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Measuring catch-up growth in malnourished populations

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Abstract: Chronic malnutrition during early childhood hinders growth and causes children to fall into a lower growth trajectory. In order to recover, children need to experience growth rates that are above the expected rate for their age. Several studies have analysed the extent of such catch-up growth by regressing adult height on early childhood height. In this paper, I show that these studies confuse catch-up growth with within-population convergence and are further plagued by a well-known statistical fallacy of regression-to-the-mean. This calls for a re-evaluation of the existing evidence. In the empirical part of the paper, I use data from the Philippines and the Kagera region in Tanzania to study catch-up growth. I find limited recovery in the Philippines cohort. In Kagera, almost 75 per cent of the children experience catch-up growth. The mean height-for-age z-score improves from -1.87 in early childhood to -1.20 by adulthood. Graphical analysis reveals that this catch-up growth takes place in puberty.

JEL Classification: I10, I12, J13

Key Words: height, undernutrition, catch-up growth, children, African height puzzle

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1. Introduction

Nutritional needs are extremely high in the first three to five years of life when the body is growing rapidly. Prolonged and severe malnutrition during this period hinders growth and causes children to fall behind their healthy and well-nourished peers (Golden, 1994; Shrimpton et al., 2001). In order to catch-up, the short and stunted children need to experience height velocity that is above the expected rate for their age. Height-for-age z-scores (HAZ) measure the height deficit relative to a healthy and well-nourished reference population. Catch-up growth is measured as the change in HAZ-score over time.

Several researchers have studied the existence of catch-up growth in populations by regressing adult height on early childhood height (e.g. Alderman et al., 2006; Fedorov and Sahn, 2005; Handa and Peterman, 2009; Mani, 2012; Martorell et al., 1992; Outes and Porter, 2012; Victora et al., 2008). In this paper, I show that these tests are uninformative about the extent of catch-up growth. Instead, they measure within-population convergence. Analysing convergence in heights is interesting in its own right as adult height distribution may reflect adult wage distribution in developing countries (Haddad and Bouis, 1991; Steckel, 1995).[1] This convergence occurs if (a) stunted and shorter children catch-up taller children, (b) taller children grow at a slower pace than others or because of some combination of (a) and (b). Only (a) is close to the concept of catch-up growth as defined in the clinical and epidemiological literature. Yet it fails to measure catch-up growth with respect to a healthy and well-nourished external population. Furthermore, regressing adult height on childhood height would not allow researchers to distinguish convergence from (c) natural variation in growth rates: initially taller children grow less rapidly, and *vice versa*. Abstracting away from measurement error, (c) refers to a well-known statistical phenomenon called regression-to-the-mean according to which statistically unusually high or low observations tend to revert to the population mean in a subsequent measurement. [2]

A well-established view in the literature is that catch-up growth after early childhood is difficult and seldom observed (e.g. Grantham-McGregor et al., 2007; Martorell et al., 1994). Given that numerous studies misinterpret convergence as catch-up growth, the evidence supporting this view is not robust. In addition, there are only a handful of data sets that follow children over their entire childhood. Findings from shorter data sets provide incomplete evidence on the extent of catch-up growth. This is particularly worrying if puberty is an important opportunity window for catch-up growth as has been

[1] However, it is not clear whether taller people earn more because they are physically more able or because height is strongly correlated with educational attainment (Glewwe et al., 2001) and cognitive ability (Case and Paxson, 2008).
[2] This point has been raised early on in the economic growth literature studying cross-country convergence in incomes (see Friedman, 1992; Quah, 1993).

suggested by recent literature based on cross-sectional data (Haas and Campirano, 2006; Moradi, 2010).

In the empirical part of the paper, I study catch-up growth using data from the Philippines and Tanzania. Both data sets permit me to analyse height developments over the entire childhood. The Philippines cohort has been used to study catch-up growth in the previous literature and is of a particular interest as it has yielded opposite results depending on the applied methods. The re-analysis in this paper finds limited catch-up growth. The mean HAZ-score[3] improves from -2.09 in early childhood to -1.90 in adulthood.

The analysis of the Tanzanian data provides new evidence for Sub-Saharan Africa – a region where the evidence is particularly thin despite hosting the most malnourished children after South-Asia (de Onis et al., 2012). Using a 19-year panel data for the Kagera region in Tanzania, I find considerable catch-up growth: the mean HAZ-score improves from -1.87 in early childhood to -1.20 in adulthood. Graphical analysis shows that this catch-up growth takes place in puberty. This finding challenges the universality of the conventional view where short and stunted children remain locked into a lower growth trajectory.

2. Human growth

For a healthy and well-nourished population, human growth can be viewed as a relatively uniform process (Boersma and Wit, 1997). Figure 1 shows the velocity of growth at different ages in childhood for a US reference population. The velocity is the highest in the first two years of life, peaking at 25 cm per year in the first year. After that, the speed remains high but falls rapidly until children turn five. During the next five years, children grow at a steady rate of around 6 cm per year. There are no marked differences between gender groups in growth rates until the age of 10. Girls enter puberty earlier but cease to grow earlier than boys. During puberty there is a short but rapid acceleration in growth rates. In reality, there is a considerable individual variation in the timing and intensity of this growth spurt (Boersma and Wit, 1997), but this is not captured in the graph based on average growth rates.

[Figure 1 here]

In general, the growth process is seen as fairly similar across populations until the onset of puberty (Habicht et al., 1974; Martorell et al., 1994). The literature is less conclusive about the growth process during puberty. Haas and Campirano (2006) use cross-country data to compare the growth in puberty across different regions and find considerable differences in growth rates across populations during

[3] I use the US 2000 NCHS/CDC as the reference population in this paper (see section 5 for more details).

adolescence. They cannot, however, fully exclude the possibility that this is due to differences in socioeconomic conditions. [4] However, the fact that there are no significant differences in mean heights between African Americans, non-Hispanic white Americans and Europeans (Eveleth and Tanner, 1976) suggests that the environment (nutrition, disease environment, etc.) plays a larger role than ethnic background in determining *adult height* (Haas and Campirano, 2006; Martorell et al., 1994; Steckel, 1995). Finally, genetics induce variation to the observed individual adult heights. For example, taller parents tend to have taller children. Such variations, however, do not show up in the population means.

Growth faltering in developing countries begins in the first three months of life and persists until the age of two or three (Eveleth and Tanner, 1976; Shrimpton et al., 2001; Victora et al., 2010). This is usually caused by insufficient or poor nutrition or by infectious diseases (Golden, 1994). Given that children are growing rapidly during these years, even a short retarded growth spell during this period quickly leads children to fall behind from their faster growing peers. To bounce back to their original growth curves, short and stunted children need to experience higher growth rates than their healthier peers. This requires that the cause of the retardation is removed (Golden, 1994).

3. The concept of catch-up growth and how to measure it

In the clinical and epidemiological literature, catch-up growth is defined as height velocity that is above the expected for the child's age and occurs after a period of growth retardation (Ashworth and Millward, 1986; Boersma and Wit, 1997; Tanner, 1981; Williams, 1981). A complete catch-up takes place if the original, pre-retardation, growth curve is attained (Ashworth and Millward, 1986; Williams, 1981). The HAZ measures the distance in height to the median child of a healthy and well-nourished population, and therefore provides the exact empirical counterpart for this definition. An increase (decrease) in HAZ means that height velocity is above (below) what is expected for child's age and gender.

