

The growth pattern of British children, 1850–1975[†]

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This article is the first to use individual-level, longitudinal measures of child growth to document changes in the growth pattern in Britain between the 1850s and the 1970s. Based on a unique dataset gathered from the records of the training ship *Indefatigable*, this study analyses the mean heights of boys at admission and their longitudinal growth using regressions that control for observable characteristics. Our findings show a secular increase in boys' mean height over time, and that height gain was most rapid during the interwar period. In addition, longitudinal growth velocity was low and similar at different ages for boys born before the 1910s, suggesting a substantially weaker pubertal growth spurt (three standard deviations lower) than that which occurs in modern populations. However, for boys born in the 1910s and later, higher growth velocities associated with pubertal growth appeared in a narrow range of ages (14 to 16 years). Thus, it appears that there was a substantial change in the growth pattern beginning in the 1910s with the emergence of a strong pubertal growth spurt. The timing of this shift implies that declines in child morbidity mattered more for the changing growth pattern than improvements in nutrition that occurred before 1910.

Because child growth is a particularly sensitive measure of nutrition and morbidity in childhood, economic historians have long used anthropometric measures such as height to understand living standards and health in the past. Most of the existing research has focused on adult measurements drawn from records of military enlistment and conscription, prisons, ship manifests, and so on.¹ In studying adult heights, anthropometric historians have had a number of goals. First, they have sought to understand changes in living standards and health over time. They contributed powerfully to the industrial living standards debate, showing that mean height and thus health deteriorated during the nineteenth century despite improvement in real wages and economic growth.² They also established that there was a secular increase in adult mean stature in Britain (and around the

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¹ Steckel, 'Heights'.

² Floud, Wachter, and Gregory, *Height*; Komlos, 'Secular trend'; idem, 'Further thoughts'; Nicholas and Oxley, 'Living standards'; Johnson and Nicholas, 'Male and female'; Cinnirella, 'Optimists or pessimists?'.

world) beginning with cohorts born in the 1870s.³ More recently, anthropometric historians have shifted from documenting trends in height to using GDP, infant mortality rates, family size, and a host of other variables to explain the increase in stature since the mid-nineteenth century.⁴ They have also explored heterogeneity in health between sub-groups of the British population, looking at gender differences in health and migrant selection among other issues.⁵

These studies have fundamentally changed our understanding of how living standards and health have varied over time and across space. However, they have also left some open questions that cannot be answered solely by analysing adult height. First and most importantly, we know little about how precisely the change in mean adult height was achieved. Adult stature is the product of 20 or more years of growth and is at times frustratingly imprecise. Children who experience a nutritional or health shock at one age can experience substantial catch-up growth that hides their earlier deprivation.⁶ Individuals can continue to grow well into adulthood, making measurements in the late teens and early twenties unreliable proxies of health.⁷ In addition, studies of adult stature also tell us only one component of the growth pattern: adult size. They cannot reveal the timing of the pubertal growth spurt or the rate of development or maturation, which affects the velocity of growth at different ages and the length of the growing years. Figure 1 illustrates these constituent parts of the growth pattern using the World Health Organization (WHO) reference reflecting the growth of healthy boys in the second half of the twentieth century. The left panel shows the height by age profile and the right the associated height velocity curve.⁸ This article assesses how the growth pattern of children changed over time, focusing primarily on the timing and velocity of growth during the pubertal growth spurt, the rapid increase in growth velocity during puberty visible in the right panel of figure 1.

Studying the growth pattern directly is important because it reveals critical information about the health of children. Child stunting is a well-known and widely accepted measure of nutritional deprivation and/or sustained disease burden, but a delayed pubertal growth spurt and an extended growing period into the early twenties (delayed maturation) also indicates poor health conditions in childhood.⁹ These aspects of the growth pattern are not always fully incorporated into measures of final adult height since two individuals may take very different growth paths to reach the same final height.

There is a great deal of evidence that suggests that components of the growth pattern have changed through history. Most research has focused on child stunting or children's heights. Floud et al. showed how the adolescent heights of working-class boys in the Marine Society and upper-class boys in Sandhurst Military Academy changed in the late eighteenth and nineteenth centuries.¹⁰ Rosenbaum

³ Floud et al., *Height*; Hatton and Bray, 'Long run trends'; NCD Risk Factor Collaboration, 'Century'.

⁴ Hatton, 'Infant mortality'; idem, 'Europeans'; Baten and Blum, 'Agricultural production'.

⁵ Horrell, Meredith, and Oxley, 'Measuring misery'; Humphries and Leunig, 'Dick Whittington'.

⁶ Steckel, 'Peculiar population'; Schneider, 'Children's growth'.

⁷ Beekink and Kok, 'Effects'.

⁸ Note that the WHO reference was estimated from cross-sectional data, and therefore underestimates the true velocity of individuals during the pubertal growth spurt; Merrell, 'Relationship'; Cole, Cortina-Borja, Sandhu, Kelly, and Pan, 'Nonlinear growth'.

⁹ Schneider, 'Children's growth', pp. 23–4.

¹⁰ Floud et al., *Height*, pp. 182–9.

