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Catch-up growth and growth deficits: Nine-year annual panel child growth from native Amazonians in Bolivia

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Abstract

Background. Childhood growth stunting is negatively associated with cognitive and health outcomes throughout life, and is probably irreversible after age 2.

Aim. To estimate growth rates for children 2≤age≤7 who were stunted (sex-age standardized z-score [HAZ]<-2), marginally-stunted (-2≤HAZ≤-1), or normal (HAZ>-1) at baseline and tracked annually until age 11 or until the panel ended; frequency of movement among height categories; and variation in height predicted by early childhood height.

Participants and methods. We used a nine-year annual panel (2002-2010) from a native Amazonian society of horticulturalists-foragers, Tsimane' (n=174 girls; 179 boys at baseline). We used descriptive statistics and random-effect regressions.

Results. We found some evidence of catch-up growth but persistent height deficits. Children stunted at baseline saw improvements of 1 HAZ unit by age 11, and had higher annual grow rates than children of normal height. Marginally-stunted boys had a 0.1 HAZ units higher growth rate than boys of normal height. Despite some catch up, ~80% of marginally-stunted children at baseline remained marginally-stunted by age 11. The height deficit increased from age 2 to 11. We found modest year-to-year movement between height categories.

Conclusions. The prevalence of growth faltering among the Tsimane' has declined over the past decade, but hurdles still lock children into height categories.

Keywords: Growth faltering, Public health, Social epidemiology, Stunting, Tsimane'

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Catch-up growth and growth deficits:
Nine-year annual panel child growth from native Amazonians in Bolivia

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Introduction

Childhood growth stunting is a public-health concern because it is associated with higher risk of mortality for a given age, lower educational attainment, and worse physical health, cognitive skills, and socioeconomic outcomes throughout life and across generations (Hoddinott et al., 2008, Prendergast and Humphrey, 2014, Schott et al., 2013, Schwinger et al., 2016, Victora et al., 2008). Stunting, defined as being 2 standard deviations (SD) below the mean age-sex standardized height z-score (HAZ) of well-nourished populations (World Health Organization, 2006, 2015), is more prevalent in low-income nations and reflects poverty, disease, and inadequate nutrition during infancy and childhood (Black et al., 2008, Victora et al., 2008). Stunting is thought by some to be irreversible after age 2 (see review in Crookston et al. (2013)), but some evidence suggests that it is reversible with improved living conditions or with public health interventions (Adair, 1999, Lundeen et al., 2014a, Prentice et al., 2013, Schott et al., 2013). These analyses have also raised the question of how to best assess catch-up growth in height based on longitudinal analyses (Cameron et al., 2005, Georgiadis et al., 2016, Leroy et al., 2015, Victora et al., 2014). Assessing the growth velocity of stunted children matters because it can provide insights into plasticity in human growth and the relative importance of environmental conditions in early life. Additionally, research suggests that growth rates during childhood may provide information about downstream health risks, including metabolic disease (Frisancho, 2003, Hoffman et al., 2000, Popkin et al., 1996).

Much of what we know about growth velocities and catch-up growth in low-income nations comes from public health trials, is confined to children < age 5, or lacks repeated annual measures from the same children for more than five consecutive years (Grantham-McGregor et al., 2007). Thus, we know little about (1) annual child growth from age 2 until age 11 (eve of puberty) with respect to the amount of catch up-growth and early height deficits, (2) two-way movement from stunting to non-stunting status, and (3) if the height of children at age 11 is tightly associated with early childhood height when childhood stunting is common.

Here we help fill the gaps by drawing on a nine-year annual panel (2002 - 2010) from a low-income, native Amazonian society of horticulturalists-foragers in Bolivia (Tsimane'). Our main aim is to characterize growth during ages 2 - 11. We focus on three sets of estimates: (1) growth rates of children $2 \leq age \leq 7$ who were stunted (HAZ < -2), marginally-stunted ($-2 \leq HAZ \leq -1$), or normal (HAZ > -1) at baseline (2002) and who were tracked annually until they reached age 11 or until the panel ended (2010) provided they were age ≤ 11 when the panel ended; (2) the frequency of movement among the three height categories (stunted, marginally-stunted, and normal); and (3) the share of variation in height by age 11 associated with height in early childhood.

Through the first set of estimates we try to answer the question of how fast children grow between ages 2 and 11 in a remote, low-income rural setting without public health interventions to redress growth faltering. We then compare growth velocities in raw units (cm/year) in our sample with growth velocities from international reference groups to explore the extent of catch-up growth and height deficits. The second set of estimates allows us to explore the amount of movement across height categories. Much has been written about the ability of stunted children to attain normal adult height, but less attention has been paid to downward movements in height categories of children who were marginally-stunted or who had normal height during childhood. During ages 2 through 11, are children once stunted always stunted, once normal always normal, or do they move among height categories? Through the third set of estimates we explore if children at the eve of puberty are locked into their early childhood height and assess the room for public policies to redress growth faltering.

Study participants and methods

We used data from the Tsimane' Amazonian Panel Study (TAPS), a bio-cultural anthropological study which measured every June-September during 2002-2010 anthropometric and socio-economic variables from all residents in 13 villages along the Maniqui River, Department of Beni (Leonard et al., 2015). The baseline sample at the start of the panel (2002) included 633 adults (≥ age 16) and 820 children (< age 16). Methods of data collection have been described in earlier publications, including two that examined child growth during the early years of the panel (Godoy et al., 2010, Tanner et al., 2014) and one in 2000, before the panel started, based on 58 villages showing that 52% of boys and 43% of girls < age 9 were stunted (Foster et al., 2005). We measured standing height following the protocol of Lohman et al. (1988) and calculated age- and sex-specific height-for-age z-scores using the World Health Organization (WHO) growth standards for children 24-60 months of age (de Onis et al., 2004, World Health Organization, 2006) and the WHO references for children > 60 months (de Onis et al., 2007). Following the WHO (2009) guidelines, HAZ measures beyond +/- 6 SDs were flagged as probably contaminated by large measurement errors and excluded from the analysis (n=6; 0.003% of total observations).