Morever, empirical analysis of catch-up growth requires longitudinal surveys where same individuals are followed over their entire childhood. Given the challenges in administering such surveys in developing country settings – where childhood malnutrition is more widespread – it is of no surprise that such surveys are rare. The most influential longitudinal surveys originate from Brazil (Pelotas Birth Cohort Study), Guatemala (The Institute of Nutrition of Central America and Panama Nutrition Trial Cohort Study), India (Delhi birth cohort study), the Philippines (Cebu Longitudinal Health and Nutrition Survey) and Senegal (Niakhar study). All these studies follow children from early childhood to adulthood. In this paper, I introduce a new data set from the remote Kagera region in Tanzania to

[4] The authors try to circumvent this by limiting the analysis only to the healthiest children in each population.

the topic that satisfies the abovementioned conditions. Several studies employ data sets that are shorter and thus do not permit the researchers to observe the final adult height of the children. As these studies are not looking at the entire growth period they are likely to underestimate the extent of catch-up growth in these populations.

Only a few papers have studied the evolution of HAZ-scores over time. In an influential study, Adair (1999) defines catch-up growth as a recovery from stunting [5]. Using the Cebu Longitudinal Health and Nutrition Survey from the Philippines, she finds that the proportion of the stunted children fell from 63 per cent at the age of two years to 50 per cent by the age of 12. Using the NCHS/WHO 1977 growth reference to convert heights into HAZ scores, she finds that the mean HAZ scores improved from -2.41 at the age of two to -1.94 by the age of 12.

A few studies group children according to their degree of stunting in early childhood and compare the height increments from early childhood to adulthood between groups and to an external healthy and well-nourished reference population. Martorell et al. (1990) use data from Guatemala where more than half of the children in the sample were stunted at the age of five. These children did not experience larger height gains than their American peers, if anything the opposite is true. In addition, the authors did not find any marked differences in height increments between shorter and taller Guatemalan children. Satyanarayana et al. (1980) and Satyanarayana et al. (1981) study growth increments using Indian cohorts of boys and girls respectively. They group children according to their severity of stunting and compare the height increments between the age of five and 17 between the groups and to a longitudinal study from Boston. These Indian boys were not found to experience any catch-up growth and also the height gains between the groups were similar (Satyanarayana et al., 1980). The initially most nutritionally deprived girls (HAZ < -4) were found growing considerably faster than the Boston girls and other Indian girls in the same sample (Satyanarayana et al., 1981). This result may however be an outcome of measurement error in initial height leading to incorrect grouping of the children.

Among the few longitudinal studies from sub-Saharan Africa, Coly et al. (2006) follow Senegalese children for nearly two decades and compare their growth rates to the NCHS/WHO 1977 reference. The mean HAZ in early childhood among girls -1.3 and among boys was -1.4. By adulthood these means reduced to -0.41 for girls and -0.58 for boys implying nearly complete catch-up. This widely neglected study also makes a clear distinction between catch-up growth relative to a healthy reference population (global catch-up growth) and relative to other children in the population (local catch-up growth).

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[5] Stunting is defined as height-for-age z-score below two standard deviations from the median of a healthy reference population.

4. The problem(s) with the regression approach

Most of the previous empirical literature (Alderman et al., 2006, Zimbabwe; Fedorov and Sahn, 2005, Russia; Handa and Peterman, 2009, China, South Africa, Nicaragua; Mani, 2012, Indonesia; Martorell et al., 1992, Guatemala; Outes and Porter, 2012, Ethiopia; Victora et al., 2008, Brazil, Guatemala, India, the Philippines, South-Africa) subscribes to the definition of catch-up growth used in the medical literature but employs regression analysis, usually using a following type of specification:

$$h_{it} = \alpha + \beta h_{i,t-1} + e_{it} \,, \tag{1}$$

where α is the intercept and e_{it} the error term. The term h_{it} is height (or height-for-age z-score) of individual i in period t and $h_{i,t-1}$ height (or height-for-age z-score) in a previous period. In studies that have an access to a sufficiently long data set, *t* usually refers to height measured in adulthood and *t-1* to height measured in early childhood. The β coefficient is then interpreted as the measure of catch-up growth. A zero β coefficient on the lagged height is taken as a complete catch-up: initial height does not predict adult height. A coefficient equal to one is interpreted as evidence that no catch-up growth takes place: short or stunted children remain locked into their lower growth trajectory.[6]

There are several problems with this approach. Most importantly, these tests confuse catch-up growth with within-population convergence. The β coefficient would fail to capture a widespread catch-up growth in the population. Such uniform movement of the distribution only affects the estimated constant, not the β coefficient. This is a particular concern if the population under scrutiny is largely malnourished. Another important caveat is introduced by regression-to-the-mean (even in the absence of measurement error). Finding that β<1 may imply convergence (reduction in the dispersion of the height distribution over time) or simply natural variation in growth rates (height distribution remains intact).

Quah (1993) demonstrates this algebraically. The β coefficient depends on the ratio of covariance between the adult height and initial height $cov(y,x)$ and the variance of the initial height $var(y,x)$ where y refers $h_{i,t}$ and x to $h_{i,t-1}$:

$$\beta = \frac{cov(y,x)}{var(x)}. \tag{2}$$

[6] Equation (1) can be transformed into a growth specification by subtracting the lagged height variable from both sides of the equation: $\Delta h_{it} = \alpha_g + \beta_g h_{i,t-1} + v_{it}$. From the transformation it follows that $\beta = \beta_g + 1$, assuming that the relationship between previous and current height is linear (e.g. Fedorov and Sahn, 2005).

We can introduce the Cauchy-Schwarz inequality that states:

$$cov(y,x) \leq \sqrt{var(x)}\sqrt{var(y)}. \tag{3}$$

Now, if there is no convergence or dispersion it follows that:

$$var(y) = var(x). \tag{4}$$

Using this and the Cauchy-Schwarz inequality in Equation (2) gives:

$$\beta \leq \frac{\sqrt{var(x)}\sqrt{var(x)}}{var(x)} = 1. \tag{5}$$

As such, even when imposing constant variance over time, β is smaller than one (the equality in the Cauchy-Schwarz holds only in the degenerate case when x and y are linearly dependent). This is why a coefficient smaller than 1 does not necessarily imply convergence, let alone catch-up growth. It is of no surprise then that most of these studies document partial convergence (i.e. $0<\beta<1$). The β estimates vary between 0.2 (Fedorov and Sahn, 2005) to 0.7 (Martorell et al., 1992).

I demonstrate these issues using the 1970 British Cohort Study (BCS70). [7] I use the height measurements from the age of five and in adulthood. [8] Table A1 of Appendix A contains the descriptive statistics for the final sample of 9,635 individuals.

The BCS70 represents a healthy and well-nourished population. By default, this cohort does not contain malnourished children and therefore I should not find any catch-up growth. Figure 2 provides the distribution of the children's HAZ scores in early childhood and adulthood. The means lie close to zero in both periods and the distributions are virtually on top of each other.

