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Original Research Article

Short but Catching Up: Statural Growth Among Native Amazonian Bolivian Children

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ABSTRACT The ubiquity and consequences of childhood growth stunting (<-2 SD in height-for-age Z score, HAZ) in rural areas of low-income nations has galvanized research into the reversibility of stunting, but the shortage of panel data has hindered progress. Using panel data from a native Amazonian society of foragers-farmers in Bolivia (Tsimane'), we estimate rates of catch-up growth for stunted children. One hundred forty-six girls and 158 boys $2 \leq \text{age} \leq 7$ were measured annually during 2002–2006. Annual Δ height in cm and in HAZ were regressed separately against baseline stunting and control variables related to attributes of the child, mother, household, and village. Children stunted at baseline had catch-up growth rates 0.11 SD/year higher than their nonstunted age and sex peers, with a higher rate among children farther from towns. The rate of catch up did not differ by the child's sex. A 10% rise in household income and an additional younger sibling lowered by 0.16 SD/year and 0.53 SD/year the rate of growth. Results were weaker when measuring Δ height in cm rather than in HAZ. Possible reasons for catch-up growth include (a) omitted variable bias, (b) parental reallocation of resources to redress growth faltering, particularly if parents perceive the benefits of redressing growth faltering for child school achievement, and (c) developmental plasticity during this period when growth rates are most rapid and linear growth trajectories have not yet canalized. Am. J. Hum. Biol. 22:336–347, 2010. © 2009 Wiley-Liss, Inc.

Childhood growth stunting—or being two standard deviations (SD) below the median height of one's age and sex peers in the USA—is widespread in rural areas of low-income nations, with recent estimates suggesting that as many as 147 million children are growth stunted (de Onis et al., 2000; Engle et al., 2007; Grantham-McGregor et al., 2007; Ricci et al., 2006; Walker et al., 2007a). Childhood growth stunting is a concern in public health because childhood growth stunting is associated with poorer cognitive performance (Pollitt et al., 1995) and with higher morbidity (Fernald and Neufeld, 2007; Hoffman et al., 2000, 2007; Schroeder et al., 1999; Victora et al., 2001; Walker et al., 2001) and because stunted children might end up as stunted adults (Coly et al., 2006; Haas et al., 1995; Liu et al., 2000). Because adult height bears a positive association with many indictors of adult well-being, such as occupation, income, wages, and longevity (Bogin and Keep, 1999; Case and Paxson, 2006; Komlos, 1994; Pollitt et al., 1995; Steckel and Rose, 2002), estimating rates of catch-up growth and identifying their determinants matter not just for the well-being of children, but also for their well-being in adulthood and old age.

As several researchers have noted (Baker et al., 2009; Lampl and Thompson, 2007; Simondon et al., 1998; Walker et al., 2007b), empirical studies of catch-up growth in rural areas of low-income nations are rare owing to the paucity of panel data (Adair, 1999; Cameron et al., 2005a; Martorell et al., 1994a). So far, researchers have found mixed evidence for catch-up growth. Some researchers have found that stunting (particularly among children $\leq$ age 2) is irreversible (Cameron et al., 2005b; Gray et al., 2008; Kalanda et al., 2005; Leonard et al., 1995; Martorell et al., 1994b); once short, always short. However, other researchers have found evidence for catch-up growth (Adair, 1999; Cameron et al., 2005a; Khatun et al., 2004; Simondon et al., 1998).

In a recent article in this journal, Cameron et al. (2005a) argued that the use of year-to-year Δ in height-for-age Z score (hereafter height Z score or simply Z score) provides more precise and meaningful estimates of catch-up growth rates than do estimates based on year-to-year Δ in raw values of physical stature (e.g., cm). Estimates of height Δ based on raw measures vary with age and depend on the ratio of height SD at baseline and follow up. The use of raw measures makes it hard to separate growth rate proper from regression to the mean. Z scores allow one to control for large differences in absolute growth rates over different ages (Baumgartner et al., 1986; Tanner and Davies, 1985). Further, estimates of growth rates based on raw measures leave unanswered how growth rates in one locality compare with the growth rate of a control group. Cameron et al. go on to argue that

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one possible reason for the weak evidence of catch-up growth might reflect the use of raw measures of height to estimate growth rates. For instance, the study in the Philippines (Adair, 1999) used *Z* scores and found evidence of catch up growth, but the study in rural Guatemala (Martorell et al., 1994b) used raw measures of height and did not find evidence of catch-up growth. The existence of catch-up growth likely reflects not just how one measures the rate of change in height, but also the easing of socioeconomic constraints that initially restricted child growth (Martorell et al., 1994b).

The purpose of this study is to contribute to the empirical literature on the existence and possible causes of catch-up growth in rural areas of low-income nations by using a new panel dataset consisting of five consecutive annual anthropometric measures and socioeconomic surveys done during 2002–2006 in a society of foragers and farmers in the Bolivian Amazon (Tsimane'). We aim to achieve three goals.

First, we estimate year-to-year Δ in the standing physical stature of children who were $2 \leq \text{age} \leq 7$ at baseline (2002) and who were followed annually over the next five consecutive years. Second, we estimate growth rates using both raw measures of height and height *Z* scores to ensure that the main conclusions about catch-up growth do not hinge on how one defines growth. Third, we test hypotheses (described later) about determinants and patterns of catch-up growth.

In particular, we test the hypothesis that in a traditional, highly endogamous rural society with high rates of time preference or impatience (Godoy et al., 2004; Kirby et al., 2002) in which adult height confers few advantages and in which adult stunting imposes few private costs on canonical indicators of socioeconomic well-being, we should see little evidence of catch-up growth. In such a setting, parents will not likely perceive now the future benefits of currently redressing growth faltering for their children. Studies have shown cross-cultural variability in how parents view child growth and appropriate size, and whether stunting might be a problem worth correcting (Jahn and Aslam, 1995; Reifsnider et al., 2000; for a review, see Lucas et al., 2007); in some cases, parents may perceive stunting as hereditary and therefore beyond their control (Reifsnider et al., 2000). As societies and economies modernize, people will likely perceive the height premium and stunting penalties as more important in part because in industrial societies height correlates positively with many desirable indicators of adult well being.

Thus, modernization should be associated with less growth faltering chiefly because it will do one or more of the following: (a) change parental values about child growth, (b) result in better dietary intake and reduce the burden of infectious disease, and (c) enhance parental understanding of the link between diet, health, and child growth from public health campaigns in industrial societies. The hypothesis is consistent with the prevailing view in public health that child growth faltering reflects poor socioeconomic conditions (Engle et al., 2007), but adds parental values and expectations about the future as a mediating path.