We limited the analysis to all children (girls = 174, boys = 179) 2 ≤ age ≤ 7 at baseline (2002) and no more than 11 years of age by 2010 because we wanted to estimate growth patterns before puberty. Restricting the upper baseline age to seven years had the advantage of ensuring that these older children were re-measured on several occasions before the end of the panel.

To analyze growth rates we computed annual changes in height in both cm and HAZ for two reasons. First, HAZ overstates the amount of catch-up growth in terms of height deficits because height standard deviations in the well-nourished reference population increases with age until middle or later adolescence (Leroy et al., 2015, Victora et al., 2014). Second, HAZ scores and height deficits had random measurement error (Godoy et al., 2008a); 10.6% of parents admitted not knowing their child's exact age and had to guess. Most analyses of stunting consider only two height categories: stunted (HAZ < -2) and not stunted (-2 ≤ HAZ). Because we are interested in changes children might undergo between stunted and non-stunted categories over the life of the panel, we split the non-stunted category into two sub-categories: marginally-stunted (-2 ≤ HAZ ≤ -1) and normal (HAZ >-1). The finer-grained sub-division allows for a more nuanced analysis of movement among height categories (Teivaanmäki et al., 2015).

For the analysis we used descriptive statistics and graphs to compare height categories at baseline with height categories later in childhood. We used the following OLS and random-effect regressions to estimate growth rates and catch-up growth:

$$Y_{ihvt} = \alpha + \beta \cdot H_{ihvb} + \gamma \cdot X_{ihvt} + \varepsilon_{ihvt} \quad \text{(Eq. 1; OLS)}$$

$$Y_{ihvt} = \alpha + \beta \cdot S_{ihvb} + \theta \cdot S'_{ihvb} + \gamma \cdot C_{ihvt} + \delta \cdot M_{hvt} + \upsilon \cdot H_{hvt} + \varepsilon_{ihvt} \quad \text{(Eq. 2; random effects)}$$

where the subscripts stand for individual (i), household (h), village (v), year (t), and baseline (b). In Eq. 1, Y_{ihvt} includes height in 2010 or at age 11 in cm and HAZ and annual change in height expressed in cm/year and HAZ/year, H_{ihvb} indicates baseline height (cm or HAZ), X_{ihvt} is a vector with covariates (child's age, sex, times the child was measured in the panel, and village fixed-effects), and ε_{ihvt} is an error term. In Eq. 2, Y_{ihvt} indicates the annual change in HAZ during 2002-2010, S_{ihvb} is an indicator variable for baseline stunted, S'_{ihvb} is an indicator variable for baseline marginally-stunted, C_{ihvt}, M_{hvt}, H_{hvt} are vectors with child (birth order, lagged weight, baseline age, gender, birth season, times the child was measured in the panel), mother (age, schooling, height, weight), and household (total children, income, wealth, area of forest cleared) covariates respectively, and village fixed-effects, and ε_{ihvt} is an error term. Appendix 1 contains definitions of the explanatory variables used in the regressions.

Results

Figure 1 shows that girls and boys 2 ≤ age ≤ 7 at baseline grew steadily during the nine years of the panel, with no obvious tapering off in height for either sex or age bracket, except for the oldest children at baseline. This figure also shows that, for every age for boys and girls, that more recent birth cohorts have higher height on average than earlier cohorts. Figure 2 shows lower growth rates for older children and higher growth rates for girls than for boys. Depending on the child's sex, older children who had been age 5-6 at baseline grew by 5.4-4.1 cm / year or 4.5-3.4% / year whereas children who had been age 2 at baseline grew by 6.1-5.8 cm / year or 5.9-5.6% / year. Over the entire period, girls grew by an average of 4.4 cm / year or 3.9% / year whereas boys grew by 3.9 cm / year or 3.5%/year (detailed standing height and annual height increments in cm during 2002-2010 by age are shown in Appendix A).

[Insert Figure 1 and Figure 2 about here]

Figure 3 shows two noteworthy results. First, we find evidence of catch-up growth in HAZ (mean HAZ and annual change in HAZ during 2002-2010 by age are shown in Appendix B). The average stunted girl or boy in 2002 saw an improvement of ~1 HAZ unit by age 11 (Appendix B). The improvements in HAZ applied on average to girls and to boys of all ages. Second, Figure 3 shows that in some age brackets, children who had not been stunted at baseline experienced growth faltering on average, with more faltering among boys than among girls. The total change in HAZ between baseline and end-line (2010) grew wider (became negative) for some girls who had normal height at ages 2-3 and for some boys of normal height in all age groups. In the next section we examine within-child changes in height categories in more detail.

[Insert Figure 3 about here]

Table I shows growth rates and final height for children $2 \leq age \leq 7$ at baseline and no more than 11 years of age during 2002 - 2010. Column A1 (section I) suggests that, for the sample of girls and boys combined, initially taller children grew at a lower rate than shorter children. Each additional cm of height at baseline was associated with a 0.02 cm / year lower annual growth rate (girls = -0.01 cm / year, $p = 0.3$; boys = -0.03 cm / year, $p = 0.005$). Column A2 (section I) suggests that baseline and end-line heights were positively associated; each additional cm of height at baseline was associated with 0.3 cm taller stature at age 11 (girls = 0.3 cm, $p = 0.001$; boys = 0.3 cm, $p = 0.001$). Column B (section I) contains similar analysis, but with height expressed in HAZ. A 1-unit increase in baseline HAZ was associated with 0.07 SD / year lower growth rate in HAZ and with a 0.5 greater HAZ by age 11 or year 2010, consistent with the visual and descriptive results presented earlier. In section II of Table I we repeated the analysis of section I of the same table, but separately for each of the initial height categories. Column A1 (section II) suggests that growth rates did not vary by baseline height categories, with one exception; among stunted children. Among stunted children, each additional cm of baseline height was associated with a 0.03 cm / year lower growth rate. The same results appear when we express height as HAZ (Column B1, section II). A one unit higher baseline HAZ among stunted children was associated with a 0.08 SD lower HAZ growth rate (Appendix C shows a comparison of annual growth rates in the three categories). As before, we find a positive association between baseline and final height, with magnitudes roughly similar among the height categories (Table I: Columns A2 and B2, section II). For instance, an additional cm of baseline height across any of the three height categories was associated with 0.1 cm taller final height and an additional HAZ unit in baseline height across any of the three height categories was associated with 0.4 - 0.7 HAZ unit taller final height.