[Figure 2 here]

I then estimate Equation (1) using height-for-age z-scores.[9] Table 1 presents the regression results. The β coefficient is estimated as 0.601. The 99 per cent confidence interval for this point estimate is [0.578; 0.623]. This finding seriously questions the validity and the interpretation of findings in the

[7] Elliott and Shepherd (2006) provide a description of the study.

[8] The self-reported nature of the adult height data poses a concern for the analysis. I conducted a host of sensitivity tests and find that the main findings are not affected by this. These tests are available from the author upon request.

[9] The dispersion in height distribution varies with age and increases as children grow older. Using raw measures of height inflates the ratio of standard deviations leading to a larger β coefficient (other things being equal). The use of height-for-age z-scores instead of raw measures of height circumvents this problem as they measure the distance to the normal growth curve at each age, making the standard deviations independent of the age when the child was measured. Cameron et al., (2005) make a similar point discussing the relationship between catch-up growth and regression-to-the-mean

previous literature using regression approach to study catch-up growth. First, it is inconceivable to find catch-up growth in healthy and well-nourished population. The descriptive and graphical analyses also show that there is negligible movement in the distribution over time. Yet, the current literature would interpret this regression result as partial catch-up growth. Second, a more sensible interpretation of the result is convergence in the height distribution (i.e. the dispersion diminished over time). Neither this is supported by the graphical analysis.

[Table 1 here]

Could this be explained by measurement error? It is true that measurement error in initial height ($h_{i,t-1}$) causes a downward bias, potentially leading to a false inference on convergence. Measurement error in $h_{i,t}$ is less harmful as it only leads to inflated standard errors. These statements hold if we make the plausible assumption that measurement error is random with zero mean and not correlated with children's characteristics. In Appendix B, I show that the magnitude of the potential measurement error is too small to drive the results in Table 1.

To further analyse what is going on, in Figure 3, I plot HAZ in adulthood on HAZ in early childhood. If the nutritional status in early childhood perfectly predicted adult outcomes (i.e. children remain locked into their growth trajectories), the regression line (dashed line in the figure) would lie on the 45-degree line (solid line). Instead, the regression line is flatter. From the figure it becomes clear that this is an outcome of regression-to-the-mean: those initially unusually short (the dots lying on the middle-left in the figure) and tall (the dots lying on the middle-right) reverted towards the mean by adulthood.

Finally, the economics literature in this topic worries about the role of omitted variables that may affect the identification of β in Equation (1). Controlling for child, household or community characteristics shifts the focus from *unconditional* to *conditional convergence*. These β estimates measure convergence, conditional on keeping the control variables constant. The concern regarding unobserved characteristics [10] has further complicated the statistical analysis. This has led to an innovative use of instrumental variable (IV) techniques in an attempt to eliminate the source of the potential unobserved heterogeneity between individuals (e.g. Fedorov and Sahn, 2005; Mani, 2012; Outes and Porter, 2012). The IV estimates do not allow us to say anything about catch-up growth – or convergence between the initially short and the rest of the population.[11] Modelling the impact of the apparent heterogeneity (by focusing on the coefficients on the control variables) is likely to provide a

[10] Child's innate healthiness, parents' preferences and unobserved community characteristics are often cited as the problematic unobserved characteristics.

[11] A similar point has been made early on in the economic growth literature (e.g. Durlauf and Quah 1998; Durlauf, Johnson, and Temple 2005).

more informative approach than eliminating it completely (and then focusing on the coefficient on the instrumented lagged dependent variable). [12] Finally, analysing conditional convergence does not solve the regression-to-the-mean problem (Quah, 1993), and the point about the misinterpretation of these regression estimates remains.

5. Data

The data for the empirical part of the paper are drawn from two longitudinal surveys: the Cebu Longitudinal Health and Nutrition Survey from the Philippines and the Kagera Health and Development Survey from Tanzania. Both studies permit me to observe children's height in early childhood and in adulthood.

Height-for-age Z-scores were calculated using the *zanthro* command in Stata 11.2 (see Vidmar et al., 2004). I use the US 2000 NCHS/CDC as the reference population (see Kuczmarski et al., 2002). The 2006 WHO Child Growth Standards (see WHO, 2006) in conjunction with the WHO Reference 2007 for 5-19 years (see de Onis et al., 2007b) resulted in more catch-up growth than NCHS/CDC. [13] I prefer the NCHS/CDC growth reference as it allows the calculation of HAZ scores from birth to 20 years of age, and is constructed using the same reference throughout the entire growth period.

The Cebu Longitudinal Health and Nutrition Survey (CLHNS) is an on-going longitudinal survey and have been used to analyse catch-up growth previously at least by Adair (1999), Eckhardt et al. (2005a), and Victora et al. (2008). Adair et al. (2011) provides a description of the survey. The sample was drawn from 33 randomly selected communities from the Metropolitan Cebu area. The baseline survey in 1983-84 consisted of 3,327 pregnant women who gave birth to 3,080 singleton children. These children were measured immediately after their birth and visited in two-month intervals until their second birthday. Follow-up surveys were administered at the age of nine, 12, 15, 19 and 22. In each round, the children were carefully measured to the nearest millimetre. I use the measurements taken at the age of two and at the age of 22. There were only very few children with implausible height measurements ($HAZ < -5$ or $\Delta HAZ > \pm 4$) that were dropped. The final sample consists of 1,795 individuals whose height measurements I have when they were two years old and when they were 22 years old.

[12] Durlauf, Johnson, and Temple (2005) make this point in the context of economic growth analysis.
[13] This is driven by the differences between the two references. In early childhood (ages 0-5), the median child in the WHO Child Growth Standards is taller than in the NCHS/CDC reference population (see de Onis et al., 2007a). In adulthood (at the age of 19), however, the height difference is negligible when comparing the WHO Reference 2007 for 5-19 years and NCHS/CDC. This highlights the difficulty in comparing studies that employ different growth standards or reference populations.

The Kagera Health and Development Survey (KHDS) design follows the World Bank's Living Standard Measurement Survey (LSMS) framework with a special emphasis on health. With 19-years, KHDS is one of the longest on-going panel LSMS-type of surveys from sub-Saharan Africa. Since the data set have not been used to analyse catch-up growth in the previous literature, I describe it in more detail below.

Kagera is a region in the north-western part of Tanzania. According to the latest National census in 2002, the region has a population of about two million people. The first interviews were held in 1991-1994 with follow-up surveys in 2004 and 2010. At the baseline in 1991-1994, more than 800 households were interviewed up to four times. The interval between the interviews was 6-7 months. These survey waves were designed and implemented by the World Bank and the Muhimbili University College of Health Sciences. The sample was drawn from a random sample stratified by adult mortality rates in the communities and the agro-climatic zones in the region. [14] The World Bank (2004) provides a comprehensive description of the baseline survey. The 2004 and 2010 follow-up surveys aimed to re-interview all individuals that were ever interviewed in the baseline survey. Beegle et al. (2006) and De Weerdt et al. (2012) provide a description of these survey rounds.

Anthropometric measurements were taken from all panel respondents who were present at the time of the household interview. In 1991-94, trained anthropometrists were responsible for measuring household members. In 2004 and 2010, enumerators, carefully trained by a qualified nurse, took the measurements usually after the household questionnaire was administered in the household. In all survey rounds, heights of children less than three years old were measured using a length board with a sliding foot piece. The heights of adults and children older than three years were measured using a height board with a sliding head piece. All heights were recorded to the nearest millimetre.