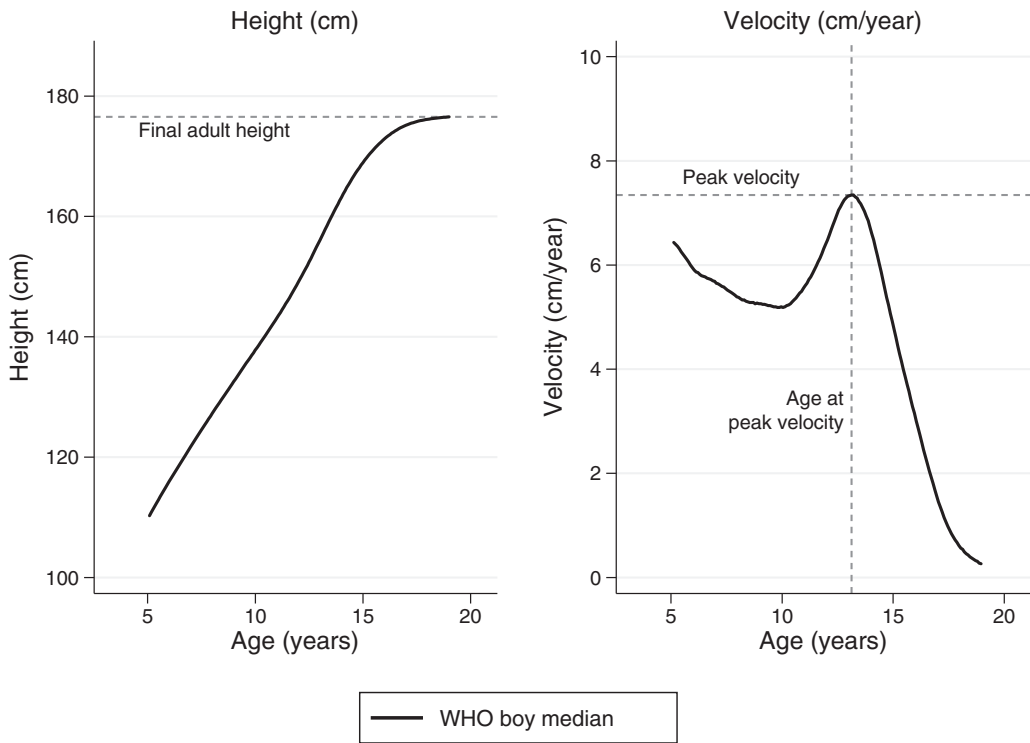


Figure 1. Characteristics of the growth pattern displayed using the WHO 2007 reference for school-aged boys.

Sources: Data from WHO, 'Growth reference 5–19 years', <https://www.who.int/growthref/tools/en/> (accessed on 15 July 2015).

used a number of datasets to illustrate the increase in height in Britain from the late nineteenth century to the 1980s.¹¹ Harris traced child growth in the twentieth century by analysing the mean height of children reported by the school medical officers in various towns across the UK.¹² However, none of these data sources are ideal for understanding how the growth pattern has changed. First, none of the existing datasets cover the complete period of the secular increase in height, that is, birth cohorts from the 1870s to the 1950s. Second, there is a dearth of individual-level datasets for the twentieth century that can be used to track changes in child growth over a number of decades.¹³ Thus, our study contributes to the existing literature by providing a consistent, individual-level dataset on child growth for boys born between the 1850s and the 1970s.

Moving beyond child height, the timing of the pubertal growth spurt and the speed of maturation have also changed over time. Using cross-sectional growth profiles, Cameron has shown that children in London at the beginning of the twentieth century had their pubertal growth spurt at later ages than modern

¹¹ Rosenbaum, '100 years'.

¹² Harris, 'Height'.

¹³ Ibid.; Schneider, 'Health'.

children, and Steckel and later Cole proved that this was a general pattern.¹⁴ A'Hearn et al. have shown that the age at which Italian men stopped growing (a proxy for the speed of maturation) declined at the end of the nineteenth century at the beginnings of the secular increase in height.¹⁵ Finally, several studies have analysed the changing growth pattern of Japanese children across the twentieth century showing that overall height increased, the age of peak pubertal growth declined, and the speed of maturation became more rapid across the century with the secular increase in height.¹⁶ However, these studies have limitations as well. No studies have been able to track changes in the timing of the pubertal growth spurt using consistent, individual-level data across the secular increase in height. In addition, nearly all studies of the growth pattern have used cross-sectional growth profiles, that is, the mean heights of different children measured at subsequent ages, to explore changes in the growth pattern rather than drawing on longitudinal, individual-level data. These cross-sectional studies are prone to selection bias because any differential selection of individuals into the sample by age will provide a biased estimate of the height-by-age profile.¹⁷ Thus, this article contributes to the existing literature by analysing longitudinal measures of child growth over time.

This article is the first to describe changes in the growth pattern of British children in the very long run from individual-level, longitudinal measures of child growth. To do this, we make use of records kept on 11,548 boys by the training ship *Indefatigable* from the 1860s to the 1990s. Critically, the ship administrators recorded the heights of the boys at admission and discharge from the ship, providing longitudinal measurements of the boys' growth. To understand how child growth changed, we analyse the mean heights of boys at each age available, their height-for-age Z-scores (measuring position relative to the modern WHO reference), and their longitudinal growth using regressions that control for compositional effects on observable characteristics.

The results show that although heights were increasing across the period, height gain was most rapid during the interwar period. This evidence corroborates other work on British and European heights.¹⁸ The longitudinal growth evidence suggests that boys born before 1910 did not experience a pronounced pubertal growth spurt like that which became common from the 1910s onward. Mean longitudinal growth velocity was remarkably flat across puberty for these early cohorts whereas a pronounced pubertal growth spurt appeared for the 1910s and later cohorts. This is a surprising finding since human biologists have long held that the pubertal growth spurt is an essential part of the growth pattern, particularly for boys.¹⁹ However, we critically evaluate our own evidence and re-evaluate other nineteenth-century historical evidence to show that the pubertal growth spurt was indeed much less pronounced in the late nineteenth century than today. Simulations suggest that the mean individual-level peak growth velocity during

¹⁴ Cameron, 'Growth'; Steckel, 'Growth depression'; Cole, 'Secular trend'.

¹⁵ A'Hearn, Peracchi, and Vecchi, 'Height'.

¹⁶ Ali, Lestrel, and Ohtsuki, 'Secular trends'; Cole and Mori, 'Fifty years'; Schneider, Ogasawara, and Cole, 'Effect'.

¹⁷ Schneider, 'Sample-selection biases'.

¹⁸ Hatton, 'Infant mortality'; idem, 'Europeans'.