[Insert Table I about here]

In Figure 4 we summarize changes in height category between baseline height categories when children were $2 \leq \text{age} \leq 7$ and height categories by the end of the panel in 2010, or when the same children had reached age 11 (the specific numbers in each height category at baseline and end-line are shown in Appendix D). On average, children recovered from growth faltering when younger. For example, 32% (28 / 87) of children who had been marginally-stunted at baseline had attained normal HAZ by age 11, and 42% of children who had been stunted at baseline had become marginally-stunted (34%) or attained normal HAZ (8%) by the time they had reached age 11. However, 7.9% of the sample saw either a deterioration in their HAZ status from normal to marginally-stunted (n =11, 4.3% of the sample) or from marginally-stunted to stunted (n = 9, 3.6% of the sample) while an additional 68 children (26.8% of the sample) remained stunted from baseline to end-line. Of the 203 children who were stunted (n = 116) or marginally-stunted (n = 87) at baseline, only 37 (18%) had attained normal HAZ by age 11. We found a strong relation between baseline and end-line height (Kendall's tau-b test: 0.6); 62% of children at end-line retained the same height category they had at baseline. In spite of this, there was movement among height categories (Figure 4); a significant proportion of stunted or marginally-stunted children moved to a category of higher height.

[Insert Figure 4 about here]

In Table II we explore year-to-year changes in height categories for the same child over the period of study. Because a child could move in and out of the categories of stunted, marginally-stunted, and normal height over the nine years of the panel, comparing height for children 2 ≤ age ≤ 7 years at baseline with their height at age 11, as in Figure 4, glosses over year-to-year changes in their height categories that might have taken place before reaching their final height at age 11. Table II and Figure 5 contain summaries of all the changes in height categories between surveys for a child, and show two results.

[Insert Table II and Figure 5 about here]

First, children seemed fairly locked into their height categories from one year to the next. For instance, the column with totals in Table II suggests that of the 333 episodes of children who had normal HAZ at some point during 2002-2009, 81% (n = 271) continued to have normal HAZ in the next annual survey, while 57 (17%) became marginally-stunted and an additional 5 children (1.5%) became stunted. The same finding appears when we consider marginally-stunted children. Of the 642 episodes of children who had been marginally-stunted during one of the annual measures, 124 episodes (19.3%) were for children who either attained normal HAZ (34 / 642 = 5.3%) or became stunted (90 / 642 = 14.0%) in the next annual survey; most (80.7%; 518 / 642) of the children who had been marginally-stunted during one annual survey continued to be marginally-stunted in the next annual survey. Last, of the 641 episodes of children with stunting at one point during the panel study, 55 episodes (55 / 641=8.6%) were for children who attained normal HAZ (5 / 641 = 0.8%) or became marginally-stunted (50 / 641=7.1%) in the next survey. Of all 1 616 episodes of annual change for all the children, 1 375 episodes (85.1%) were for children who remained in their height category from one annual survey to the next annual survey, 89 episodes (5.5%) captured children who improved their HAZ status, and 152 episodes (9.4%) were for children who experienced a worsening of their HAZ status from one survey to the next. Even though there were changes in HAZ from one year to the next, as shown earlier with the annual growth rates, most of these changes had to do with children changing height within a category (e.g., a stunted children becoming taller, but still remaining stunted), instead of movement across categories (e.g., a stunted child attaining normal height). The second noteworthy finding of Table II is that both girls and boys were likely to experience about the same mobility between height categories.

These results then raise two questions: to what extent do baseline biological and socioeconomic conditions during early childhood lock children into their height at age 11? And to what extent do baseline conditions affect change? Table III contains regression results to estimate the share of variation of height by age 11 predicted by antecedent child heights. The results suggest that early childhood height predicts 50-70% of the variation in height by age 11. If at least half of the variation in the height of children by age 11 can be predicted by biological and socioeconomic factors during early childhood, what could explain the remaining variation?

[Insert Table III about here]

Table IV contains regression results to attempt to identify the covariates of child growth rates (Eq. 2; Appendix E shows a definition of the variables included in the regression). Table IV supports some of the findings presented earlier, suggesting that stunted and marginally-stunted children grew at faster rates than their age and sex peers of normal height. The coefficients of Table IV suggest that the HAZ of stunted girls at baseline grew by 0.1 HAZ units / year more than the HAZ of girls of normal height, while the HAZ of stunted boys at baseline grew by 0.2 HAZ units / year more than the HAZ of boys of normal height. Marginally-stunted girls and boys also had higher growth rates than their age and sex peers of normal height, but the growth rates for marginally-stunted children were half as large as the growth rates of stunted children, and results were only significant for boys. Marginally-stunted boys had 0.1 HAZ unit higher HAZ growth rate than boys of normal height. Beyond showing that the HAZ of stunted and marginally-stunted girls or boys grew at higher rates than the HAZ of children of normal height, Table IV shows one striking result. Except for boys born during the dry season, none of the other covariates was associated with child growth. Boys born during the dry season had 0.05 HAZ units / year higher growth rates than boys born during other seasons.

[Insert Table IV about here]

We did additional analysis to assess the robustness of results and explore new topics. The results of these additional regressions are not shown. We included lagged child weight-for-age z scores instead of raw weight measures in kg, and found much weaker results for the rates of growth of stunted and marginally-stunted children. We added morbidity or the number of days the child had been confined to bed owing to illness, and found essentially the same results as those shown in Table IV. Last, we ran separate OLS regressions for girls and boys with village fixed-effects and a binary outcome: one if the child was stunted at baseline but improved by end-line either by becoming marginally-stunted or normal in height, and zero if the child remained stunted at both baseline and end-line. We used all the same covariates as in Table IV. None of the covariates was significantly associated with the probability of changing height status except baseline age. Each additional year of age at baseline was associated with a 10 percentage point decrease in the probability of improving a child's height status, with about the same magnitudes for girls and boys.