The sample for this study is constructed from children who were between 12 and 59 months old at the time of the four waves of the baseline survey in 1991-94 and who are at least 18 years in 2010. This cohort of 884 children is followed from the 1991-94 round through the 2010 round. In 2010, 559 of these children were interviewed and measured, 69 had died and 256 were not found or their heights were not measured. I drop all children whose height was not measured in 2010 or whose date of birth is not known. After dropping the few children with implausible height measurements (HAZ< -5 or ΔHAZ> ±4) the final sample contains 540 children from 365 households. If the child was measured

[14] The four agro-climatic zones are: Tree Crop Zone, Riverine Zone, Annual Crop Zone, and Urban Zone. I do not find statistical differences in HAZ scores between children residing in high or low adult mortality communities. HAZ scores across the four agro-climatic zones are found statistically different. The results of these statistical tests are not reported here but available upon request from the author.

more than once when she was 12 to 59 months old during the four interview rounds at the baseline, I took the last measurement.[15]

Sample attrition may bias results. Attrition due to death is less of a problem as catch-up growth analysis is focused on the height developments of the surviving. Attrition due to other causes is more problematic. If such attrition is positively correlated with health, then studies are likely to under-report catch-up growth in the sample. I address this issue by comparing the early childhood HAZ scores by attrition status.

Table 2 examines children's height-for-age values by the sample status. Attrition in the CLHNS is due to death and moving outside the Cebu metropolitan area (Eckhardt et al., 2005a). Out of the 3,080 children born in 1983-84 I have heights at the age of five for 2,493. Out of these, 1,791 form the final sample. As can be seen in Table 2, children who form the final sample have lower HAZ scores at the age five. A two-tailed t-test with adjustment for unequal variances reports that this difference of 0.049 is small and not statistically different from zero (p-value = 0. 286).

In KHDS, children who did not form the final sample have slightly higher HAZ scores than those who did. A two-tailed t-test shows, however, that this difference is not statistically significant. Further examination, presented in Table C1 in the Appendix C, reveals that children who deceased after the first round had lower HAZ-scores than those who survived and form the final sample. Children who were not traced or present at the time of the measurement have slightly better HAZ scores than children who form the final sample. However, according to a two-tailed t-test, neither of these observed differences is statistically significant. Sample attrition does not seem to be therefore associated with higher or lower HAZ scores in the CLHNS and KHDS samples.[16]

[Table 2 here]

Finally, to calculate the HAZ-scores, I also need to know children's ages at the time of measurement. Imprecision in ages may substantially bias HAZ-scores, especially among younger children. Fortunately, for both samples, I know the date of each household visit and have the date-of-birth for each child forming the final sample.

[15] An alternative strategy would be to take the mean over these observations to address the potential measurement error in these data. The findings are not affected by this choice.

[16] Table C2 of the Appendix C provides an overview of the HAZ-scores in KHDS by migration status for each child in the sample. By 2010, I find that half of the sample had migrated. Had we not tracked individuals, I would have lost half of the sample. Surprisingly, however, migration does not seem to be correlated with nutrition status. According to a two-tailed t-test, the difference in the adult HAZ-scores between children who remained in the baseline village and those who migrated by 2010 is not statistically different from zero.

6. Catch-up growth in the Filipino and Tanzanian cohorts

Next, I re-analyse the extent of catch-up growth in the CLHNS cohort and provide new evidence for Sub-Saharan African using the Kagera cohort. Column 1 in Table 3 shows that the mean HAZ score in the CLHNS cohort at the age of two is -2.09. [17] More than 50 per cent of the children are stunted, and 18 per cent are severely stunted. By adulthood, the mean HAZ score has increased only by 0.19 units of standard deviation and 45 per cent are stunted. The share of severely stunted children has fallen to nine per cent. Figure 4 provides distributions of the children's HAZ scores in early childhood and adulthood in the CLHNS cohort. There is limited movement over time. Only the left hand tail of the distribution shifts right suggesting that the very shortest children caught-up others, but as a whole there is very little catch-up growth, or convergence. These findings disagree with the conclusions in Adair (1999) who analysed catch-up growth until the age of 12 and found considerable catch-up growth in this cohort. This could be due to the use of different external reference population or to the fact that she did not have height data for the entire growth period.

[Table 3 & Figure 4 here]

The second column in Table 3 shows the descriptive statistics for the KHDS cohort. The mean HAZ scores in 1991-94, when the children are less than five years old, is 1.86 standard deviations below the median of the US-reference group. Approximately 44 per cent of the children are stunted (HAZ<-2) and 16 per cent are severely stunted (HAZ<-3). [18] Interestingly, in 2010, the cohort has been able to catch-up with the reference group: the mean height-for-age z-score in the sample is now -1.20. In 2010, 20 per cent are stunted and only three per cent severely stunted. There is also a clear gender difference. The mean HAZ-score in the female sample increases from -1.71 to -0.98 whereas for males the catch-up growth is somewhat more modest: mean HAZ increases from -2.01 to -1.42. These statistics suggest that the Kagera children are able to catch-up the growth losses incurred in early childhood. Figure 5 shows the full distributions of the HAZ scores in each point in time. The figure reinforces the descriptive statistics: there is considerable catch-up growth in the sample. This can be seen as the adult height distribution shifting right relative to the early childhood distribution.

[Figure 5 here]

[17] This is close to the gender disaggregated means reported in Eckhardt et al (2005b) who also use the NCHS/CDC growth standards to convert heights to HAZ-scores. The authors use the CLHNS cohort to study the association between height increments and socioeconomic status.

[18] These percentages agree with the statistics reported in the 1991/92 Tanzanian Demographic and Health Survey for the same region: 44 % of the children under 5 years old in Kagera were found stunted and 19.5 % severely stunted (Ngallaba et al, 1993)

Figures 6 and 7 offer another cut of the data. Here I plot the change in HAZ on HAZ in early childhood. The horizontal line goes through zero. The dots above this line are children whose HAZ scores improved between the two periods. The dots below this line belong to children whose HAZ score worsened. The figure also contains a vertical line that goes through zero. The dots on the left of this line belong to children who had a negative HAZ score in early childhood. The top left corner contains the children who experienced catch-up growth: after initial growth retardation ($HAZ_{t-1} < 0$), they experienced growth that was above what was expected for their age ($\Delta HAZ>0$). This corner corresponds directly to the definition of catch-up growth used in the clinical and epidemiological literature.

As can be seen from Figure 6 nearly all (99%) of the CLHNS children had negative HAZ scores at the age of two. More than 58 per cent of the children caught-up. The HAZ-scores in this group increased on average by 0.7 unit of standard deviation (median = 0.6). However, nearly 41 per cent of the initially short children fell further behind. Only one per cent of the children had a positive HAZ score at the age of two. Nearly all of these children experienced growth retardation later in life.

[Figure 6 here]

Figure 7 shows that 95 per cent of Kagera children had negative HAZ scores when they were first measured. More than 74 per cent experienced catch-up growth. The mean improvement in HAZ scores among these children is 1.1 units of standard deviation (median = 0.97). Nearly 21 per cent of the children had negative HAZ-scores in early childhood and fell further behind later in life. Only five per cent of the children had initially positive HAZ-scores. Most of these experienced slower growth than was expected.