We define "catch-up growth" as the difference in the year-to-year Δ in height or growth rate in height between children who were stunted at baseline and children who were not stunted at baseline. If stunted children exhibit a higher growth velocity, then they should be catching up to the reference group, though it is an open question how many years would have to elapse before stunted children could catch up; it is possible that with a low rate of growth, stunted children might never catch up by the end of the growth period. The improvements in growth status evaluated in this study do not reach the clinical definition of significant catch up growth, defined as a change in *Z*-score of 0.67 within the first 2 years of life (Ong et al., 2000). Nor do these conditions meet the designation of Cameron's (2007) "unexpectedly rapid catch-up growth," which implies a mismatch between exhibited growth and genetic potential. Rather, here we explore the potential for recovery from stunting under conditions of chronic infection and marginal nutrition, a situation that is less easily interpreted, but may represent more common scenario in low-income nations or in those populations at the earliest stages of transition to a market economy.

HYPOTHESES AND THEIR RATIONALE

Hypothesis 1

Catch-up growth until the age of 10 will not likely take place in this population because prior research among the Tsimane' using cross-sectional data suggests that stunting is widespread throughout the lifecycle (Foster et al., 2005; Godoy et al., 2005) and that it affects 45% of children 2- to 10-years-old (McDade et al., 2007). This hypothesis is in line with our thinking that catch-up growth will most likely take place only when traditional rural societies modernize, a transition that is just beginning to take place among the Tsimane'. Also, the hypothesis fits with the case studies cited in the previous section documenting an absence of catch up growth in rural areas of low-income nations such as Guatemala.

Hypothesis 2

If catch-up growth takes place, it will be more likely to take place in communities nearer to market towns because these communities will be most likely to have access to modern health facilities and to be modernizing.

Hypothesis 3

Catch-up growth rates will be similar for girls and for boys because prior research based on a short panel (~4–5 consecutive quarters, 2002–2003) among the Tsimane' suggests little evidence of girl-boy disparities in a wide range of well-being indicators (Godoy et al., 2006b, 2007b), including parasite infections (Tanner, 2005) and anthropometric measures of short-run and long-run nutritional status (Godoy et al., 2006b).

THE TSIMANE': SETTING AND PRELIMINARY FINDINGS

Setting

The Tsimane' are a native Amazonian society of farmers and foragers in the department of Beni, Bolivia. They number ~8,000 people and have been in sporadic exposure to Westerners since the early 1950s (Huanca, 2008). Like many native Amazonian societies, Tsimane' practice hunting, fishing, plant collection, and slash-and-burn agriculture (Vadez et al., 2004). Tsimane' live in small villages of ~20 households (~6 people/household) and practice preferential cross-cousin marriage. The last five decades have seen the spread of modern health care facilities and a secular decline in adult mortality (Gurven et al., 2007), but no secular change in adult standing physical stature (Godoy et al., 2006a) or in infant and child mortality (Gurven et al., 2007).

In a recent article, we show that during 2002–2006 Tsimane' adults experienced significant improvements in many indicators of well-being (Godoy et al., 2009b). For example, during 2002–2006 Tsimane' adults experienced an annual growth in BMI of 0.71% after controlling for many covariates. During the last year of observation (2006), men and nonpregnant women in the sample had an average BMI of 23.56 and 23.69, respectively. Given these BMI values, higher levels of BMI indicated better short-run nutritional status. The annual growth rate in BMI of 0.71% implies that, if continued and if all else remains constant, in a decade, on average, Tsimane' men will have a BMI of 25.29 and Tsimane' women will have a BMI of 25.43, near the upper limit of the range of recent recommendations of a healthy BMI (Brabec et al., 2007). On the negative side, the years 2002–2006 saw an increase in the self-reported number of ailments during the 2 weeks before the day of the interview (+7.35%/year). The most common ailments include gastrointestinal and respiratory infections, particularly parasitic infections (Byron 2003; Tanner, 2005).

Preliminary findings from research in progress

The most important published findings from our research that bear directly on this article include: (a) like other native Amazonian societies (Blackwell et al., 2009; Godoy et al., 2005). Tsimane' have high rates of childhood growth stunting (Foster et al., 2005; McDade et al., 2007), owing partly to the pervasiveness of parasite infections and immune activation (McDade et al., 2005; Tanner, 2005), (b) no strong evidence of disparities in anthropometric indicators of short-run or long-run nutritional status, perceived health, or modern human capital between girls and boys 2–13 years of age (Godoy et al., 2006b), (c) positive but weak associations between local knowledge of plants and the health of children or adults (McDade et al., 2007; Reyes-García et al., 2007b), (d) high levels of economic self-sufficiency (Godoy et al., 2007a) yet some variation in market exposure, and (e) responsiveness of adult and child height to weather perturbations that took place during gestation or during the first years of life (Godoy et al., 2008a,b).

MATERIALS AND VARIABLES

Materials

We use a panel composed of five consecutive years of annual observations (2002–2006). The panel follows 962 females and 1,033 males of all ages from all households (n = 331) in 13 Tsimane' villages (Leonard and Godoy, 2008) (The complete data and its documentation, along with publications from the Tsimane' Amazonian Panel Study (TAPS) project, are available for public use at the following address: http://people.brandeis.edu/~rgodoy/). We spent 1995–2001 doing background studies among the Tsimane' to identify villages for the panel study, to gain the trust of study participants, and to refine methods of data collection.

We selected the 13 villages to capture geographic variation in closeness to the market town of San Borja (mean = 25.96 km; SD = 16.70), the only town along the Maniqui River. In capturing variation in distance to the market town we tried to capture variation in market exposure or modernization, which likely affects the growth rate of child height (Hypothesis no. 2).

The 13 villages of the panel study are representative of other Tsimane' villages in child height. In 2000, as part of the background studies, we conducted research in 59 Tsimane' villages and took anthropometric measures of children; the 13 villages of the current panel study formed part of the 59 villages surveyed in 2000. Using data from the 2000 survey, we computed the height Z score using the norms from the National Center for Health Statistics (NCHS), USA (Hamill et al., 1979), for children in the 13 villages of the panel study (n = 88) and for children in the other 46 villages (n = 377). Children in the 13 villages of the panel study had an average height Z score of −1.79 (SD = 1.53), compared with the children in the other villages, who had a height Z score of −1.63 (SD = 1.78). A two-sided t-test for the equality of the two means produced a t-statistic of 0.79 (P = 0.42).

The panel includes 1,995 people, but the sample used here contains individual and household-level data for 146 girls and 158 boys $2 \leq \text{age} \leq 7$ during the baseline year (2002). When tracked over five consecutive years, these children were between 7 and 12 years old at the end of the study period (2006). We limit the analysis to children who were at least 2 years of age at the start of the study and no more than 12 years of age by the end of the 5 years of observation to ensure that puberty did not affect the estimates of growth rates in height. Byron (2003) found that Tsimane' girls reach menarche by 12–13 years of age, so limiting the study to children before they reached puberty allows us to obtain more precise estimates of catch-up growth for these young children. One problem with the upper age bracket chosen has to do with the timing of premenarche height velocity. If Tsimane' girls reach menarche by the age of 12–13, then their peak height velocity will likely take between 10–12 and 11–13 years of age. Furthermore, in additional analysis, we show that excluding girls aged 10–12 years affects the estimates of annual growth rates. Thus, to address these concerns, we also estimate catch-up growth rates for children below 10 years of age.