Discussion

In this section we discuss three topics. First, how much catch-up growth and growth deficit do we see by age 11? Second, what might explain the mobility of children among height categories (beyond the child's age at baseline)? Last, we discuss some of the main limitations of our study.

Catch-up growth and growth deficit by age 11

We found some evidence of some, but partial catch-up growth. Each cm shorter stature at baseline was associated with 0.02 cm / year higher growth rates. Stunted children at baseline grew by 0.02 cm / year more than children of normal height (Table I). 41% of children stunted at baseline became marginally-stunted or attained normal height by the time they had reached age 11 (Figure 4 and Appendix D). Table IV suggests that stunted children had higher HAZ growth rates than children of normal height, and Figure 3 shows that children who had been marginally-stunted at baseline saw an improvement of one HAZ unit by the time they reached age 11. These results are in broad agreement with growing evidence from low-income and middle-income nations showing evidence of catch-up growth (Coly et al., 2006, Crookston et al., 2010, Crookston et al., 2013, Hirvonen, 2014, Outes and Porter, 2013, Said-Mohamed et al., 2015, Schott et al., 2013, Victora et al., 2008).

Is the growth rate of Tsimane' children enough to ensure convergence to international standards? To answer the question we compared growth velocities between our sample and a reference population and also estimate height deficits. Recall that the average Tsimane' girl $2 \leq \text{age} \leq 7$ at baseline grew by 4.4 cm / year until she reached age 11 while the average Tsimane' boy $2 \leq \text{age} \leq 7$ at baseline grew by 3.9 cm / year until he reached age 11. In the USA, median annual growth rates between $2 \leq \text{age} \leq 11$ were higher than among Tsimane' children, and averaged 6.6 cm (range: 5.7 – 8.6 cm) among girls and 6.3 cm (range: 5.1 – 8.3 cm) among boys (Tanner and Davies, 1985). Thus, the difference in the average growth velocities for the two populations in favor of the reference population hints at more divergence in final height rather than catch-up.

We present further evidence for divergence in height in Figure 6, which shows the standing height of Tsimane' children expressed in cm, but as a percent of the height of children of the same age and sex in various international reference groups. We focus on two age brackets considered in this study, two and 11, to assess if the height deficit shrinks during this period. Figure 6 suggests that, irrespective of the height category or of the child's sex, the height deficit of Tsimane' children increased from age two to age 11. The two strands of linked evidence – differential growth velocities in favor of the international reference group and an increase in the height deficit of Tsimane' children from age two to age 11 – both suggest divergence rather than convergence in height. Our finding of increasing HAZ with increasing growth deficit echoes the results of recent international comparisons of child growth from the Young Lives study (Lundeen et al., 2014b). But as noted in that study, it is not clear whether height deficits or HAZ is the more useful indicator. And one cannot sort out which is preferable by looking at associations between each of these and outcomes of greater interest, such as cognitive skills or productivities because for a given age-specific reference group of height, height deficits and HAZ are perfectly correlated.

[Insert Figure 6 about here]

The absence of convergence in height might be traceable to the absence of economic transformations in this remote rural economy. The mean monetary daily earnings per person toward the end of the panel reached only $0.9, about half the global poverty line (US$1.9 PPP) used by the World Bank (2015). Low income and the absence of public-health interventions geared to redressing growth faltering could explain the deficit. That said, the share of stunted Tsimane' children has fallen. Recall from the earlier discussion that in 2000 among Tsimane' children <age 9, 43% of girls and 52% of boys were stunted. The last survey of the panel (2010) suggests that, compared with 2000, for children <age 9, the share of girls who were stunted had dropped from 43% to 30%, and the share of boys who were stunted had dropped from 52% to

34%. Thus, although living conditions might be improving for the Tsimane’, as reflected in the declining share of stunted children, the improvements in living conditions are not large enough to reduce or eliminate the height deficit.

Mobility of children among height categories

Changes in household socioeconomic conditions might not be large and permanent enough to move children into higher height categories. For instance, in Table IV we saw that socioeconomic attributes of the household or human-capital attributes of the mother bore no statistically significant association with child growth rates. Possible reasons for the negligible role of household socioeconomic attributes or maternal human-capital attributes could relate to the following: (1) the widespread practice of sharing resources and reciprocity in this strongly endogamous society, (2) low levels and little variation in socioeconomic and human-capital variables related to maternal education, and (3) endogeneity, including random errors in the measure of these variables. When combined, the three factors might attenuate the effect of socioeconomic and human-capital attributes on child growth.

Our results about mobility among height categories resemble results from other studies. In rural DR Congo, Kismul et al. (2014) reported low mobility among childhood height categories. In rural Malawi, Teivaanmäki et al. (2015) found a large drop in the share of stunted children from age two to age 10 (~80% to ~39%) and an increase in the share of non-stunted children from about ~15% to ~45%, but they did not find much change in the share of children who were marginally-stunted. In a sample of 143 shantytown children in Lima, Peru, half the sample remained stunted from 6 months of age until age nine (Berkman et al., 2002). The Young

Lives international comparison of four nations (Vietnam, Peru, India, Ethiopia) with a total sample size of 7 266 children estimated changes in HAZ between ages one and eight (Crookston et al., 2013). They found that, depending on the country, 69-82% of the children did not change their height category. In addition, 18% to 32% of the sample was normal at age one but then became stunted at age eight, or was stunted at age one and then became normal at age eight. The estimates from the Tsimane' are broadly consistent with these results, though they show more mobility than the results of the Young Lives study. For example, Figure 4 (Appendix D) suggest that 62% of the Tsimane' sample did not change their height category compared with 68-82% from the Young Lives study, while 38% of Tsimane' children changed their height categories compared with 18-32% from the Young Lives study. In general, we find a fair amount of mobility as compared with the assertions of "irreversibility" and a critical window that closes at age two in prominent studies such as Victora et al. (2008, 2010)

The pattern of mobility among height categories with Tsimane' children raises the question of why children fall into the stunted, marginally-stunted, or normal category. If socio-economic conditions of households or maternal human-capital attributes do not explain much of the variation in Tsimane' childhood growth rates between ages two and 11, as Table IV suggests, then what makes children fall into one of the three categories? We have no satisfactory answer. One possibility has to do with environmental events. In an earlier publication we showed that rainfall variability during gestation and infancy was negatively associated with maternal height (Godoy et al., 2008b). If there is an association between maternal and child height or child growth rate, then this might explain why children fall into a height category. The problem with this interpretation is that in the sample studied, maternal height bore no strong association with children growth rate (Table IV). Another environmental factor could be birth season. As noted in Table IV, a boy's birth during the dry season was associated with a 0.05 HAZ units higher growth rate. One problem with this interpretation is why would season of birth have no effect on the growth rate of girls.