¹⁹ Tanner, *History*, p. 134.

puberty was 3.6 cm per year (three standard deviations) lower than the 1960s British growth standard.²⁰ Our findings suggest that a key component of the secular increase in height was this fundamental change in the growth pattern. The fact that this change only occurred from the 1910s birth decade cohort onward suggests that declines in child morbidity and improved hygiene were probably the most important factors in explaining the shift, though nutrition-related interventions such as the expansion of free school meals and the milk-in-schools programme are likely to have contributed as well.

I. The *Indefatigable* dataset

This article is based on records of boys admitted to the training ship *Indefatigable* between 1865 and 1995.²¹ The *Indefatigable* was founded in 1865 in Liverpool with the mission to train the sons and orphans of sailors and other poor and destitute boys for careers in the Navy or merchant marine.²² The boys entered the ship at 10 to 14 years of age and were discharged by the age of 15 to 18.

Although the *Indefatigable* survived for 130 years, it changed as an institution over time. In the beginning, the ship was mainly financed by voluntary contributions and support from public societies.²³ However, the sources of funding and the types of children the ship took changed over time, with the ship relying more on state funding and drawing boys from across the distribution of parental occupations. The *Indefatigable* was a wooden frigate with sails, a retired Navy ship of the line in the early years. This ship was replaced by a steel-hulled, steam and sail ship in 1914. Both of these ships were docked on the river Mersey near Liverpool, giving the ship ready access to clean water, fresh food, and medical care.²⁴ The boys' living quarters were on the lower decks. The first *Indefatigable* was 186 feet long and 54 feet wide and could accommodate over 200 boys.²⁵ The boys occasionally took the ship out into the broad river to practise sailing, but they did not go on long-distance voyages. The *Indefatigable* was based on the river Mersey until 1941 when German air raids became severe in Liverpool and the ship's executive committee and administrators thought it safer to move ashore. They first moved to a camp at Clawdd Newydd, but due to the continuous deterioration of the camp's condition, the ship was finally and permanently moved ashore at Plas Llanfair, Anglesey in 1945.²⁶

In order to understand how conditions on the ship that might influence child growth changed over time, we have conducted a careful study of the institutional history of the *Indefatigable* from the annual reports of the institution (1865–1990),

²⁰ Tanner and Whitehouse, 'Clinical longitudinal standards'.

²¹ National Museums Liverpool (hereafter NML), Maritime Archives and Library (hereafter MAL), D/IND/3/2/1-40, *Indefatigable* and National Sea Training School for Boys, Register Books, vols. 1–40; Schneider and Gao, 'Indefatigable training ship'.

²² NML, MAL, D/B/115N/1, *Indefatigable* and National Sea Training School for Boys, annual reports of the *Indefatigable* (1865–81), 'First Annual Report [1866]', pp. 5–7.

²³ Only after the 1970s did tuition fees from parents become an important part of the ship's income.

²⁴ NML, MAL, D/B/115N/1, *Indefatigable* and National Sea Training School for Boys, annual reports of the *Indefatigable* (1865–81), 'First annual report [1866]', p. 8.

²⁵ Evans, *Indefatigable*, p. 16, citing an article in the *Liverpool Review* on 21 Jan. 1888.

²⁶ NML, MAL, D/IND/1/4/1, *Indefatigable* and National Sea Training School for Boys, annual reports of the *Indefatigable* (1940–90), 'Seventy-sixth annual report [1941]', pp. 4–5; 'First annual report [1945]', p. 3.

monthly chairman's reports to the executive committee (1939–43 and 1956–8), and recollections of former *Indefatigable* boys collected in Evans's book *The Indefatigable*.²⁷ The information available in these sources is not as detailed as for other institutions studied in the literature;²⁸ however, we are confident about four facts regarding life on the *Indefatigable* that would matter for child health and measuring child growth.

First, there were no minimum or maximum height requirements for admission, even though other physical requirements, such as eyesight, were used as medical reasons to reject boys.²⁹ Minimum or maximum requirements are never mentioned in the annual reports and there is no evidence in the height distributions that suggests that truncation was occurring.³⁰ Second, the physical development of the boys was closely monitored and cared for by the staff.³¹ The captain regularly emphasized the physical training of the boys in the annual reports, expressing his worries or satisfaction concerning the boys' physical development.³² For a time, they even tracked the boys' weights at more frequent intervals than admission and discharge.³³ There was also a weekly medical inspection carried out by medical officers, and boys with illness were sent to hospital for further treatment.³⁴

Third, the boys were always fed sufficient and wholesome food, even if the variation and taste of the food was limited.³⁵ Unfortunately, the information on the boys' diet is not detailed enough to make precise estimates of the caloric and nutritional content. However, rich anecdotal evidence from various reports and memoirs suggests that the food was sufficient for the boys to grow: information on the boys' diet is presented in online appendix S4. Likewise, evidence on real food expenditure per boy shows that expenditure was more or less constant over time, though there was a dip during the 1940s and 1950s (see figure 8). Fourth, with

²⁷ Evans, *Indefatigable*; NML, MAL, D/B/115N/1, *Indefatigable* and National Sea Training School for Boys, annual reports of the *Indefatigable* (1865–81); NML, MAL, *Indefatigable* and National Sea Training School for Boys, D/CC/IND/1/1–2, annual reports of the *Indefatigable* (1901–34); NML, MAL, D/IND/1/4/1, *Indefatigable* and National Sea Training School for Boys, annual reports of the *Indefatigable* (1940–90); NML, MAL, D/IND/1/4/2, *Indefatigable* and National Sea Training School for Boys, chairman's reports to the executive committee (1939–43, 1956–8); NML, MAL, 413.Nat/PM, *Indefatigable* and National Sea Training School for Boys, T.S. *Indefatigable*.

²⁸ Schneider, 'Health'.

²⁹ NML, MAL, D/B/115N/1, *Indefatigable* and National Sea Training School for Boys, annual reports of the *Indefatigable* (1865–81), 'First Annual Report [1866]', p. 9; NML, MAL, 413.Nat/PM, *Indefatigable* and National Sea Training School for Boys, 'Centenary of the *Indefatigable*, 1864–1964', pp. 22–4.