Of the 304 children $2 \leq \text{age} \leq 7$ measured at baseline, 72.37% were present during all five surveys. About 7% (6.25%) were present during only the first survey, 6.25% were present during only two surveys, 2.63% were present during only three surveys, and 12.50% were present during four surveys. In the sensitivity analysis, we control for attrition bias by adding the variable count or the number of surveys in which the child was present to the main regressions. If attrition is systematic and related to both the growth rate and to baseline stunting, then the addition of the *count* variable should change the parameter estimate of the variable for baseline stunting.

We collected annual data during visits to the village lasting 5–7 consecutive days. We reserved most of those days for interviews, but we also set aside 1 day to take anthropometric measures from all study participants in the village school. Interviews lasted about 1 h/adult and usually took place in the home of the participant. Reported information about children came from the child's principal caretaker (typically the mother). Four Bolivian university graduates conducted the surveys and took anthropometric measures and four Tsimane' who worked in the panel study from its inception served as translators.

Variables: height and age

We used the protocol of Lohman et al. (1988) to measure height. We recorded standing physical stature (cm) to the nearest millimeter using a portable stadiometer.

We found evidence of rounding error or digit heaping in height measures. Rounding error is a type of random measurement error because some measures will be rounded up and other measures will be rounded down. If measured accurately, the last digits of measured height should have been evenly distributed among the 10 digits. That is, ~10% of the last digits should have been zeros, another 10% should have been ones, and so on. Instead, measures of height ending in the digit zero accounted for 20.44% of observations among girls and for 17.80% of observations among boys. We did not correct for digit heaping to retain fidelity to the raw data, but later discuss the consequences of random measurement error for the inferences made about the rate of growth.

We asked the child's principal caretaker to report the age of the child each year of the survey. Some parents had birth certificates or reported the exact child's birth date, but other parents did not know the exact birth date and estimated (or guessed) the age in years.

We used the age and height data to estimate age and sex-standardized height Z scores following NCHS standards (Hamill et al., 1979; WHO, 1995). We use NCHS standards rather than the WHO growth standard because the latter apply only to children <5 years of age; beyond 5 years of age, the recommendations are to continue to rely on the NCHS data that we use.

Control variables

Multivariable models of child statural growth control for three broad related vectors of variables: (1) child attributes, (2) maternal attributes, including conditions before and during pregnancy, and (3) household and community socioeconomic and demographic attributes at baseline and during the period of child growth. In the regression analysis we condition for these three vectors of variables, described next.

Child attributes. These include variables such as sex, age, birth date (Fernald and Neufeld, 2007), birth season (Kalanda et al., 2005; Prentice and Cole, 1994), birth order (Adair, 1999; Baker et al., 2009), morbidity (Martorell et al., 1995; Stein et al., 2004), and lagged weight (Eckhardt et al., 2005; Maleta et al., 2003). We do not have data on birth order proper. Rather, we estimate the child's age rank among the children living in the household.

Maternal attributes. These include variables such as current age (Baker et al., 2009; Eckhardt et al., 2005; Fernald and Neufeld, 2007), schooling (Fernald and Neufeld, 2007; Grantham-McGregor et al., 2007; Kalanda et al., 2005; McDade et al., 2007), morbidity (Kalanda et al., 2005), and frequency of stress and stress-related behaviors (Grantham-McGregor et al., 2007; Gray et al., 2008).

Households and communities. Child growth responds to household demographics (e.g., number of children or younger children (Adair, 1999) and total household size (Fernald and Neufeld, 2007)), levels and changes of household income and wealth (Adair, 1999; Grantham-McGregor et al., 2007), price of food and medicines, and dietary intake (particularly proteins and energy-rich foods) (Baker et al., 2009; Eckhardt et al., 2005; Grantham-McGregor et al., 2007; Kain et al., 2005; Leonard et al., 1995, 2000; Stein et al., 2004). We control for community-level variables (e.g., prices) by using a full set of dummy variables for villages ($n = 13 - 1 = 12$). The appendix contains a description of the control variables.

ANALYSIS

The analysis unfolds in two sequential, linked phases. To set the stage, we first provide descriptive and visual analysis of growth in height for each sex separately. Second, we estimate the effects of baseline stunting on growth rates using panel linear multiple regressions with individual random effects, clustering by child, and with robust standard errors. The regression includes year-to-year Δ in HAZ as an outcome; as explanatory variables we include baseline stunting measured as a dichotomous variable and all the covariates described in the previous section. We ran five different types of regressions, each with and without a full set of village dummy variables: (I) only baseline stunting, (II) child attributes added to (I), (III) mother's attributes added to (I), (IV) household socioeconomic attributes added to (I), and (V) a full model with baseline stunting and attributes of the child, mother, and household (II–IV). For the statistical analysis we used Stata for Windows, version 10 (Stata Corporation, College Station, TX).

RESULTS

Descriptive analysis

Figure 1 and Table 1 suggest three points: (a) girls and boys resembled each other in height at baseline, (b) girls grew at slightly higher rates than boys, and (c) girls and boys by 2006 had gained about the same height.

At baseline (Table 1, column "2002, A"), girls and boys of the same age had similar heights. The last two columns of Table 1 suggest that during 2002–2006, girls had slightly higher annual growth rates in height than boys. Two-sided t-test of growth rates by the child's sex suggests that girls grew by 5.51 cm/year in height (SD = 2.26) while boys grew by 5.13 cm/year in height (SD = 2.26); the difference in favor of girls (0.37 cm/year), though small, was statistically significant ($t = 2.53$, $P = 0.011$). Expressed as a %Δ/year, girls grew by 5.24%/year (SD = 0.23) while boys grew by 4.85%/year (SD = 0.23; $t = 2.48$, $P = 0.013$). (The growth rates in cm/year and %/year reported in this paragraph differ slightly from the growth rates in Table 1 because the growth rates reported in the paragraph are based on the pooled sample in a two-sided t-test).

In Table 1, the column "total cm" suggests that by the end of the 5 years, girls and boys had gained, on average, about the same height. Depending on the age at baseline, during 2002–2006 girls had gained a total of 21.4 cm (range: 19–24, SD = 3.7) when compared with boys who had gained 21.0 cm (range: 18–25, SD = 3.6).