Limitations

The study rests on a small sample size and too short a duration to permit examination of adolescence, though the study contains more repeated annual observations than most similar studies. It is possible that Tsimane' have a longer growth period than children in other settings; if so, then the amount of time to catch-up and reduce the growth deficit would be longer than the age span considered in this study. Previous research among indigenous populations of highland Peru (Frisancho and Baker, 1970) and nomadic pastoralists in Kenya (Little and Johnson Jr, 1987) have documented extended growth periods under conditions of chronic nutritional stress. However, we doubt a longer growth period would yield stronger evidence for catch-up growth and for eliminating the growth deficit because adult Tsimane' are short (females = 151 cm, 4.8 SD, males=162.9 cm, 4.8 SD), and have shown no secular change in height during the 20th century (Godoy et al., 2006). Also, the metrics to estimate catch-up growth during late childhood and adolescence remain imperfectly developed because of the onset of puberty. Thus, even if we had data for a longer growth period it is unclear how we could estimate meaningful growth rates for cross-cultural comparisons (Leroy et al., 2015).

Conclusion

The fact that 50-70% of the height variation by age 11 was predicted by height in early childhood lends credence to the idea that in low-resource settings at least half of the blame or half of the credit for growth and faltering might be traceable to events during gestation and the first two years of life. We do not try to answer the question of how much of child height by age two is shaped by biological or by socioeconomic factors, but since at least half of the variation in height by age 11 remains unaccounted for by height during early childhood one might reasonably conclude that there is room after age two to redress growth faltering, though the long-term health consequences of promoting linear growth after age two remain contested (Victora et al., 2014).

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Declaration of interest statement

The authors declare they have no conflict of interest.

Appendices

Appendix A: Standing height and annual height increments during the panel study

Table V. Standing height and annual height increments in cm during 2002 - 2010 for Tsimane' children, 2 ≤ age ≤ 7 at baseline (2002) but no more than 11 years old by 2010

Age in 2002	Sex	Standing height in cm during: 2002			2003			2004			2005			2006		
		N	A	SD	N	A	SD	N	A	SD	N	A	SD	N	A	SD
2	Girls	37	80.8	4.3	26	86.9	3.6	30	93.4	3.9	31	99.5	3.7	29	106.1	3.3
	Boys	33	81.4	5.0	22	87.2	5.7	30	94.6	4.8	29	101.3	4.9	28	106.8	5.1
3	Girls	29	89.4	4.6	21	93.1	4.4	24	100.4	3.2	24	106.6	3.5	21	111.8	2.9
	Boys	34	89.0	5.6	28	93.6	5.3	23	100.7	5.6	24	105.9	4.6	23	111.9	6.1
4	Girls	29	95.4	5.6	21	100.5	5.6	25	105.0	6.2	25	111.4	5.3	25	115.8	6.8
	Boys	32	97.9	4.4	23	101.7	5.6	25	107.8	4.0	27	113.1	4.6	25	118.5	4.3
5	Girls	31	103.6	5.4	25	107.5	4.6	25	113.7	5.0	26	117.5	5.3	25	123.3	6.1

	Boys	25	103.7	6.0	22	107.4	5.2	24	112.4	4.9	23	117.2	5.2	23	122.3	4.7
6	Girls	48	112.5	8.2	38	115.8	7.8	39	120.3	6.1	40	126.9	7.1	39	133.9	7.8
	Boys	55	111.8	7.3	44	115.0	6.5	44	120.6	6.5	48	125.3	6.9	46	130.4	8.2
Total	Girls	174	97.5	13.3	131	102.4	12.3	143	107.5	11.3	146	113.4	11.4	139	119.6	12.0
	Boys	179	98.2	12.8	139	102.9	11.8	146	108.6	11.2	151	114.2	10.7	145	119.6	10.9

Notes: N = number of observations. A = average; SD = standard deviation. Sample includes all children in the 13 villages of TAPS. Height measured following the protocol of Lohman et al. (1988). Blank cells means that the child's age >11.

Table V. Continued

Age in 2002	Sex	Standing height in cm during: 2007 N	2007 A	2007 SD	2008 N	2008 A	2008 SD	2009 N	2009 A	2009 SD	2010 N	2010 A	2010 SD	Average change in height, 2002 - 2010: End-line - 2010	Annual Change in: cm	Annual Change in: %
2	Girls	28	112.2	3.1	27	117.8	4.4	22	122.7	4.8	24	129.4	6.3	48.6	6.1	5.9
	Boys	25	112.4	5.6	26	119.0	8.5	23	123.4	5.1	25	127.4	5.8	46.0	5.8	5.6
3	Girls	19	117.8	3.5	22	122.9	3.8	16	132.6	8.2	18	137.0	5.4	47.6	6.0	5.3
	Boys	24	117.0	4.6	21	120.9	4.9	21	126.5	4.6	22	132.1	6.3	43.1	5.4	4.9
4	Girls	20	121.7	8.0	21	128.4	9.1	20	134.6	9.6				39.2	5.6	4.9
	Boys	23	123.8	4.8	22	128.9	4.8	17	133.3	4.8				35.4	5.1	4.4
5	Girls	22	130.0	6.7	21	135.8	6.8							32.2	5.4	4.5
	Boys	21	127.5	4.7	21	132.8	5.0							29.1	4.8	4.1
6	Girls	12	136.6	7.0										24.1	4.8	3.9
	Boys	22	132.4	6.0										20.7	4.1	3.4
Total	Girls	101	121.9	10.1	91	125.7	9.2	58	129.5	9.3	42	132.7	7.0	35.2	4.4	3.9
	Boys	115	122.2	8.9	90	125.1	8.3	61	127.2	6.3	47	129.6	6.4	31.4	3.9	3.5

Notes: N = number of observations. A = average; SD = standard deviation. Sample includes all children in the 13 villages of TAPS. Height measured following the protocol of Lohman et al. (1988). Blank cells means that the child's age >11.