[Figure 7 here]

7. Timing of the catch-up growth in the Kagera cohort

The descriptive analysis finds considerable catch-up growth in the KHDS cohort. Coly et al. (2006) find that the near complete catch-up growth documented in the Senegalese cohort takes place in puberty. To analyse the timing of this catch-up growth in the Kagera cohort, I would need to compare growth rates at different points in childhood. Unfortunately, assessing children's annual growth patterns is not feasible using the panel data as I only have two or three data points for each child. Fortunately, I can use the cross-sectional data to mimic children's growth patterns.[19] Using the baseline data in 1991-94, I constructed mean HAZ-scores at each age until the age of 20. To account

[19] See Moradi (2010) for a similar exercise using Living Standards Measurement Surveys from Cote d'Ivoire and Ghana.

for concerns that the observed catch-up growth in these cross-sectional data may be an artefact of selective mortality (see Bozzoli et al., 2009; Rouanet, 2011), I drop all children who did not survive their 18th birthday. [20] Figure 8 shows the growth patterns for both gender groups (solid lines). Similar to the evidence presented in Shrimpton et al. (2001), growth retardation in this sample begins immediately after birth and continues until 2-3 years of life. After four years of age, the HAZ-scores remain relatively stable until the age of 10 to 11. At this age, the median child in the US reference group enters the adolescent growth spurt (see Figure 1). The HAZ-scores fall rapidly at this point suggesting that puberty is delayed for the Kagera children. For boys, the HAZ-scores continue to fall until the age of 15 at which point the HAZ-curve shoots up. By the age of 19, the growth ceases. By now boys have caught-up the height losses incurred during puberty but HAZ-scores have also improved further to nearly restore their early childhood levels. Girls begin their adolescent growth spurt earlier and are able to completely restore their original HAZ-scores.

[Figure 8 here]

The shortcoming of using cross-sectional data to construct growth curves is that I cannot be sure whether the observed growth patterns are driven by age or by birth cohort effects. That is, whether the observed differences between the age cohorts are arising because they are observed at different ages (age effect) or because they were born into different environmental conditions (birth cohort effect). To circumvent this, I exploit the panel feature of the data and plot the growth curves for the same children whose pre-adult HAZ-scores I have in the later rounds of the survey (i.e. 2004 and 2010 rounds). These are the two dashed lines in Figure 8 starting at the age of 11.[21] These curves lie very close to the original growth curves lending support to the age effects story. The three panel data observations further confirm these patterns. At the average age of three, the mean HAZ score for girls is -1.71 and for boys is -2.02. In puberty (average age of 14), girls' mean HAZ score has improved to -1.25 and boys' to -1.89.[22] In adulthood, the girls' mean HAZ score stands at -0.98 and boys' at -1.42.

This evidence shows that puberty is an important opportunity window for the Kagera children to catch-up their healthy and well-nourished peers. The finding is in tune with the recently emerged evidence from studies employing cross-sectional data sets suggesting that puberty may be a critical period for children's growth. In a famous study, Steckel (1987) documents a remarkable catch-up growth of African American slaves during puberty. The slave records show that children remain highly malnourished until puberty during which the height deficit to an external reference population halved. This catch-up is credited to improved diets when the slaves entered the labour force between

[20] This mortality information originates from the 2010 survey when the panel respondents are adults.
[21] The dashed curves are less smooth because of fewer observations.
[22] These means are based on a slightly smaller sample due to missing height observations in the 2004 round.

eight and 12 years (Steckel, 1987; 2000). Stein (1975) shows that children exposed to the Dutch Winter Famine in 1944-1945 were able to completely catch-up other, non-exposed, cohorts. Haas and Campirano (2006) plot the pubertal growth rate on height just before the onset of puberty. They find that children from populations that have lower pre-pubertal heights seem to experience greatest growth during puberty. Moradi (2010), using multivariate regression analysis and a sample of more than 200,000 women from Sub-Saharan Africa, finds that economic growth has a positive effect on adult height during early childhood but also during puberty. Finally, Akresh et al. (2012) provide indirect evidence on this by comparing female adult heights between cohorts exposed to the Nigerian civil war in 1967-70. Strikingly, they find that the most negatively affected children were the ones aged 13 to 16 during the war.

8. Concluding discussion

The empirical analysis of catch-up growth requires long panel data or cohort studies that span the entire growth period. Catch-up growth is defined as growth in height that is above the expected for the child's age and occurs after a period of growth retardation. Height-for-age z-score measures the height distance in standard deviations to a healthy and well-nourished reference population. The evolution of HAZ scores over time therefore provides the exact counterpart of the definition used in the clinical and epidemiological literature.

The evidence of catch-up growth is plagued by studies that confuse catch-up growth with convergence. Analysing within-population convergence may be interesting itself but regressing HAZ in adulthood on childhood HAZ does not allow researchers to distinguish convergence from regression-to-the-mean.

Aside from the methodological contribution, I re-analyse the influential Cebu Longitudinal Health and Nutrition Survey from the Philippines and find limited catch-up growth. I also provide new evidence for sub-Saharan Africa. Using long panel data for the Kagera region in Tanzania, I document considerable catch-up growth. Nearly 75 per cent of the children experienced catch-up growth: after a period of growth retardation (HAZ<0) in early childhood they experienced growth that was above the expected (ΔHAZ>0). The mean HAZ-score in the cohort improves from -1.87 in early childhood to -1.20 by adulthood. Without catch-up growth, girls would have been nearly 5 centimetres shorter adults. For boys, the difference between the predicted adult height in early childhood and the actual adult height is around 4.5 centimetres. The graphical analysis shows that most of this observed catch-up growth takes place in puberty. Coly et al. (2006) document similar extensive pubertal catch-up growth among Senegalese children.

These findings have implications to our understanding of child development in developing country settings. In particular, puberty seems to offer an opportunity window for physical recovery for these two African cohorts. This opens questions for future research. First, can this be explained by genetics? Second, if not, would it be possible to reverse adverse health outcomes through policy interventions during puberty?

Finally, the evidence on the catch-up growth in these African cohorts speaks to the recently emerged height and income debate in the sub-Saharan African context. Deaton (2007) finds that, contrary to most other countries in the world, disease environment and national income are not good predictors of female adult height in African countries. African women are taller than their economic and disease environment suggests. Deaton (2007), Bozzoli et al. (2009) and Gørgens et al. (2012) explain this *African height puzzle* as a selection effect: childhood mortality is concentrated on the genetically short children thus shifting the mean adult height right. Moradi (2010, 2012) proposes an alternative explanation that African children experience a considerable catch-up growth in puberty. The results presented here provide support to this hypothesis.