³⁰ The heights at admission and discharge were not always perfectly normally distributed, but these follow the well-known shift in skewness during the pubertal growth spurt; Schneider, 'Sample-selection biases', p. 19; A'Hearn et al., 'Height', p. 2.

³¹ NML, MAL, D/B/115N/1, *Indefatigable* and National Sea Training School for Boys, annual reports of the *Indefatigable* (1865–81), 'Third annual report [1868]', p. 13.

³² After 1920, the boys' health conditions, including their mental health, are reported in a separate section in each annual report including information about the number of boys who were ill and how they were treated; NML, MAL, *Indefatigable* and National Sea Training School for Boys, D/CC/IND/1/1–2, annual reports of the *Indefatigable* (1901–34); D/IND/1/4/1, annual reports of the *Indefatigable* (1940–90).

³³ NML, MAL, D/IND/1/4/2, *Indefatigable* and National Sea Training School for Boys, chairman's reports to the executive committee (1939–43, 1956–8), 'Chairman's reports to the executive committee [1940]'.

³⁴ NML, MAL, D/IND/1/4/2, *Indefatigable* and National Sea Training School for Boys, chairman's reports to the executive committee (1939–43, 1956–8), 'Chairman's reports to the executive committee [1939]'.

³⁵ One of the bye-laws for the management of the ship by the executive committee was as follows: 'the diet shall be sound, wholesome food, and the rations shall be settled from time to time as the Committee shall deem expedient. The provisions shall be well dressed and served at stated hours'; NML, MAL, D/B/115N/1, *Indefatigable* and National Sea Training School for Boys, annual reports of the *Indefatigable* (1865–81), 'Third annual report [1868]', p. 13.

regard to workload, boys who entered the ship were supposed to engage in ordinary school duties, learn seamanship, and carry out routine labour on board such as scrubbing the decks, cleaning the living spaces, and doing laundry. The daily timetable varied over time, but generally the boys were supposed to be up around 6 a.m. and asleep by 8.30–9.00 p.m.³⁶ The boys' physical workload remained similar before and after the *Indefatigable* moved on shore in 1941 and later to Anglesey in 1945.

II. Key variables and potential selection bias of the dataset

The training ship administrators kept incredibly consistent registers from the 1860s to the 1990s, recording information about each boy's birthplace, address, father's occupation, orphan status, and height and weight at admission and discharge.³⁷ For certain sub-periods, they recorded additional information such as the child's school, the income of his parents, and the ages of his brothers and sisters, among other things, but these data were not available for the long period studied here. Overall, the dataset is large and robust. For each birth decade cohort, we have a sample of boys varying from 496 to 1,220 (see online appendix table S1).

The *Indefatigable* dataset contains longitudinal measurements of height and weight for 77.2 per cent of boys in years when it was recorded. Unfortunately, there are two periods, 1933–41 and after 1974, when height and weight were not recorded at discharge, which introduces gaps into our longitudinal data (see online appendix figure S1). These gaps and their effect on our understanding of the growth pattern of children will be discussed at length later, in section V. Despite these issues, the dataset provides a unique lens with which to study changes in children's growth over time.

However, it is important to consider representativeness and selection bias in our sample, especially since we are studying a very long period during which the British economy and society changed dramatically. Looking at geographic coverage, the sample is drawn from across the UK (see figure 2) though the ship recruited heavily from Lancashire and its surrounding counties and also from London and the south-east. The school also drew a lot of boys from North Wales after it was relocated there in 1941.

We have also analysed the parental occupations recorded in the data to understand the class background of *Indefatigable* boys. The percentage of boys whose father's or mother's occupation was listed varied considerably over time from 41 to 90 per cent, but the general pattern of occupational structure remained the same despite these fluctuations (see online appendix figures S3 and S4). We classified the occupations into HISCO codes and then converted these codes to HISCLASS occupational categories in order to compare the *Indefatigable* boys with the population occupational composition available in the census.³⁸ In the early years, the vast majority of the boys were of working-class backgrounds, but this

³⁶ NML, MAL, D/CC/IND/1/1-2, *Indefatigable* and National Sea Training School for Boys, annual reports of the *Indefatigable* (1901–34), 'Annual report [1924]', p. 5; Evans, *Indefatigable*, pp. 26, 32, 64.

³⁷ Information on race was not recorded in the original records. One might be able to determine Irish and/or Welsh ethnicity from the boys' names, birth places, and religion, but this would not be possible for the anonymized data from 1912 onwards.

³⁸ van Leeuwen, Mass, and Miles, *HISCO*; van Leeuwen and Maas, *HISCLASS*.