Appendix B: Mean HAZ and annual change in HAZ during the panel study

Table VI. Mean height-for-age z score (HAZ) and annual change in HAZ during 2002 - 2010 for Tsimane' children, 2 ≤ age ≤ 7 at baseline but no more than age 11 by 2010, measured annually during 2002 - 2010: Stunted (HAZ < -2) and non-stunted (HAZ ≥ -2) children compared

		Mean height-for-age z score (HAZ) during:														
Age in		2002			2003			2004			2005			2006		
2002	Sex	T	S	NS	T	S	NS	T	S	NS	T	S	NS	T	S	NS
2	Girls	-2.3	-3.0	-1.0	-2.2	-2.7	-1.5	-2.2	-2.6	-1.5	-2.1	-2.4	-1.6	-1.8	-2.1	-1.5
	Boys	-2.5	-3.4	-0.9	-2.5	-3.2	-1.2	-2.1	-2.5	-1.2	-1.8	-2.3	-1.1	-1.9	-2.3	-1.2
3	Girls	-2.0	-3.1	-1.1	-2.2	-2.9	-1.5	-1.8	-2.3	-1.4	-1.6	-2.0	-1.3	-1.7	-2.0	-1.4
	Boys	-2.4	-3.4	-0.9	-2.3	-3.0	-1.4	-2.0	-2.7	-1.1	-2.0	-2.5	-1.3	-1.9	-2.5	-1.0
4	Girls	-2.1	-2.8	-1.0	-1.9	-2.5	-0.8	-2.0	-2.6	-1.0	-1.7	-2.2	-1.0	-1.9	-2.6	-0.9
	Boys	-1.8	-2.9	-1.2	-1.9	-3.1	-1.2	-1.8	-2.5	-1.3	-1.7	-2.4	-1.3	-1.6	-2.3	-1.3
5	Girls	-1.4	-2.6	-0.8	-1.4	-2.3	-1.0	-1.3	-2.1	-0.9	-1.5	-2.3	-1.0	-1.5	-2.3	-0.9
	Boys	-1.6	-2.8	-0.7	-1.8	-2.6	-1.0	-1.8	-2.6	-1.1	-1.8	-2.6	-1.1	-1.8	-2.4	-1.2
6	Girls	-1.5	-2.7	-0.8	-1.6	-2.6	-1.0	-1.8	-2.7	-1.3	-1.6	-2.7	-1.1	-1.5	-2.5	-0.9
	Boys	-1.6	-3.0	-0.9	-1.8	-2.7	-1.3	-1.6	-2.8	-1.2	-1.7	-2.8	-1.2	-1.6	-2.7	-1.2
Total	Girls	-1.8	-2.9	-0.9	-1.8	-2.6	-1.1	-1.8	-2.5	-1.2	-1.7	-2.3	-1.2	-1.7	-2.3	-1.1
	Boys	-2.0	-3.2	-0.9	-2.0	-2.9	-1.2	-1.8	-2.6	-1.2	-1.8	-2.5	-1.2	-1.7	-2.4	-1.2

Notes: T = total; S = stunted (HAZ < -2 SD); NS = not stunted (HAZ ≥ -2 SD).

Table VI. Continued

Age in 2002	Sex	Mean height-for-age z score (HAZ) during: 2007 T	S	NS	2008 T	S	NS	2009 T	S	NS	2010 T	S	NS	Change in mean HAZ, 2002-2010 End-line – 2010 T	S	NS	% stunted at baseline, but not at end-line
2	Girls	-1.7	-1.9	-1.4	-1.6	-1.7	-1.4	-1.7	-1.9	-1.4	-1.6	-1.9	-1.1	0.7	1.1	-0.1	75
	Boys	-1.8	-2.2	-1.1	-1.5	-1.7	-1.1	-1.5	-1.7	-1.1	-1.7	-2.0	-1.0	0.9	1.4	-0.1	77
3	Girls	-1.6	-2.0	-1.3	-1.6	-2.0	-1.3	-1.0	-1.7	-0.4	-1.3	-1.7	-0.9	0.7	1.4	0.2	69
	Boys	-1.9	-2.3	-1.3	-2.0	-2.3	-1.5	-1.8	-2.1	-1.3	-1.7	-2.1	-1.1	0.7	1.2	-0.2	70
4	Girls	-1.9	-2.5	-0.9	-1.7	-2.5	-0.7	-1.6	-2.3	-0.6				0.5	0.5	0.4	59
	Boys	-1.6	-2.3	-1.1	-1.5	-2.1	-1.1	-1.6	-2.0	-1.3				0.2	0.9	-0.2	73
5	Girls	-1.5	-2.1	-0.8	-1.3	-2.1	-0.8							0.0	0.5	0.0	30

	Boys	-1.7	-2.3	-1.2	-1.6	-2.2	-1.0							0.0	0.6	-0.3	36
6	Girls	-1.4	-2.5	-0.6										0.1	0.2	0.1	24
	Boys	-1.8	-2.7	-1.2										-0.1	0.3	-0.3	42
Total	Girls	-1.6	-2.2	-1.0	-1.6	-2.0	-1.0	-1.5	-2.0	-0.7	-1.4	-1.8	-1.0	0.4	1.0	-0.1	54
	Boys	-1.7	-2.3	-1.2	-1.6	-2.0	-1.2	-1.6	-1.9	-1.3	-1.7	-2.0	-1.1	0.3	1.1	-0.1	61

Notes: T = total; S = stunted (HAZ < -2 SD); NS = not stunted (HAZ ≥ -2 SD).