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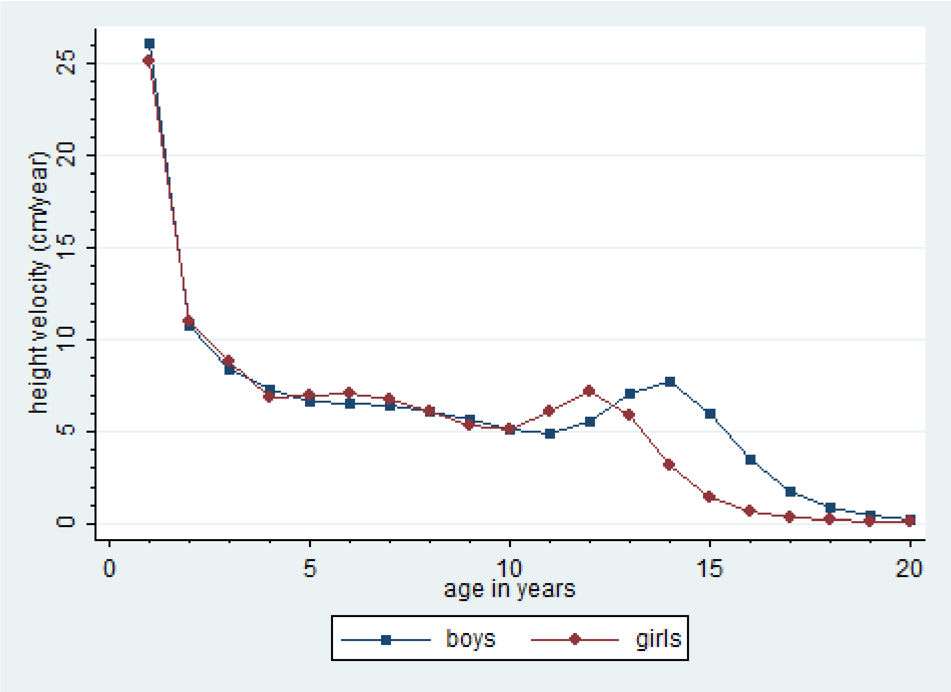
Figures

Figure 1: Velocity of height over the course of childhood



Source: Own calculations from 2000 CDC Growth Charts Data for the United States

Figure 2: The evolution of the height-for-age z-scores (HAZ) distribution over time in British cohort study (BCS70)
(kernel density estimates)

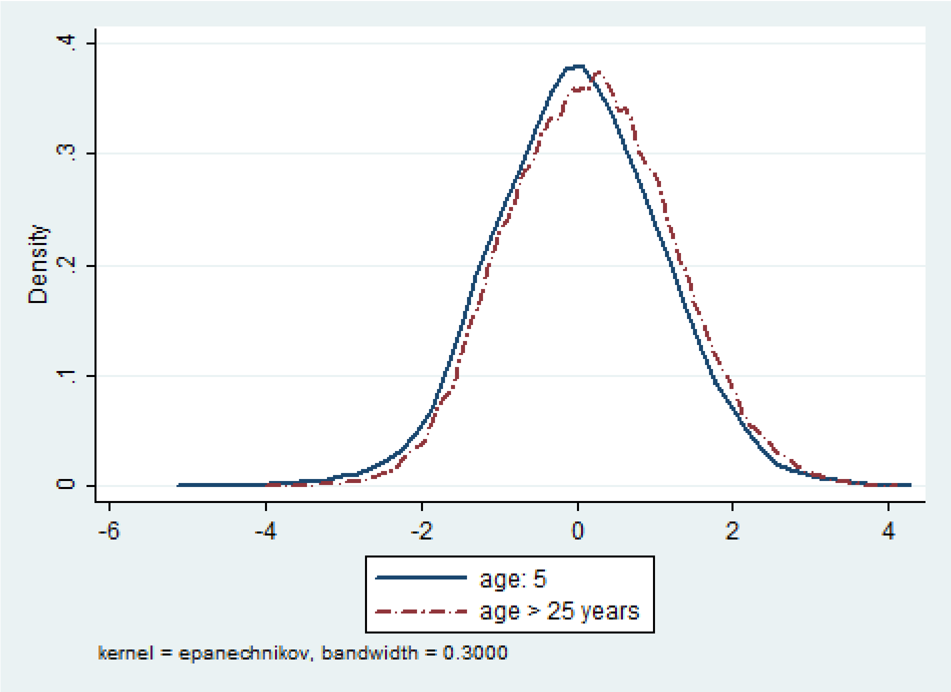


Figure 3: HAZ in adulthood on HAZ in early childhood
the British cohort (BCS70)

Figure 4: The evolution of the HAZ distribution over time in the Philippines cohort (CLHNS)
(kernel density estimates)

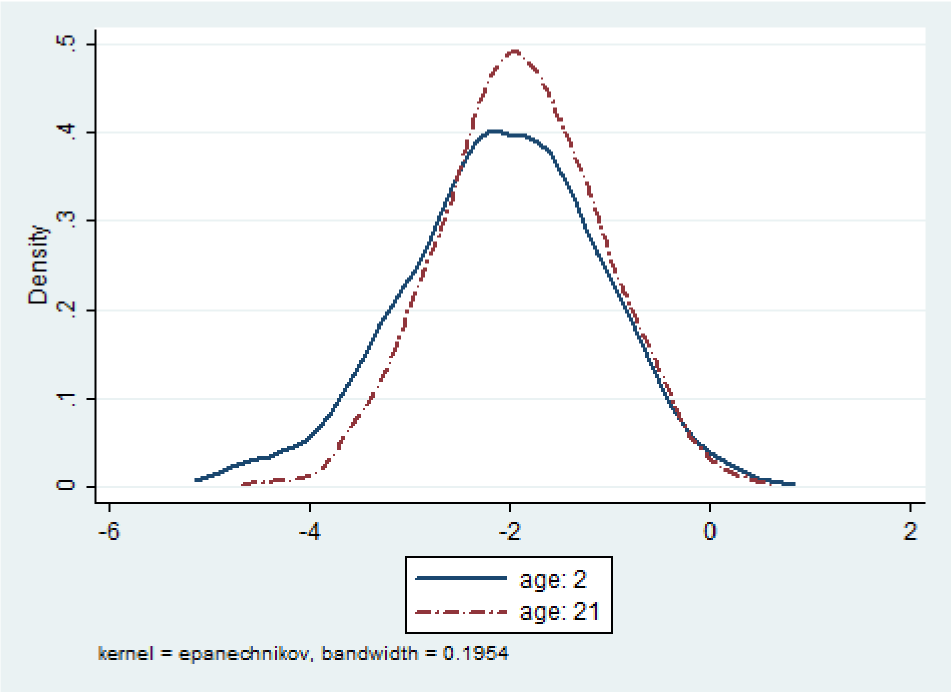


Figure 5: The evolution of the HAZ distribution over time in Kagera cohort (KHDS) (kernel density estimates)