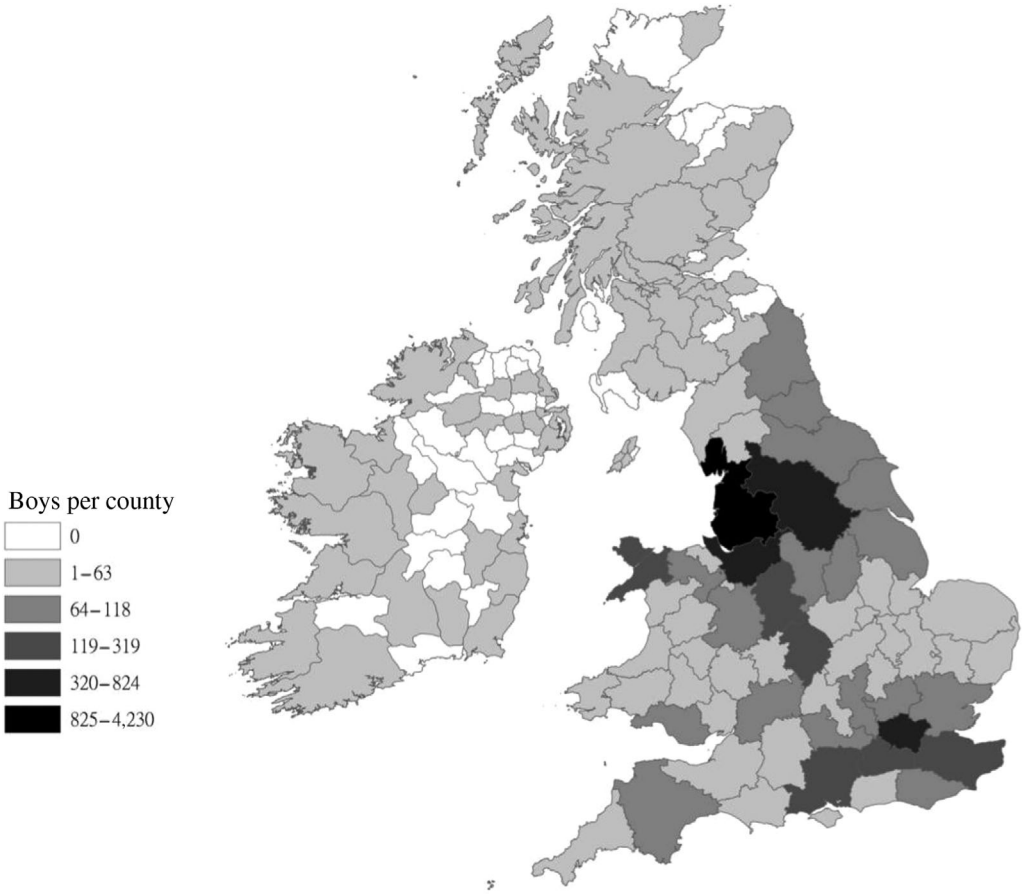


Figure 2. Number of Indefatigable boys born in each county, 1850–1979

Notes: Dark shades correspond to a larger number of boys. Counties are based on 1851 borders. 89.9% of cases had a recorded and identifiable birth county.

Sources: Indefatigable dataset (see n. 21 and online app. S1).

share fell over time, especially after the Second World War (see online appendix figure S3).

Figure 3 compares the share of boys in each HISCLASS category in an admission decade to the census of that decade. Figure 3a shows how the typical comparison would work: we compare the percentage of the sample in each HISCLASS group to the percentage in the census of England and Wales. To compare across years in figure 3b, we subtract the share in the census from the share in the *Indefatigable* sample, showing the percentage point difference between the two. Surprisingly, the upper HISCLASS groups were over-represented in many decades. Medium-skilled and low-skilled workers tended to be under-represented and unskilled workers tended to be over-represented. In general, agricultural workers were under-represented. While the figure clearly shows that the *Indefatigable* was not a perfect random sample of British boys, this should not affect our estimation of the changing growth pattern since we include controls for these occupational categories in all specifications.

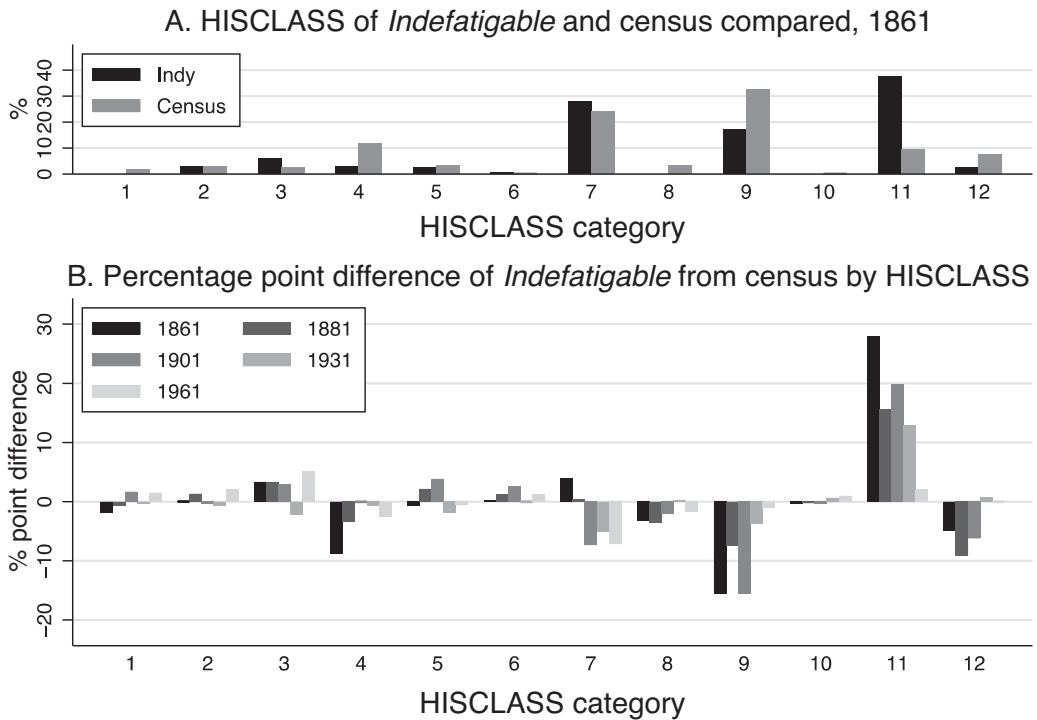


Figure 3. *HISCLASS* parental occupation composition of the *Indefatigable* sample and various censuses of England and Wales

Notes: We use the HISCO classifications in the Integrated Census Microdata (I-CeM) datasets for the 1861, 1881, and 1901 censuses, and we reclassify occupations from the 1931 and 1961 censuses into the HISCLASS system to make comparisons with the *Indefatigable* data. The HISCLASS categories taken from van Leeuwen and Maas, *HISCLASS*, are as follows: 1: higher managers; 2: higher professionals; 3: lower managers; 4: lower professionals and clerical and sales personnel; 5: lower clerical and sales personnel; 6: foremen; 7: medium skilled workers; 8: farmers and fishermen; 9: lower skilled workers; 10: lower skilled farm workers; 11: unskilled workers; 12: unskilled farm workers.