Appendix C: Comparison of annual growth rates in the three height categories, stunted, marginally-stunted, and normal height

To compare the annual growth rates of children in the three height categories, we ran one regression with two dummy variables, one for stunted children and one for marginally-stunted children, using children of normal height as the excluded category while controlling for all the variables indicated in Table I in the main text. These results are shown in Table VII. We found that stunted children grew by 0.03 cm/year less or 0.16 SD/year more than children of normal height, while marginally-stunted children grew by 0.13 cm/year less or 0.07 SD/year more than children of normal height; except for the growth of stunted children expressed as changes in HAZ, none of the other results were statistically significant at the 5% level or lower. Columns A2 and B2 suggest that, on average, stunted children were 11.5 cm or 1.6 SD shorter than children of normal height and that marginally-stunted children were 5.4 cm or 0.8 SD shorter than children of normal height, with all results significant at the 1% level.

Table VII. Linear regression results for height growth rates during 2002 - 2010 in relation to baseline (2002) stunting among Tsimane' children 2 ≤ age ≤ 7 at baseline but no more than 11 years old by 2010.

Explanatory variables	Dependent variable is standing height in 2010 or at age 11 when exiting the panel; height expressed in:			
	[A] Centimeters (cm)		[B] HAZ	
I. Baseline stunting	[1] Change cm/year	[2] Final height	[1] Change HAZ/year	[2] Final HAZ
Stunted	-0.03	-11.54**	0.16**	-1.62**
Marginally- stunted	-0.13	-5.42**	0.07	-0.82**
II. Child				
Age	0.03	0.19**	0.004	-0.01*
Male	-0.78**	-3.24**	-0.05	-0.29**
Survival	0.04	-0.57**	-0.002	-0.07**
V. Constant	4.88**	147.55**	-0.15	0.63**
R^2	0.02	0.49	0.02	0.50
N	1,619	1,728	1,619	1,728

Notes: For definition of variables see Appendix 1. OLS regressions include a child's age, sex, and number of times the child was measured in the panel, village fixed effects, constant, and robust standard errors. * and ** significant at < 5% and < 1%.

Appendix D: Changes in height category among Tsimane' children at baseline and end-line

Table VIII. Changes in height category among Tsimane' children 2 ≤ age ≤ 7 at baseline (2002) and end-line (2010) or age 11, whichever came first

	Baseline height			
Final height	Normal	Marginally- stunted	Stunted	Total
Normal	39	28	9	76
Marginally-stunted	11	50	39	100
Stunted	0	9	68	77
Total	50	87	116	253

Notes: Kendall's tau-b =0.6 and ASE (asymptotic standard error) = 0.03. Children who dropped out of the panel before reaching age 11 are excluded.

Appendix E: Definition of explanatory variables used in regressions of Table 4 (Eq. 2)

Table IX. Definition of explanatory variables used in regressions of Table 7, children 2 ≤ age ≤ 7 in 2002, but age ≤ 11 by 2010

Category	Variable definition	Variable name
I. Child:	Birth order	Pseudo birth order; 1 = youngest, 2 = next youngest, etc. Birth order determined by child's age in household, not by asking mother about the exact birth order of the child. This variable only includes children living in the household at the time of the survey
	Lagged weight	Weight of subject during previous year
	Age	Best estimate of child's age in whole years
	Male	Child's sex: 1 = male, 0 = female
	Dry-season birth	Subject was born during the dry season (May - July); 1 = yes, 0 = no
	Survival	Number of times child appears in the panel
II. Mother:	Baseline age	Best estimate of mother's age in whole years at baseline
	Schooling	Mother's maximum school grade attained
	Current height	Measured standing physical stature of child's mother (cm)
	Current weight	Mother's weight in kg
III. Household	No. of children	Number of children in the household
	Current income	Natural log of household monetary income earned during the 2 weeks before the day of the interview. Income sources include money from sales and wage labor
	Current wealth	Natural log of the monetary value of sum of stock of domesticated animals + asset wealth in goods produced locally (e.g., canoes) and commercial goods owned by the entire household
	Forest clearance	Natural logarithm of old-growth and fallow forest cleared by the household during the year before the interview. Raw variable measured in *tareas* (10 *tareas* = 1 hectare)
Community	Village fixed	Full set of dummy variables for villages (n = 13 - 1 =

attributes 12)

Appendix F: Height deficit of Tsimane children, age 2 and 11, compared with age and sex peers of international reference groups

To construct Figure 6 we first obtained median values for the standing height of girls and boys ages 2 and 11 from international reference groups, as shown in the notes to the table below. We call this the reference group. We subtracted the mean height of Tsimane’ from the height of their age and sex peers and expressed the deficit as a percentage of the height of the child in the reference group.

Table X. Input values for Figure 6, height deficit of Tsimane children, age 2 and 11, compared with age and sex peers of international reference groups, deficit expressed as percent of the height of reference group

		Tsimane’					
		Height: cm			Deficit: As % of reference		
Age	Height of reference group (cm)	Stunted	Marginally-stunted	Normal	Stunted	Marginally-stunted	Normal
Boys							
2*	87.1	78.2	83.2	86.8	10.22	4.48	0.34
11†	143.1	126.8	132.9	140.5	11.39	7.13	1.82
Girls							
2*	85.7	77.2	81.2	85	9.92	5.25	0.82
11†	145	129.3	134.8	142.9	10.38	7.03	1.45

Notes: * The median values for the reference group, age 2, come from the WHO Child Growth Standards (World Health Organization, 2006; Chapter 3, Table 20, p. 43 for boys and Chapter 3, Table 29, p. 70 for girls). † The median value for the reference group, age 11, come from the 1977 National Center for Health Statistics/WHO reference data http://www.who.int/growthref/en/

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Tables

Table I. Height growth rates for Tsimane' children 2≤age≤7 at baseline (2002) tracked until 2010 or until they reached age 11