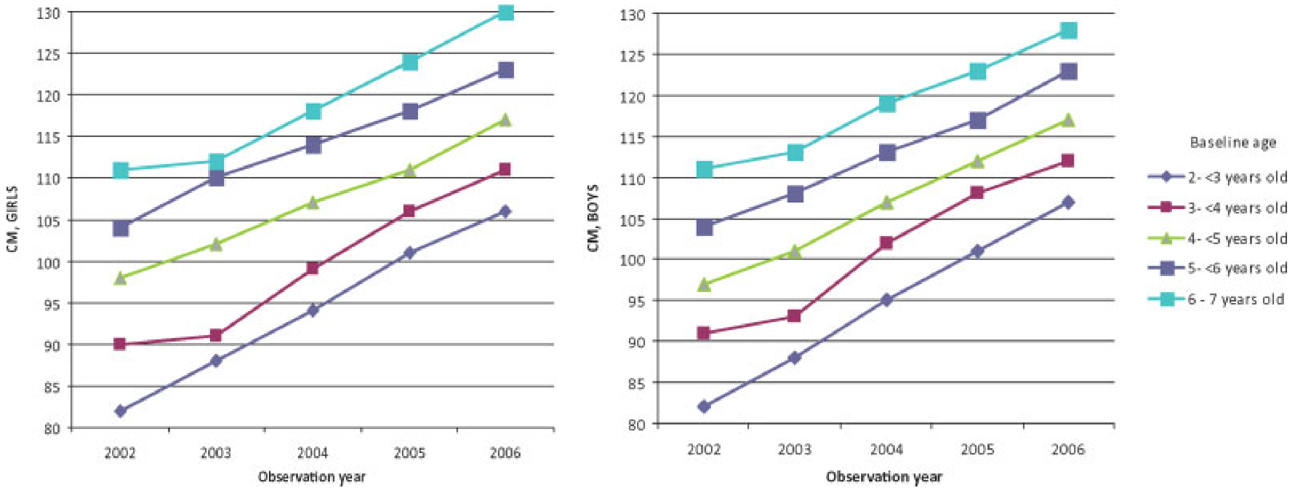

Fig. 1. Mean height (cm) for Tsimane' girls and boys, 2 ≤ age ≤ 7 at baseline, 2002, measured annually during 2002–2006. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

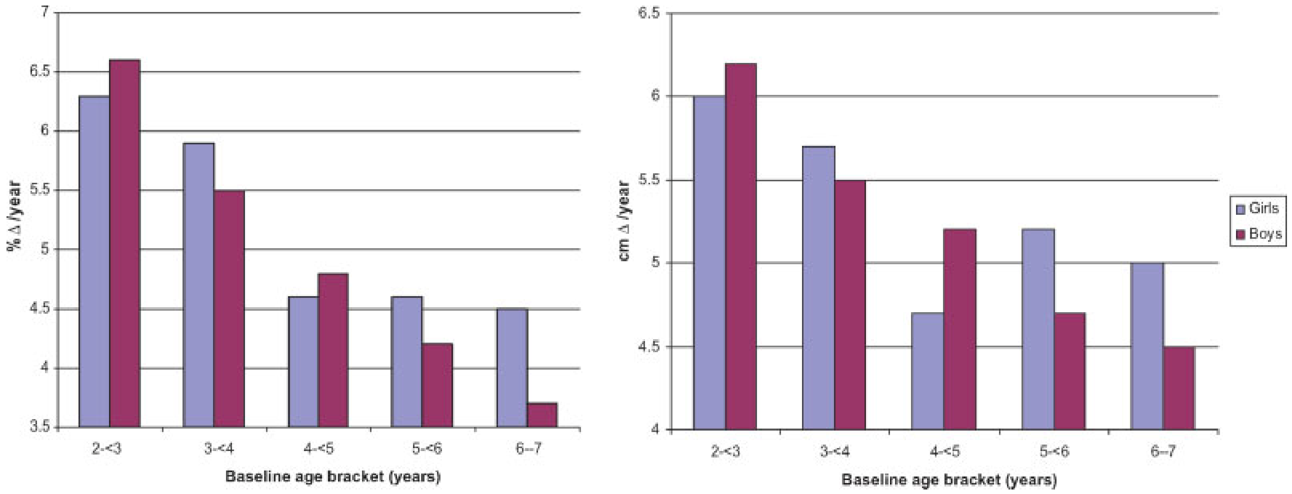

Fig. 2. Annual change in height during 2002–2006 for Tsimane' children, 2 ≤ age ≤ 7, at baseline, 2002, measured annually during 2002–2006. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

Figure 2 and the last two columns of Table 1 ("Annual Δ") suggest that growth rates were highest for the youngest (and also shortest) children. Growth rates declined with baseline age, from 6.0–6.2 cm/year or 6.3–6.6%/year among children who were 2 years of age at baseline to 4.5–5.0 cm/year or 3.7–4.5%/year among children who were 6 years of age at baseline. A random-effect linear panel regression (not shown) with Δ cm in height as an outcome and age as an explanatory variable suggests that over the 5 years of observations, each additional year of age was associated with a decline in the growth rate of height of 0.06 cm/year ($z = 1.71$, $P = 0.088$), equivalent to 0.33%/year. The velocities at this stage of development are age-dependent, but compare well with reference data from the USA (Baumgartner et al., 1986; Tanner and Davies, 1985)

Table 2 and Figure 3 show year-by-year Δ in height Z scores for the entire sample and for stunted and for nonstunted girls and boys separately. Relative to their peers in the USA, Tsimane' girls and boys converged to the USA norm, but, at least for the pooled sample, the rate of catch-up was low. The column "Total HAZ" suggests that the total change in height Z score between 2002 and 2006 for girls and for boys was for the most part positive, but small. Between 2002 and 2006, the average Tsimane' girl got closer in height to her same-age and same-sex peers in the USA by 0.02 SD in height Z score, while the average boy got closer to his same-age peers in the USA by 0.03 SD in height Z score.

The change in height Z score between 2002 and 2006 was larger among stunted children than among nonstunted children. Table 2 (column "Total HAZ") suggests that whereas stunted girls and boys converged to the USA norms or gained, on average, a total of 0.49 SD (girls) and 0.45 SD (boys) in height Z score during 2002–2006, nonstunted girls and boys diverged from USA norms. Nonstunted girls lost a total of 0.35 SD and non-

TABLE 1. *Height status and year-by-year height increments (cm) during 2002–2006 for Tsimane' girls and boys, 2 ≤ age ≤ 7 at baseline, 2002*[a]

		Height in cm during:																		Δ average height, 2002–2006		
Age in 2002	Sex	2002[c]				2003				2004				2005				2006				Total cm, 2006 minus 2002[b]	Annual Δ	
		N	M	A	SD	N	M	A	SD	N	M	A	SD	N	M	A	SD	N	M	A	SD		cm	%[d]
2	Girls	38	82	83	5.1	25	88	88	4.0	30	94	95	4.6	32	101	101	4.9	30	106	107	3.3	24	6.0	6.3
	Boys	32	82	82	4.9	22	88	87	4.8	29	95	94	4.5	27	101	101	4.6	26	107	107	4.9	25	6.2	6.6
3	Girls	25	90	88	4.7	18	91	92	4.4	21	99	100	3.3	21	106	105	3.4	19	111	111	3.3	23	5.7	5.9
	Boys	36	91	91	6.6	29	93	95	6.4	25	102	103	5.9	28	108	108	5.1	27	112	113	6.3	22	5.5	5.5
4	Girls	35	98	97	6.4	28	102	102	5.5	29	107	106	6.4	29	111	111	6.3	28	117	116	6.2	19	4.7	4.6
	Boys	34	97	98	5.7	25	101	102	6.6	28	107	108	5.3	30	112	113	5.6	28	117	119	5.2	21	5.2	4.8
5	Girls	21	104	103	6.0	15	110	108	5.2	18	114	114	5.6	20	119	118	6.2	19	123	124	7.2	21	5.2	4.6
	Boys	21	104	104	4.8	19	108	108	4.5	16	113	113	4.2	16	118	117	4.7	16	123	123	4.4	19	4.7	4.2
6	Girls	27	111	111	9.4	20	112	113	8.2	23	118	119	7.3	24	124	125	8.0	24	130	131	10	20	5.0	4.5
	Boys	35	111	109	8.3	29	113	113	7.2	30	119	118	7.4	32	123	123	7.5	29	128	127	8.2	18	4.5	3.7
Tot[e]	Girls	146	94	95	12.2	106	99	100	10.8	121	105	106	10.5	126	111	111	10.4	120	115	117	11.0	21	5.5	5.1
	Boys	158	96	96	11.6	124	101	101	10.9	128	107	107	10.3	133	111	112	9.5	126	117	118	9.6	21	5.2	5.0