Sources: *Indefatigable* dataset (see n. 21 and online app. S1); HISCO codes for the 1861, 1881, and 1901 censuses were drawn from the I-CeM Nesstar Catalogue, <http://icem-nesstar.data-archive.ac.uk/webview/> (accessed on 12 March 2016); 1931 census: General Register Office, *Census of England and Wales, 1931. Occupation Tables*, pp. 15–22; 1961 census: idem, *Census 1961, England and Wales. Occupation Tables*, pp. 15–25. The HISCO and HISCLASS systems are described by van Leeuwen et al., *HISCO*, and van Leeuwen and Maas, *HISCLASS*, respectively.

More troubling than lack of perfect representativeness is selection bias. As Bodenhorn et al. have highlighted, selection bias comes in two forms: selection on observable characteristics, which can be mitigated by controlling for the characteristics in regression models, and selection on unobservable characteristics.³⁹ Although their critique has been challenged, it is still important to consider whether selection on unobservables of the type they discuss might be important for the *Indefatigable*.⁴⁰ This is especially true since Schneider has highlighted a number of ways in which sample-selection bias might influence the growth pattern of children in various datasets, mostly through selection on age into the sample.⁴¹ Selection on age is less of an issue for this dataset since we observe

³⁹ Bodenhorn, Guinnane, and Mroz, 'Sample-selection biases'.

⁴⁰ Komlos and A'Hearn, 'Clarifications'; Zimran, 'Sample-selection bias'.

⁴¹ Schneider, 'Sample-selection biases'.

growth velocity at the individual level and do not impute it by comparing the mean heights of different individuals at different ages. However, it is still important to consider selection on unobservables into the sample and how this may affect the trends we find.⁴²

The two potentially most problematic sources of selection on unobservables are the changing target population and funding sources for the school. Before the 1920s the school was mainly funded by charitable contributions and subscriptions, but from the 1920s onward, public bodies and the Department of Education took up a larger share of the funding. This was because the school began admitting a larger number of boys who were in the care of a poor law union, a local children's society, or a local authority. Beginning in the 1940s, the school began collecting some tuition fees from families who could afford to pay them. Income from fees, however, was relatively small compared to income from public bodies and donations until the 1970s when fees became the main source of revenue for the school.⁴³ Unfortunately, it is not straightforward to determine which boys were funded by the state or by their parents. There is some evidence on this in the records but it was not consistently recorded and therefore is unhelpful for trying to control or adjust for these selection mechanisms. However, as will become clear later, there is little reason to believe that these changes in selection explain the main findings from our analysis. Although it might seem that children in state care were worse off than those children admitted in the earlier period, this is unlikely to be true because many of the earlier children were orphans and the designation of state care just marked the expansion of state provisioning for at-risk children in the early twentieth century. The shift toward fees as the main revenue stream came too late in the 1970s to explain the sharp changes that we find for boys born from the 1910s onwards. Thus, we do not believe that these potential selection biases present insurmountable challenges to our analysis, and we have continued to use the *Indefatigable* dataset given its rich information and very long time coverage.

III. Methodology

Before presenting the results graphically, it is first necessary to discuss how we measure growth and estimate the results. We construct four dependent variables to study child growth in our dataset. There are two cross-sectional indicators: the admission height in centimetres and the admission height-for-age *Z*-score of boys. The *Z*-scores are calculated from the 2007 WHO growth reference for school-aged children and capture how the historical children compare to how we would expect healthy children to grow today.⁴⁴ We also use two longitudinal indicators: height velocity (centimetres per year) and the change in height-for-age *Z*-score while the child was on the ship. We group these indicators at one-year age intervals in our analysis, but for the *Z*-scores precise ages become even more important because

⁴² Unfortunately, the econometric tests for selection bias recommended by Bodenhorn et al. are not possible for child data since they rely on the equality of mean heights at each age in adulthood for individuals of the same birth cohort.

⁴³ NML, MAL, *Indefatigable* and National Sea Training School for Boys, annual reports of the *Indefatigable*, various years.

⁴⁴ For more information on the WHO growth reference and its use with historical data, see Schneider, 'Technical note'. More detail on the construction of the height-for-age *Z*-scores is available in online app. S1.

age is an input into the Z-score calculation. Unfortunately, for boys born in the nineteenth century we often only know the boy's age at his last birthday, that is, his age rounded down to the nearest year, rather than his precise age in years and months. Thus, to calculate the Z-scores of the WHO reference, we have to assign a more precise age to these boys. Online appendix S2 discusses several alternative methods for dealing with this issue. In the end, we add 0.5 years to those with rounded-down, imprecise ages and show that this would not strongly influence our results.

Our goal is to understand how height and height velocity by age profile changed over time. Thus, we implement a series of ordinary least squares regressions that control for all observable characteristics to ensure that compositional changes in our sample are not driving any changes in the growth pattern. We control for parents' HISCLASS category, child's county of birth, whether the child was born in several categories of urban districts, and whether the child was an orphan or had been deserted.⁴⁵ In addition, to generate age profiles, all regressions include one-year binned age dummies to capture non-linear differences in growth across ages. We also interact these age dummies with birth decade dummies to allow the relationship between age and height to vary over time. We provide more detailed discussion of the estimation procedure and control variables in online appendix S3.

When analysing longitudinal growth velocity, it is also necessary to control for and adjust the data based on how long each child spent on the ship. There was some measurement error in the recording of heights and weights on the ship usually because children were only measured to the nearest quarter- or half-inch. For cross-sectional measurements such as height at admission, this measurement error may increase the standard deviation around the mean, but because it is not systematic, it would not influence the mean of the distribution. However, this is not the case for measuring longitudinal growth, which presents four issues. First, a very small number of children actually became shorter during their time on the ship. We checked all of these cases in the original records and then excluded children with negative height growth from the analysis since these measurements are very likely to have been transcription errors in the original records. Second, children who remained on the ship for a relatively short period were more likely either to be given the same height measurement (rounded down) or to be rounded to the next measurable interval at their discharge measurement. Thus, these children were more likely to have either a growth velocity of zero or an extremely high velocity because they grew, for instance, half an inch in one month. To deal with this measurement error, we have excluded all children who were on the ship for less than four months. This is a less arbitrary way of reducing the measurement error than removing outliers and zero values, and indeed there are some outliers and zero value velocities that remain.⁴⁶

The third issue with measuring longitudinal growth from the *Indefatigable* data arises from the fact that we observe many of the boys during their pubertal growth spurt. The pubertal growth spurt is a relatively short period of high velocity growth, but unfortunately, the data only allow us to measure growth velocity as

⁴⁵ Urban population from Bennett, Robson, Law, and Langton, 'Urban population database'.