		Dependent variable is standing height in 2010 or at age 11 when exiting the panel; height expressed in:			
		[A] Centimeters (cm)		[B] HAZ	
Group	Baseline height expressed in:	[1] Change cm/year	[2] Final height	[1] Change HAZ/year	[2] Final HAZ
[I] Pooled				^	^
	Centimeters	-0.02*	0.33**		
	R^2	0.02	0.39	^	^
	N	1619	1728		
	HAZ	^	^	-0.07**	0.52**
	R^2	^	^	0.03	0.54
	N			1619	1728
[II] Stunted, marginally-stunted, and normal					
Stunted	Centimeters or HAZ	-0.03**	0.17**	-0.08**	0.40**
(HAZ < -2)	R^2	0.03	0.21	0.05	0.28
	N	775	821	775	821
Marginally-stunted	Centimeters or HAZ	-0.02	0.16**	-0.08	0.71**
(-2 ≤ HAZ ≤ -1)	R^2	0.03	0.28	0.02	0.22
	N	541	586	541	586
Normal	Centimeters or HAZ	-0.01	0.15**	-0.07	0.52**
(HAZ > -1)	R^2	0.09	0.71	0.14	0.67

N	303	321	303	321

Notes: OLS regressions include a child's age, sex, and number of times the child was measured in the panel, village fixed effects, constant, and robust standard errors. ^ = variable intentionally left out. * and ** significant at <5% and <1%. For regressions in column [B], section II, baseline height is expressed in HAZ.

Table II. Intra-subject changes in height categories between annual surveys for children 2≤age≤7 at baseline in 2002 and no more than 11 years old by 2010.

Stunting status. During two surveys, child height changes:		Girls (n=174)		Boy (n=179)		Total (n=353)	
From	To	N	%	N	%	N	%
Normal	Normal	124	15.8	147	17.7	271	16.8
	Marginally-stunted	36	4.6	21	2.5	57	3.5
	Stunted	4	0.5	1	0.1	5	0.3
	(Subtotal)	(164)		(169)		(333)	
Marginally-stunted	Normal	16	2.0	18	2.2	34	2.1
	Marginally-stunted	260	33.1	258	31.0	518	32.1
	Stunted	42	5.4	48	5.8	90	5.6
	(Subtotal)	(318)		(324)		(642)	
Stunted	Normal	3	0.4	2	0.2	5	0.3
	Marginally-stunted	25	3.2	25	3.0	50	3.1
	Stunted	275	35.0	311	37.4	586	36.3
	(Subtotal)	(303)		(338)		(641)	
Total		785	100	831	100	1616	100

Notes: Numbers in cells are episodes of year-to-year change in height category.

Table III. Share of variation in child height by age 11 explained by height during early childhood

Explanatory variable is child height in cm at age:	Dependent variable is child height in cm at age 11					
	[A] Girls			[B] Boys		
	Coef	R^2	N	Coef	R^2	N
3	0.4*	0.17	18	0.8***	0.64	22
4	1.2***	0.70	36	0.8***	0.55	39
5	1.1***	0.67	55	0.7***	0.55	56
6	1.1***	0.55	73	0.9***	0.74	81
7	1.1***	0.54	102	0.9***	0.71	110
8	1.1***	0.72	117	1.0***	0.81	127
9	1.***	0.77	138	1.0***	0.78	158
10	0.8***	0.67	157	1.0***	0.84	182

Notes: Regressions are OLS with robust standard errors, clustering by child, age when child first enters the panel, and constant.

Table IV. Random-effect panel linear regression results for annual change in HAZ during 2002-2010 in relation to baseline (2002) stunting, controlling for child, mother, household, and community fixed effects among Tsimane' children 2≤age≤7 at baseline but no more than 11 years old by 2010.

Explanatory variables	Dependent variable: year-to-year change in height z score (HAZ)	
	Girls	Boys
I. Baseline stunting		
Stunted	0.13*	0.21**
Marginally-stunted	0.07	0.10**
II. Child		
Birth order	0.01	0.02
Lagged weight	-0.01	-0.01
Baseline Age	0.003	-0.014
Dry-season birth	0.009	0.05*
Survival	0.001	0.008
III. Mother:		
Age	-0.001	0.003
Schooling	0.006	-0.007
Current height	0.006	0.003
Current weight	-0.002	-0.002
IV. Household:		
No. of children	-0.01	-0.01
Current income	-0.001	-0.008
Current wealth	-0.02	-0.003
Forest clearance	0.04	-0.01
V. Constant	-0.65	-0.41
R^2 overall	0.03	0.05
R^2 between	0.17	0.14
R^2 within	0.01	0.01
N	769	789

Notes: For definition of variables see Appendix 1. Regressions include clustering by child, village fixed-effects, and robust standard errors, and also includes a variable for the number of times the child was measured. In section I, the excluded category is children with HAZ>-1. *p≤0.05, **≤0.01

Figure captions

Figure 1. Mean height (cm) for Tsimane' children, 2 < age < 7 at baseline [2002] and no more than age 11 by 2010, measured annually.

Note: Sample excludes children > 11 years of age

Figure 2. Mean annual change in height for Tsimane' children, 2 < age < 7 at baseline (2002) and no more than age 11 by 2010, measured annually

Notes: * Annual change in cm = (average height at end-line – average height in 2002) / number of years in between. ** Annual change in % = ln (average height at end-line / average height in 2002) / number of years in between. The sample excludes children > 11 years of age.

Figure 3. Total change in HAZ (z-score) for Tsimane' children, 2 < age < 7 at baseline (2002) and no more than age 11 by 2010, remeasured at end-line

Notes: For some age brackets, change is very small and not visually noticeable through the bar graphs. The sample excludes children > 11 years of age.

Figure 4. Changes in height category among Tsimane' children 2-7 years at baseline (2002) and end-line (2010) or age 11, whichever came first

Figure 5. Intra-subject changes in height categories between annual surveys for children 2-7 years at baseline (2002) and no more than 11 years of age by 2010

Figure 6. Height deficit of Tsimane children, age 2 and 11, compared with age and sex peers of international reference groups: Deficit expressed as percent of the height of reference group

Notes: See Appendix B for methods and further results.