from stunted to non-stunted]	-0.06	-0.03	0.05	0.07
	(0.21)	(0.09)	(0.08)	(0.07)
Δ HAZ⁰ [stunted in both periods (persistently stunted)]	-0.37**	-0.07	-0.06	0.02
	(0.17)	(0.08)	(0.07)	(0.08)
Number of observations (children)	842	839	839	839
R^2	0.73	0.62	0.58	0.63
C. Change in the total amount of HAZ from the first to the last measure				
Total change in HAZ	-0.10	-0.01	0.03	-0.01
	(0.08)	(0.05)	(0.04)	(0.05)
Number of observations (children)	842	839	839	839
	0.73	0.61	0.57	0.63

Notes: *, **, and *** significant at ≤10%, ≤5%, and ≤1%. ΔHAZ⁻, ΔHAZ⁺, and ΔHAZ⁰ are binary variables with 1=faltered, recovered, or persistently stunted respectively; 0=remained non-stunted in both periods. The excluded group in all regressions was children who were non-stunted in both periods. Regressions include household fixed effects, a child's sex, a child's age and HAZ during the first year of measure, a variable for the number of years elapsed between the year of the child's first and the year of the child's last HAZ measure, baseline measure of the outcome, walking distance (hours) from the village to the nearest town, and a constant. Regressions include robust standard errors (in parentheses) adjusted for clustering at the village level.

Figure Captions

Figure 1. Map showing location of [1] 13 Tsimane' villages of the nine-year (2002-2010) annual longitudinal study along the Maniqui River and [2] 40 additional Tsimane' villages of the randomized controlled trial (RCT), both in the department of Beni, Bolivia

Notes: The shading of the territory denotes elevation (Mamsl = meters above sea level). The square symbols and letters in each town are approximately proportional in size to the population of the town. The Tsimane' territory is an administrative division and does not capture all the lands inhabited by the Tsimane'.

Figure 2. Completed grade of schooling by height category

Notes: For the test of statistical significance we ran an OLS regression of completed grade of schooling (outcome) against two binary variables, stunted and moderate stunting, with non-stunted children as the excluded category. ** $p < 0.05$; years of completed schooling was significantly less for stunted children than for non-stunted children, but there was no significant difference between moderately stunted and non-stunted children in the regression ($p = 0.52$). See Table 1 for definition of variables.

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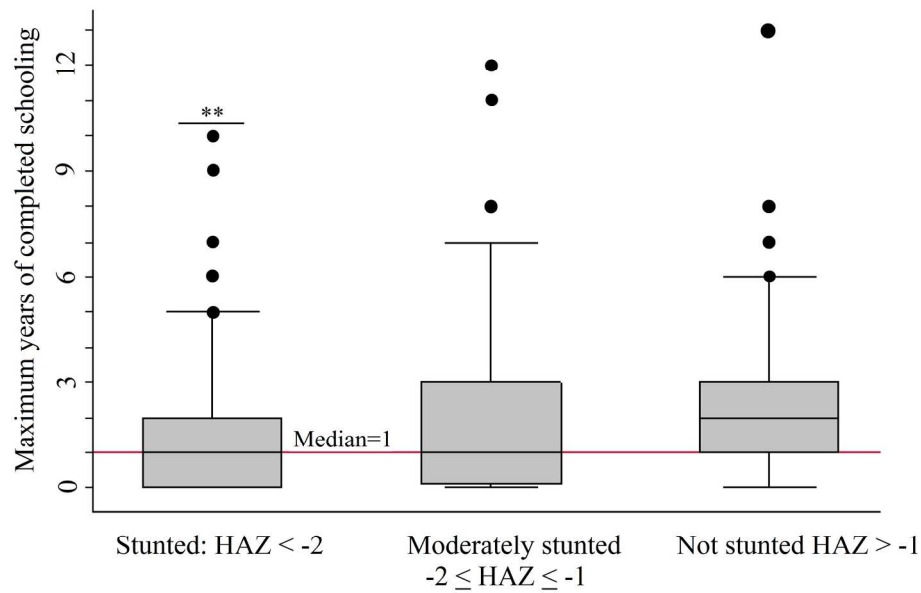
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191x125mm (300 x 300 DPI)