[a] All values are truncated.
[b] Total cm, 2006 minus 2002, computed as the difference between the child's average height in 2006 minus the average height in 2002.
[c] N, sample size; M, median; A, average (mean); SD, standard deviation.
[d] % growth rate/year were estimated through random-effects regression, where log height was regressed against observation year.
[e] Tot, total for all age brackets.

stunted boys lost a total 0.61 SD in height Z score relative to their same sex and age peers in the USA during 2002–2006. A bivariate individual random-effect regression (not shown) of Δ height (outcome variable) against baseline stunting with clustering by child and with robust standard errors supports the idea that stunted children had higher rates of statural growth than their nonstunted peers, with stronger results if one estimates Δ in height Z scores rather than in raw or in log-transformed measures of height. Those regression results suggest that, compared with their non-stunted peers, children stunted at baseline grew, on average, by 0.17 cm/year ($P = 0.17$), 0.65%/year ($P = 0.001$), or by 0.18 SD/year ($P = 0.001$) more.

If we examine the last column of Table 2 we see that catch-up growth was more marked among girls than among boys. For example, 25% of the girls who had been stunted at baseline were no longer stunted at follow-up, whereas among boys the comparable figure was only 13%.

To examine the robustness of the results just described and to compare our results with those of Cameron et al. (2005a), we estimated pair-wise correlations between baseline height and Δ height (height in 2006 minus height in 2002), each measured both in cm and in Z scores. Like Cameron et al., we found more significant results when using annual Δ in height Z scores than when using annual Δ in raw measures of height. We found negative correlations between baseline height and Δ height, suggesting catch-up growth. The correlations were −0.77 ($P = 0.001$) with height Z score and −0.51 ($P = 0.010$) with height measured in cm.

Main regression results

Table 3 contains the main regression results and three noteworthy findings.

First, the regression results confirm the results of the graphical and descriptive analysis just presented about catch-up growth. If we examine row I ("baseline stunting") for the full model (column V) we see that children who had been stunted at baseline moved closer to the norms of their same-sex and age peers in the USA by +0.11 SD/year. The magnitude of the effect shrinks as we move from left (e.g., column I) to right (column V), or as we control for the role of third variables. For instance, a naive estimate of growth rate (outcome variable) against baseline stunting without any covariates (column I) would suggest a convergence rate of +0.18 SD/year (column IA) or +0.20 SD/year (column IB) for stunted children. After conditioning for third variables, these estimates fall to +0.11 SD/year (columns VA and VB).

Second, among child attributes (row II) we found that birth order bore a significant positive association with the rate of growth but the number of younger sibling bore a significant negative association with catch-up growth. The presence of each additional younger sibling in the family lowered the rate of growth by 0.26 SD/year (column IIA) or by 0.29 SD/year (column IIB). An increase in the child's birth order (e.g., being first-born child compared with being a second-born child) was associated with an increase in the rate of growth of 0.26 SD/year (column IIA) or 0.29 SD/year (column IIB).

Third, the most complete model, (column VB), with controls for child, maternal, and household socioeconomic attributes, and village fixed effects makes sharper the

TABLE 2. Mean height-for-age Z score (HAZ) and Δ HAZ during 2002–2006 for Tsimane' girls and boys, 2 ≤ age ≤ 7 at baseline, measured annually during 2002–2006, by baseline stunting[a]

		Mean height-for-age Z score (HAZ) during:															Δ in mean HAZ, 2002-2006			
		2002[c]			2003			2004			2005			2006			Total HAZ, 2006 minus 2002[b]			% stunted at baseline, but not in 2006
Age in 2002:	Sex	T	S	NS	T	S	NS	T	S	NS	T	S	NS	T	S	NS	T	S	NS	%
2	Girls	−1.65	−2.62	−0.59	−1.52	−2.42	−1.18	−1.93	−2.53	−1.29	−1.83	−2.27	−1.34	−1.64	−2.08	−1.04	0.01	0.54	−0.45	21
	Boys	−2.01	−2.92	−0.84	−2.28	−2.74	−1.72	−2.07	−2.49	−1.43	−2.00	−2.40	−1.45	−2.04	−2.43	−1.54	−0.03	0.49	−0.70	28
3	Girls	−2.13	−2.92	−1.12	−2.33	−2.82	−1.34	−1.92	−2.30	−1.29	−1.88	−2.22	−1.32	−1.75	−2.06	−1.32	0.38	0.86	−0.20	45
	Boys	−1.73	−3.13	−0.48	−1.80	−2.86	−0.81	−1.67	−2.71	−0.98	−1.79	−2.57	−1.20	−1.74	−2.71	−0.96	−0.01	0.42	−0.48	0
4	Girls	−1.67	−2.79	−0.73	−1.68	−2.45	−0.83	−1.89	−2.59	−1.11	−1.87	−2.43	−1.25	−1.81	−2.47	−1.14	−0.14	0.32	−0.41	28
	Boys	−1.71	−2.94	−0.73	−1.95	−3.13	−0.97	−1.82	−2.70	−1.04	−1.75	−2.62	−0.99	−1.64	−2.47	−0.94	0.07	0.47	−0.21	7
5	Girls	−1.35	−2.92	−0.57	−1.23	−2.68	−0.76	−1.10	−2.33	−0.67	−1.26	−2.40	−0.71	−1.19	−2.31	−0.59	0.16	0.61	−0.02	28
	Boys	−1.75	−2.74	−0.86	−1.92	−2.71	−1.05	−1.84	−2.57	−1.22	−1.94	−2.63	−1.25	−1.57	−2.39	−1.24	0.18	0.35	−0.38	28
6	Girls	−1.15	−2.83	−0.16	−1.46	−2.55	−0.78	−1.28	−2.53	−0.83	−1.22	−2.40	−0.67	−1.19	−2.6	−0.39	−0.04	0.23	−0.23	0
	Boys	−1.97	−3.48	−0.84	−2.01	−3.12	−1.22	−1.91	−3.13	−1.09	−1.97	−3.09	−1.20	−1.90	−2.97	−1.03	−0.07	0.51	−0.19	7
Tot[d]	Girls	−1.60	−2.78	−0.60	−1.71	−2.57	−0.95	−1.71	−2.48	−1.03	−1.66	−2.34	−1.05	−1.58	−2.29	−0.95	0.02	0.49	−0.35	25
	Boys	−1.84	−3.06	−0.73	−1.99	−2.92	−1.12	−1.85	−2.71	−1.13	−1.88	−2.66	−1.20	−1.81	−2.61	−1.12	0.03	0.45	−0.61	13

[a] All values are truncated

[b] Total HAZ, 2006 minus 2002, is the difference between the average HAZ for 2006 minus the average HAZ for 2002.