⁴⁶ We only exclude 83 longitudinal growth observations on these grounds because height at discharge was often not recorded for boys who were only on the ship for a short period. See online app. S1 for more detail.

the difference between the boy's height at discharge and admission divided by the length of time between measurements. This is problematic because the child's measured growth velocity would be influenced by the amount of time he spent on the ship. If we observed a boy for one year starting at age 14, we would have a good chance of catching some of his pubertal growth spurt. However, if we observed the same boy for three years, the growth velocity measured would include the pubertal growth spurt but also several years of slower growth bringing down the overall velocity. Thus, it is important to control for each child's duration of stay on the ship. The relationship between duration of stay and height velocity is non-linear, so we tried two approaches: a series of dummy variables capturing lengths of stay by half-year interval and controlling for the reciprocal of duration of stay. In the end, the reciprocal of duration of stay provided the best control and was used to estimate the adjusted height velocity and change in height-for-age Z-score measures.

The fourth issue with measuring longitudinal growth relates to how to assign ages to a growth velocity measure. Because we observe the velocity of growth as a line between admission and discharge, we have to decide an age to ascribe to the growth. We decided to use the midpoint between admission and discharge as the age for the growth velocity though this does not affect the results too much. However, because we do not observe precise ages for many children born in the nineteenth century, we do not have a precise admission age from which to measure the midpoint. Online appendix S2 discusses this issue at length, describing the extent to which the imprecision may lead us to place individuals in the wrong age bin and how this additional error would influence the velocity by age profile. We find that although we may place 28.5 per cent of the velocity sample in the wrong midpoint age bin, this does not strongly influence the velocity age profile nor does it bias our results.

A final consideration for all indicators is whether the relationship between each of the covariates and the outcome variables changed across the decades. By including, for instance, a dummy variable indicating that the child's mother had died in a regression on the full sample, we are assuming that the influence of the mother having died on a child's height was equal from the 1850s to the 1970s. This assumption may not be accurate, so we have tested for parameter stability for all variables across the birth decades. For nearly all of the variables, there was no statistically significant difference in the parameters across birth decades. The only exception to this was the reciprocal of duration of stay variable, so it was interacted with birth decade cohort dummies to capture the changing parameters over time. We also checked to make sure that the parameters were stable across different ages and again found that the parameters were remarkably stable. Online appendix S3 presents the parameter stability checks in detail.

Rather than presenting the regression tables, we have instead provided figures that show the predicted values for each dependent variable by birth cohort and age holding all other observable characteristics constant. These are simpler to interpret given the number of interactions in the underlying regressions. The adjusted figures in the graphs refer to the reference group in the regressions, which in this case means boys whose parents were both co-resident and living and were unskilled labourers (HISCLASS 11), born in Lancashire in a large urban district with more than 50,000 urban inhabitants in 1851. In the velocity regressions we have also used a duration of stay of 1.5 years to create the adjusted figures.

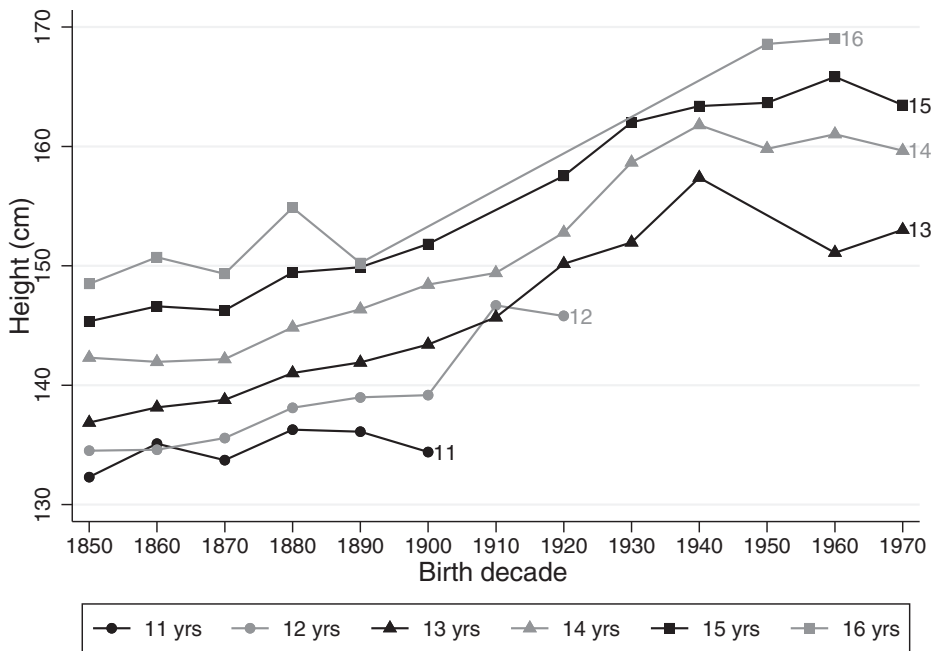


Figure 4. *Adjusted height by birth decade and admission age for Indefatigable boys, 1850–1970*

Notes: Ages are one-year binned admission age categories. The heights reported are predicted from a regression controlling for all observable characteristics. See online app. S3 for more detail.

Sources: *Indefatigable* dataset (see n. 21 and online app. S1).