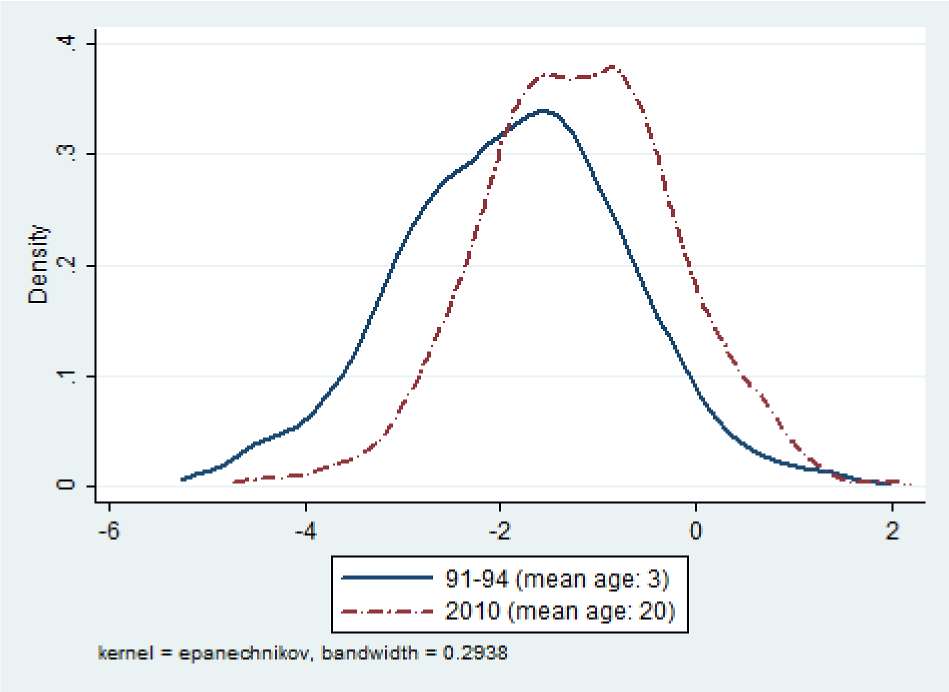


Figure 6: Change in HAZ between early childhood and adulthood on HAZ in early childhood the Philippines cohort (CLHNS)

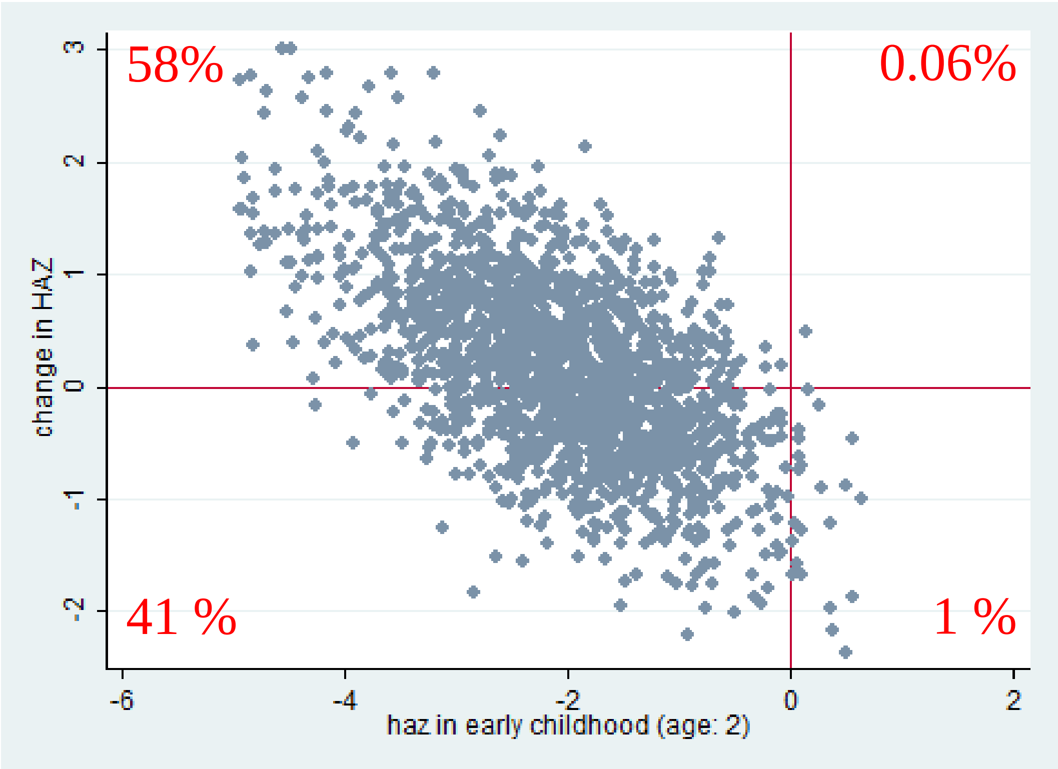


Figure 7: Change in HAZ between early childhood and adulthood on HAZ in early childhood the Kagera cohort (KHDS)

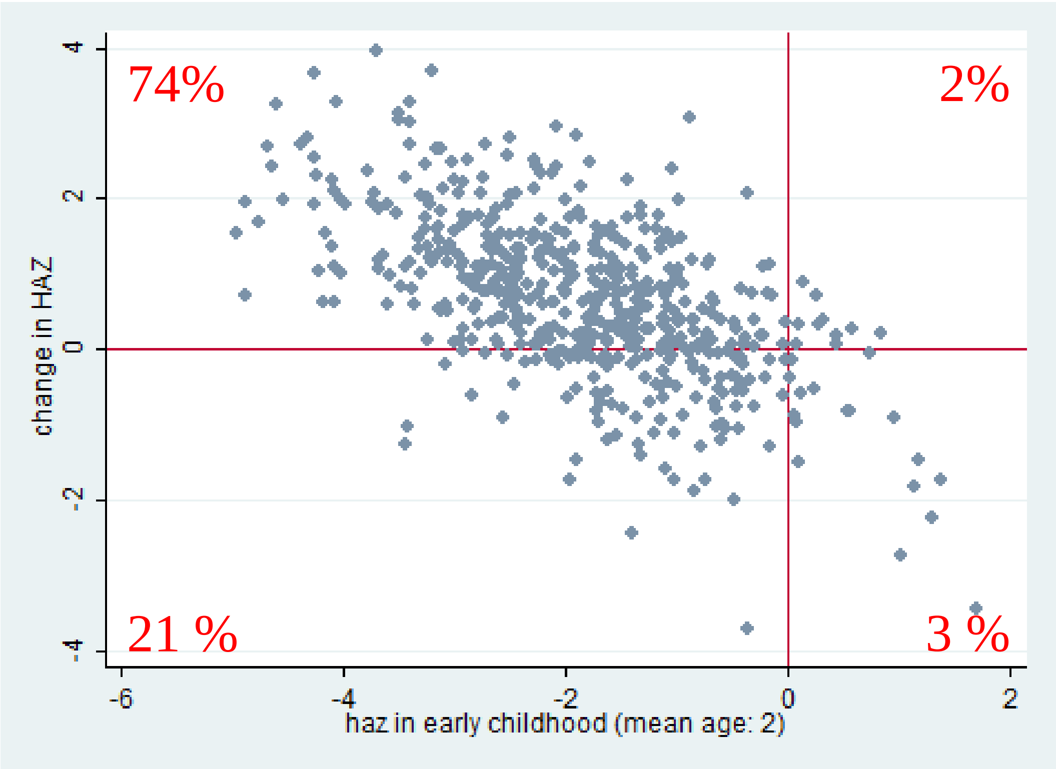
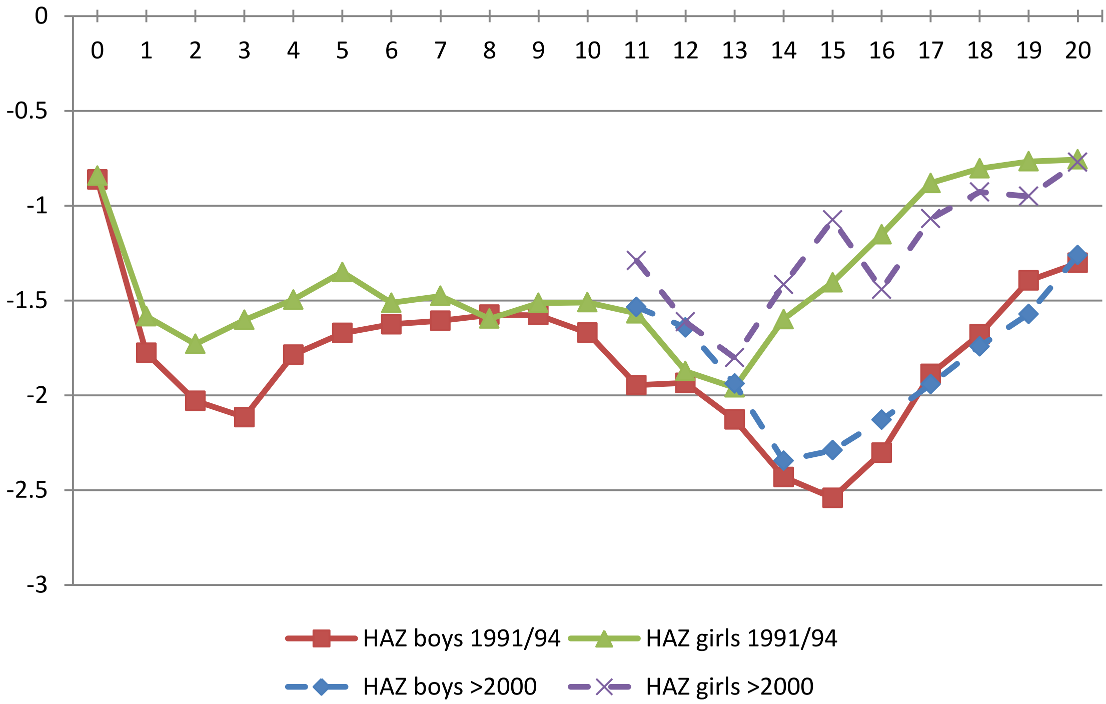