[c] T, total (stunted + not stunted); S, stunted (HAZ< –2) at baseline; NS, not stunted at baseline (≥−2 HAZ).

[d] Tot, total for all age brackets.

results discussed so far but also suggests that household monetary income is associated with a lower rate of growth. In the most complete model, we find that stunted children had a growth rate 0.11 SD/year higher than the growth rate of nonstunted children. Higher birth order continued to be positively associated with growth rate, with 0.30–0.55 SD/year higher growth rates for each step up in birth order. Each additional younger child in a household continued to suppress the growth rate in height by 0.27 SD/year (column VA) or by 0.53 SD/year (column VB). Monetary income bore a negative association with child growth rate. Because we express income in natural logarithms, the coefficients of column V imply that a 10% increase in monetary income is associated with a 0.10 SD/year reduction in the growth rate of height. The finding that monetary income bears a negative association with statural growth can probably be explained by changes in monetary expenditures. Elsewhere (Godoy et al., 2007b) we show that as monetary income increases, Tsimane' allocate a greater share of their monetary income to highly visible luxury items that signal individual prosperity and fitness to others in the community. If so, then it is possible that with higher monetary income the share of income allocated to expenditures in nutritious food declines because these expenditures are not visible to others and do not bring prestige.

Sensitivity analysis

To test the robustness of the main results of the most complex model, column VB, we did additional analysis, summarized in Table 4 and discussed next. Unless indicated otherwise, the regressions in Table 4 are identical to the regression of column VB. For ease of comparison, in row 1 of Table 4 we include the estimate of the growth rate of children stunted at baseline from regression VB (Table 3).

We first added a variable (*count*) that captured the number of annual measures taken for a child (range: 1–5) (row 2). We added the variable to assess whether attrition might bias estimates of catch-up growth. The estimate for catch-up growth did not change (0.11 SD/year) after conditioning for the frequency of survey participation. A two-sided t-test of height Z score in 2002 between those who remained for at least two rounds and those who left permanently after the first survey suggest no significant difference in height. During 2002, (pre)-permanent attriters had a height Z score of -1.65 (SD = 1.75) and children who remained for at least two or more surveys had a height Z score of -1.73 (SD = 1.48; $t = 0.324$, $P = 0.745$).

In row 3, we show the results of a regression excluding girls 10 years of age or older at the end of the study (2006) because they may have entered the premenarche growth acceleration phase during the period under study. Excluding these girls lowered the rate of growth to 0.08 SD/year ($P = 0.042$), still positive though slightly lower than the original estimate of 0.11 SD/year.

It is possible that catch-up growth might have reflected favorable but idiosyncratic conditions of particular years. For instance, suppose that some years had enjoyed unusually favorable weather, making it possible to forage and farm more, and to suffer from less sickness. Then, the rate of growth would be affected by idiosyncratic events of particular years. To condition for this confounder, we added a full set of dummy variables for all the years of the panel

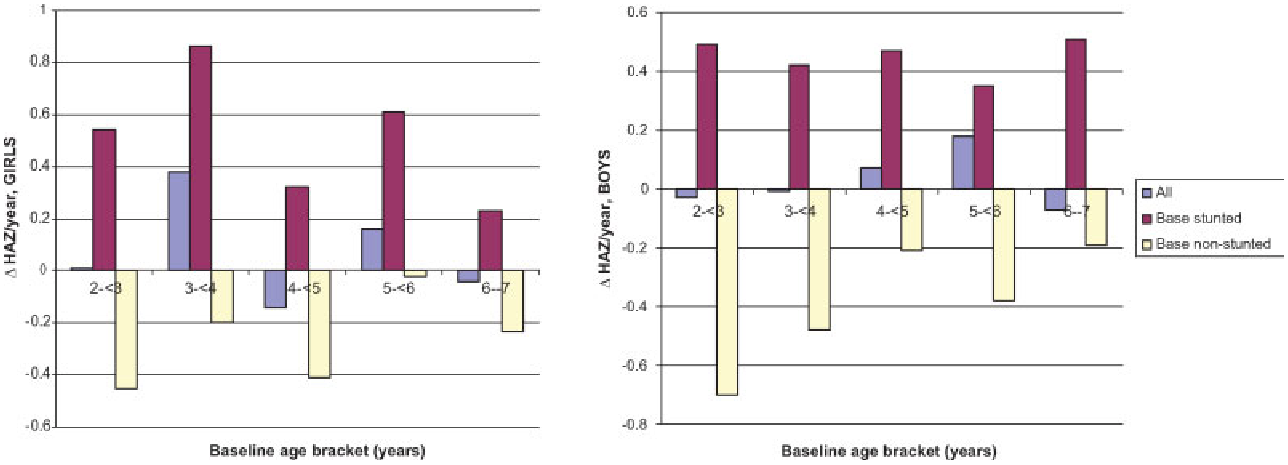

Fig. 3. Total change in HAZ (*z*-score) for Tsimane' girls and boys, $2 \leq$ age ≤ 7 at baseline, 2002, measured annually during 2002–2006. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

TABLE 3. Random-effect panel linear regressions results for growth rate in height 2002–2006 in relation to baseline stunting (2002), adjusted for child, mother, and household and community attributes among Tsimane' children 2–7 years of age at baseline[a]