Figure 8: HAZ scores by age (cross-sectional data) Kagera (KHDS)



Tables

Table 1: Estimating convergence in the British cohort (BCS70) (Dependent variable: HAZ in adulthood)

	BCS70
HAZ in early childhood	0.601***
	(0.009)
intercept	0.164***
	(0.008)
Number of observations	9,635
R^2	0.383

*note: *** p<0.01, ** p<0.05, * p<0.1*
White (1980) adjusted standard errors are in parenthesis

Table 2: Attrition in the Philippines (CLHNS) and Kagera (KHDS) surveys: initial HAZ-scores by sample category

	CLHNS		**KHDS**	
final sample	no	yes	no	yes
observations	702	1791	344	540
HAZ:				
mean	-2.139	-2.090	-1.804	-1.864
std. dev.	1.041	0.983	1.262	1.155
difference	-0.05		0.06	
t-test	-1.07		0.71	

note: t-test based on Welch t-test on the difference in means between the two groups

Table 3: Evolution of HAZ scores in the Philippines (CLHNS) and Kagera (KHDS) cohorts

	CLHNS		KHDS	
	mean	**std. dev.**	**mean**	**std. dev.**
age in months (t=0)	24	0.267	41.03	14.704
height (t=0)	79.20	3.590	89.64	10.269
height (t=1)	157.4	8.205	161.7	8.267
HAZ_1 (t=0)	-2.09	0.982	-1.86	1.155
HAZ_2 (t=1)	-1.90	0.815	-1.20	1.002
difference in HAZ:	0.19	0.799	0.66	1.07
t-test: $HAZ_{t=1} = HAZ_{t=2}$	6.14		10.01	
percentage: $HAZ_{t=1} < -2$	52%		44%	
percentage: $HAZ_{t=2} < -2$	45%		20%	
percentage: $HAZ_{t=1} < -3$	18%		16%	
percentage: $HAZ_{t=2} < -3$	9%		3%	
sample size	1,791		540	

note: t=0 refers to early childhood, t=1 to adulthood.
HAZ scores calculated using the US 2000 NCHS/CDC as the reference population

Appendix A

Table A1: Evolution of HAZ scores in the British cohort (BCS70)

	BCS70	
	mean	**std. dev.**
age in months (t=0)	60.84	1.307
height (t=0)	108.8	5.035
height (t=1)	171.0	9.881
HAZ_1 (t=0)	0.01	1.056
HAZ_2 (t=1)	0.17	1.026
difference in HAZ:	0.16	0.91
t-test: $HAZ_{t=1} = HAZ_{t=2}$	10.56	
percentage: $HAZ_{t=1} < -2$	3%	
percentage: $HAZ_{t=2} < -2$	1%	
percentage: $HAZ_{t=1} < -3$	1%	
percentage: $HAZ_{t=2} < -3$	0%	
sample size	9,635	

note: t=0 refers to early childhood, t=1 to adulthood. HAZ scores calculated using the US 2000 NCHS/CDC as the reference population

Appendix B

The impact of measurement error on $\boldsymbol{\beta}$

In a simple linear bivariate regression such as Equation (1), the magnitude of this downward bias can be calculated using the following formula (see, for example, Deaton, 1997):

$$\beta \frac{{\theta_x}^2}{{\theta_e}^2 + {\theta_x}^2} = \beta\lambda, \quad (7)$$

where θ_x is the true standard deviation of the correctly measured height (unobserved), and θ_e is the standard deviation of the measurement error. The measurement error inflates the denominator causing a downward bias in the convergence estimate. The term λ is then the reliability ratio measuring the magnitude of the downward bias.

The standard deviation in the early childhood height observed in the British cohort is 5.034. To get a sense of the potential bias, I calculate the impact of various level of zero-mean measurement error on

β. As can be seen in Table B1 below, a small level of measurement error leads to a negligible downward bias in the β coefficient. Even measurement error that has a standard deviation of 1 cm (i.e. 32 % of the height measurements contain more than 1 cm of measurement error), biases the estimate downward only by four percentage points and cannot explain the convergence finding in Table 1. It is difficult to imagine measurement error of this magnitude in any carefully constructed survey. In this light, adjustments, such as instrumental variables techniques, to address measurement error seem unnecessary.

Table B1: the impact of measurement error (ME) on $\boldsymbol{\beta}$

std. dev. of ME	reliability ratio
0.01	0.999996
0.1	0.999606
0.25	0.997541
0.5	0.990235
0.75	0.978293
1	0.962051
1.25	0.941944
1.5	0.918482

Note: standard deviation of height used in this example is 5.034, based on my own calculations from the BCS70 data

Appendix C

Table C1: KHDS Attrition tests: initial HAZ scores by sample category

	N	mean	sd	t-stat*
in the final sample	540	-1.86	1.155	n/a
deceased after 1991-94	69	-2.10	1.396	1.37
not measured in 2010	257	-1.74	1.220	-1.32
missing date of birth	18	-1.51	1.198	-1.22

** Welch t-test testing the difference in means against the first category (in the final sample)*

Table C2: KHDS adult HAZ scores by migration status in 2010

	2010			
	N	mean	sd	t-stat*
non-migrant	258	-1.21	1.012	n/a
migrant	282	-1.20	0.995	-0.0299

** Welch t-test testing the difference in means against the first category (non-migrant)*