	Dependent variable: year-to-year Δ in height *Z* score (HAZ)									
	I		II		III		IV		V	
Explanatory variables	A	B	A	B	A	B	A	B	A	B
I. Baseline stunting	0.189**	0.202**	0.094**	0.105**	0.190**	0.190**	0.189**	0.203**	0.116**	0.116**
II. Child:										
Birth order	b	b	0.268**	0.295**	b	b	b	b	0.308**	0.558**
No. of younger siblings	b	b	−0.254**	−0.290*	b	b	b	b	−0.273*	−0.531**
Lagged weight	b	b	−0.015*	−0.012	b	b	b	b	−0.012	−0.007
Age	b	b	0.028	0.027	b	b	b	b	0.019	0.011
Male	b	b	−0.042	−0.081**	b	b	b	b	−0.031	−0.072**
Current illness	b	b	−0.011	−0.024	b	b	b	b	−0.022	−0.029
Dry-season birth	b	b	0.004	0.014	b	b	b	b	0.036	0.041
III. Mother:										
Age	b	b	b	b	−0.001	−0.001	b	b	0.001	0.001
Schooling	b	b	b	b	0.015	0.015	b	b	−0.003	−0.004
Current height	b	b	b	b	0.003	0.001	b	b	0.006*	0.002
Current weight	b	b	b	b	0.002	0.001	b	b	−0.000	−0.000
Current illness	b	b	b	b	0.028	0.020	b	b	0.010	0.002
Laughter	b	b	b	b	0.053	0.074*	b	b	0.003	0.030
IV. Household:										
No. of children	b	b	b	b	b	b	−0.006	−0.008	−0.021	−0.016
Current income	b	b	b	b	b	b	−0.003	−0.005	−0.011**	−0.016**
Current wealth	b	b	b	b	b	b	0.001	−0.003	0.005	0.007
Forest clearance	b	b	b	b	b	b	0.016	−0.007	0.044	0.036
V. Constant	−0.081**	−0.594**	−0.187	−0.222	−0.800*	−0.346	−0.092	−0.597**	−1.256**	−0.991**
Village fixed effect: present	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes
R^2 overall	0.038	0.071	0.028	0.067	0.051	0.075	0.039	0.074	0.057	0.086
N	915		704		869		914		673	

For definition of variables, see appendix.

[a] Regressions include clustering by subject and robust standard errors. $^{*}P \leq 0.05$, $^{**}P \leq 0.01$.

[b] Variable intentionally excluded.

study (with years 2002 and 2003 as the excluded categories) (row 4) and found that the baseline estimate of catch-up growth did not change.

Given the heterogeneity of prices, weather, and ecological conditions across villages and years, we also used a village-year fixed effect model (instead of a simpler village fixed-effect model) and found that the growth rate increased to 0.12 SD/year (row 5).

In row 6, we added a measure of total household practical ethnobotanical knowledge because previous research suggests that parental ethnobotanical knowledge might be associated with better child health (McDade et al., 2007). We found that the growth increased from 0.11SD/year to 0.13 SD/year.

Last, we reestimated catch-up growth using year-to-year Δ of height measured in cm rather than in *Z* scores and still found positive but statistically nonsignificant results (row 7). When defining growth rate in height as the annual Δ of height measured in cm, we found that children who had been stunted at baseline grew by 0.16 cm/year ($P = 0.233$) more than their nonstunted peers, a result consistent with the earlier discussion about less sig-

TABLE 4. Sensitivity analysis of main regression results from Table 3, column VB, and test of hypotheses

	Coefficient of baseline stunting	Description of modification of column VB
1	0.11**	Benchmark regression (Table 3, column VB). H1
Sensitivity analysis of hypothesis #1:		
2	0.11**	Control for # times child present in the study
3	0.08*	Excludes girls 10 more or years of age who may have entered premenarche growth acceleration
4	0.11**	Control for full set of dummy variables for years
5	0.12**	[4]+ full set of dummy variables for community-years
6	0.13**	Control for total household practical ethnobotanical skills
7	0.16 cm/year	Outcome = height Δ cm/year
Hypotheses:		
8a	0.008	Regression VB only for children living nearer to towns. H2
8b	0.21**	Regression VB only for children living far from towns. H2
9a	0.09*	Regression VB only for girls. H3
9b	0.14**	Regression VB only for boys. H3

$^{*}P \leq 0.05$, $^{**}P \leq 0.01$.

nificant evidence for catch-up growth when using raw measures of height rather than *Z* scores of height.

Hypotheses

To test hypothesis no. 1 about the absence of catch-up growth in a traditional society, we examine the row "baseline stunting" in Table 3 and reject the hypothesis because both the main results and the additional analysis presented in Table 4 all suggest positive and significant catch-up growth rates for children stunted at baseline.

To test hypothesis no. 2 about higher rates of catch-up growth among children in communities nearer to market towns, we split the sample into two groups: children who resided in villages in the lowest 25% of the village-to-town distance (i.e., nearer to towns) (row 8a) and children who resided in the top 25% of the village-to-town distance (i.e., farther away from towns) (row 8b). In bivariate analysis not shown we found no significant different in the share of children stunted at baseline between children living in remote and nearby communities ($\chi^2 = 1.34$, $P = 0.246$). Contrary to expectations, we found that children stunted at baseline who lived in more remote locations had higher growth rates (0.21 SD/year, $P = 0.001$) (row 8b) than did children residing in villages nearer to town (0.008 SD/year, $P = 0.891$) (row 8a). A pooled regression (results not shown) for all children with an additional interaction term, near * baseline stunting, showed that stunted children nearer to towns had a rate of growth that was 0.31 SD/year ($P = 0.018$) lower than the rate of growth of children in communities farther away.

Because we control for village fixed effects, the dichotomous dummy variable for proximity to market town likely picks up attributes of the community that change across years, such as incidence of epidemics, changes in prices of food and medicines, and pests and diseases of crops and animals. Unfortunately, we lack the data to identify the aspect of town propinquity that might be implicated in the lower rate of stature growth.

To test hypotheses no. 3 about the absence of a differential effect in catch-up growth between girls and boys, we ran separate regression for girls (row 9a) and for boys (row 9b) and found that boys had higher catch-up growth rates (0.14 SD/year, $P = 0.002$) than girls (0.09 SD/year, $P = 0.019$). Nevertheless, a pooled regression (not shown) similar to the regression in VB (Table 3), but with an additional interaction term, male * baseline stunting, showed that the marginal difference in growth rate in favor of boys was statistically nonsignificant ($P = 0.425$).

These results provide limited support for the widely documented finding that compared with females, males have greater linear growth responses to early improvements in nutrition (Gray and Wolfe, 1980; Greulich, 1951; Kuzawa, 2005, 2007). Fetal restriction models in rats have also demonstrated that males experience greater growth deficits in response to in utero nutritional scarcity than female rodents (Kuzawa and Adair, 2003; Oyhenart et al., 1998). Although these findings suggest that sex-specific differences in Tsimane' catch-up growth may be traced to events occurring during fetal development, we have no measure of events (nutritional status, maternal illness, traumatic events) occurring in utero nor accurate estimations of birth weight in this study to evaluate this pathway.

Finally, among child attributes, we found that birth order bore a significant positive association with the rate of growth but the number of younger sibling bore a significant negative association with catch-up growth. The result is consistent with the findings of Adair (1999) among children in the Philippines. She found that first-borns were also more likely to have catch-up growth. We have no satisfactory answer for the finding. As far as we know, Tsimane' culture does not value first-borns over children born later. However, given the prevalence of eating out of a common pot, it is possible that first-born children get first picks at the food and perhaps get more food than younger sibling. Another possible explanation is that first-borns will have higher growth rate if they had been more likely to be stunted at baseline. We tested for this possibility and did not find supportive evidence. At baseline, each step up in the birth order (e.g., being a first-born rather than being a second-born) was associated was a 13% ($P = 0.001$) lower probability of being stunted at baseline. Another possibility for why the elder children might have higher rates of growth relates to the weakening of maternal health with each subsequent pregnancy and birth. Unfortunately, we do not have data to test this explanation.

LIMITATIONS

Besides omitted variable bias, discussed in the next section, a limitation of this study has to do with insufficient cultural information to explain why and how catch-up growth occurs. For example, we do not have information about parental expectations regarding the benefits or penalties of adult height for their children, nor do we have information on cultural valuation of first-born children versus children born later. Nor do we have information about cultural expectations for the allocation of monetary expenditures, and how culturally constructed patterns of monetary expenditures might influence child nutrition or rates of child growth. We have no data on how parents allocate resources among their stunted and nonstunted children. In short, we lack fine-grained data on the cultural mechanisms that might explain catch-up growth in this population.

DISCUSSION AND CONCLUSIONS

Contrary to expectation, we found evidence of catch-up growth among children who had been stunted at baseline for the pooled sample and among children living in villages farther from market towns. We next try to explain why there might be catch-up growth during prepuberty years; none of the explanations are entirely satisfactory.

Omitted-variable bias

Although we control for a range of covariates that have become standard in studies of catch-up growth, we could not control for other variables that affect both the likelihood of childhood stunting at baseline and the rate of growth. For example, unmeasured attributes of household deprivation or scarcity at baseline would likely be positively associated with baseline stunting and negatively associated with statural growth. The problem with this line of thinking is that the omission of these types of variables produces a negative indirect effect, thereby attenuating rather than increasing the estimated rates of catch-up growth. Conditioning for these types of omitted variables would produce even higher rates of catch-up growth, though other unmeasured variables could positively affect growth rates.

Socioeconomic explanation: parental reallocation of resources

Few studies document whether parents in low-to-middle income countries perceive growth faltering in their children and consequently take steps to redress it. One such study of mothers in Nepal found that they were fairly accurate to recognize stunting and wasting in children less than 3 years old but were less accurate for children aged 3–5 years (Moffat, 2000). This study does not investigate whether the mothers reallocated resources to address "smallness" in their children. In ethnographic open-ended interviews, Tsimane' parents in our study reported using medicinal plants and wild foods to redress growth faltering (reference unavailable; unpublished work in progress). Elsewhere, we show that maternal traditional ecological knowledge is associated with improvements in multiple measures of child health (McDade et al., 2007). Parents' reallocation of resources may also explain the steep rate of growth in more remote communities where presumably one might find a greater abundance of wild and semi-domesticated plants and perhaps a more nutritious diet.

Nevertheless, these explanations face several problems. First, in the regression results shown in rows [5] and [6] of Table 4, we condition for community-year and for community fixed effects and for ethnobotanical knowledge. Community-year and community fixed effects would sweep away the role of variables such as abundance of wildlife and farm resources in the community and the measure of ethnobotanical skills should remove the confounding role of this important form of human capital. Second, taking steps to redress growth faltering is inconsistent with very high rates of time preference, impatience, or myopia we have documented for this population (Godoy et al., 2004; Kirby et al., 2002; Reyes-García et al., 2007a). That is, people who discount the future heavily should be less likely to make long-run investments in their own or in their offspring's growth.

Growing recognition of the costs of growth faltering in academic achievement

Another possible explanation has to do with parents recognizing the importance of formal schooling and with their realization that redressing growth faltering might have academic pay offs for their children. To explore this topic, we examined the academic achievement of children $6 \leq \text{age} \leq 11$ stunted at baseline. We set the lower age limit at 6 years because that is the age when most Tsimane' children enter school. Children stunted at baseline were 10.12% ($P = 0.02$) less likely to be enrolled in school during the survey year and had 0.34 less schooling than their same sex and age peers ($P = 0.017$). The problem with this interpretation is that, if true then we should have found a higher rate of growth in communities nearer to market towns, which presumably have a greater demand for schooling, though it is also possible that the rate of growth would have been lower in communities closer to town without the countervailing effect of formal schooling.

In sum, we found evidence of catch-up growth among children in this traditional society. The higher rates of catch-up among children < 5 are consistent with our expectations, given that the linear growth rate is highest from fetal development through 2–3 years of age, compared with childhood and adolescence (Martorell et al., 1995). During this window, the metabolic allotment for growth accounts for the greatest proportion of a child's overall energy budget at this age (Butte 2005). Therefore, this age group is particularly sensitive to changes in nutrition and insults from infectious disease that may impose constraints on energy available for growth (Gluckman and Pinal, 2003; Scrimshaw, 2003). For the Tsimane', the competing energy demands from immune activation in response to pathogen exposure have been associated with reduced linear growth over the following 3 months in children 2–4 years. This disparity in height is most evident for those children with low energy stores of subcutaneous fat at the time of immunostimulation (McDade et al., 2007). In addition, this age is when positive centile crossing is most plausible, because growth rates are most rapid and linear growth trajectories have not yet canalized. Although recovery from early insults and perturbations in this population underscores the dynamic plasticity of this critical developmental period, the long-term costs associated with catch-up growth have yet to be explored as these individuals reach adulthood (Cameron, 2007, West-Eberhard, 2003).

The panel study in progress with the Tsimane' should allow us to explore these topics in the future, and will facilitate a more nuanced understanding of the downstream health correlates of population facing chronic challenges to growth (Ong et al., 2000). This study also underscores the point that transitions in cultural and economic contexts are not uniform or monolithic, even within a given population. While Tsimane' children exhibit a high prevalence of stunting characteristic of other Amazonian populations, our analyses demonstrates significant individual variation in potential for catch-up growth.

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APPENDIX

TABLE . Definition of control variables used in regressions, children $2 \leq age \leq 7$

Control variables	Definition
I. Child:	
Birth order	Pseudo birth order; 1 = youngest, 2 = next to youngest, etc. Birth order determined by child's age in the 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
No. of younger siblings	Number of younger siblings living in the household
Lagged weight	Weight of subject during previous year
Age	Best estimate of child's age in whole years made by TAPS team
Male	Child's sex: 1, male, 0, female
Current illness	Natural logarithm of total number of self-reported days in bed due to illness during the 14 days before the day of the interview. +1 added to raw values before taking logarithms
Dry-season birth	Subject was born during the dry season (December–June); 1 = yes, 0 = no
II. Mother:	
Age	Best estimate of mother's age in whole years made by TAPS team
Schooling	Mother's maximum school grade achievement
Current height	Measured standing physical stature of child's mother (cm)
Current weight	Mother's weight in kg
Current illness	Natural logarithm of total number of self-reported days in bed due to illness during the 14 days before the day of the interview. +1 added to raw values before taking logarithms
Laughter	Mother laughed during interview; 1 = yes, 0 = no
III. Household:	
No. of children	Number of children in the household
Current income	Natural log of household income earned during the 2 weeks before the day of the interview. Income sources include sales and wage labor
Current wealth	Natural log of sum of wealth of traditional and modern physical assets owned by the 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)
IV. Community	
Village fixed attributes	Full set of dummy variables for villages (n = 13 − 1 = 12)