IV. Main results

This section explores the changes in the growth pattern using the four different indicators discussed earlier. Figure 4 shows the adjusted admission heights of boys aged 11 to 16 born in each decade between the 1850s and the 1970s. The secular increase in stature is clear as boys of all ages became taller over time. However, there were four distinct periods of height increase in the data. First, there was stagnation or extremely modest improvement in boys' heights for the birth cohorts of the 1850s to 1870s. Second, there was modest improvement starting in the 1880s birth cohort and continuing to the 1910s birth cohort. This was associated with an increase in admission height of 1.75 and 1.84 cm per decade at age 13 and 14 respectively.⁴⁷ Then, there was a period of much more rapid growth occurring in boys born in the 1920s to 1940s. This corresponded to an increase in admission height of 3.86 and 4.11 cm per decade, over twice as fast as the previous period. Finally, there was stagnation more or less from the 1950s to the 1970s. Thus, it appears that the interwar period was the fastest period of improvement in children's admission heights, corroborating evidence collected across Europe showing a similar trend for adult heights.⁴⁸

⁴⁷ We have focused on ages 13 and 14 because these two age groups have consistently large sample sizes across nearly all birth cohorts over the period studied.

⁴⁸ Hatton, 'Europeans'.



Figure 5. Adjusted height-for-age Z-score by birth decade and admission age for Indefatigable boys, 1850–1970

Notes: Ages are one-year binned admission age categories. The height-for-age Z-scores reported are predicted from a regression controlling for all observable characteristics. See online app. S3 for more detail.

Sources: Indefatigable dataset (see n. 21 and online app. S1).

This relatively straightforward picture becomes harder to interpret when looking at the children’s height-for-age Z-scores at admission (figure 5). The first thing to notice is that the boys’ position relative to the modern WHO reference changes with age. Boys admitted at age 11 or 12 in the nineteenth century were much taller relative to modern standards than their 13- to 16-year-old counterparts, and the difference is large at one standard deviation of the modern reference. Read simply, this would suggest that boys in the nineteenth century became worse off as they aged. However, the real explanation for this pattern is the different timing of the pubertal growth spurt between the modern and historical populations. Eleven-year-olds in the *Indefatigable* sample appear taller relative to modern standards because eleven-year-olds in the modern reference had not started their pubertal growth spurts yet. As the modern children began their pubertal growth spurt, the *Indefatigable* boys continued to grow at slower height velocities, which made them appear to fall behind the reference. In addition, it is clear that these differences in the timing of the pubertal growth spurt create problems with interpreting change in the admission height-for-age Z-scores across birth cohorts. Both the absolute increase in the Z-scores over the entire period and the trends in Z-score increases vary across the different ages. How are we then to know what periods were more important than others?

In the end, there is relatively little to draw from figure 5, but it does make an important methodological critique of the existing literature. Figures like figure 5

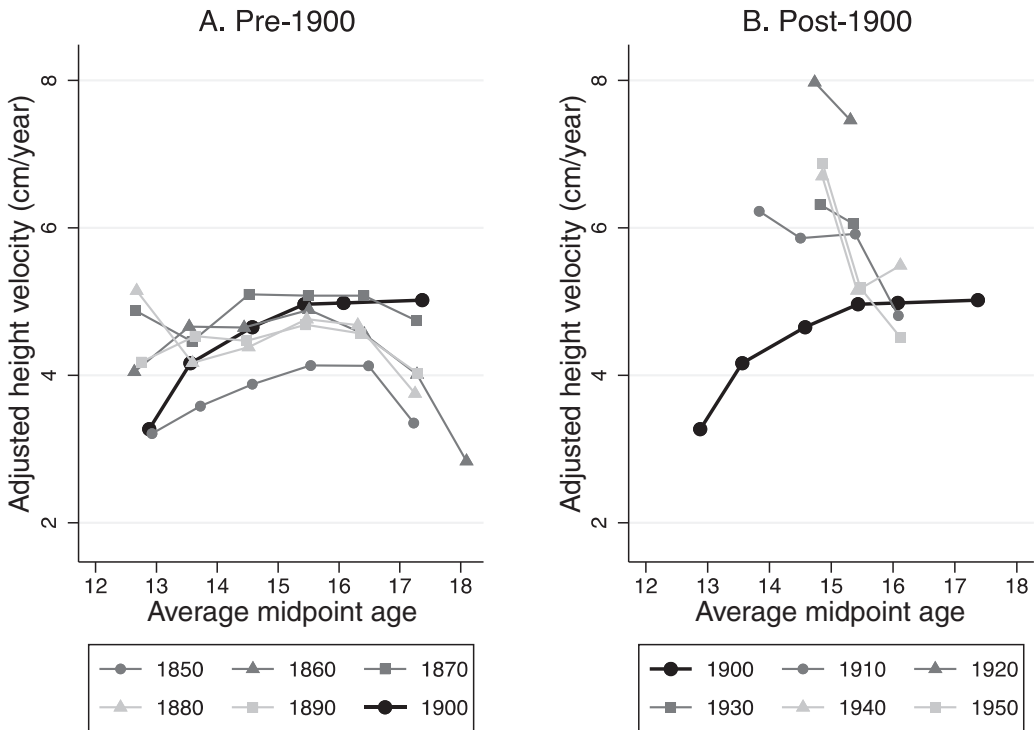


Figure 6. *Adjusted height velocity by age profiles by birth decade for Indefatigable boys*

Notes: Ages are one-year binned midpoint age categories. The velocities reported are predicted from a regression controlling for all observable characteristics. See online app. S3 for more detail.

Sources: *Indefatigable* dataset (see n. 21 and online app. S1).

have been standard in the anthropometric history literature since Harris analysed changes in British children's growth in the first part of the twentieth century.⁴⁹ Many authors have pooled height centiles from various age groups without accounting for these systematic differences that occur around the pubertal growth spurt. This is especially problematic when discussing both boys and girls since they experience the pubertal growth spurt at different ages. Thus, in the future, best practice should be either to control explicitly for age-related differences or to avoid the problem altogether by only analysing younger children with centiles or Z-scores of modern references.

We can expand upon this discussion of change in admission heights over time by utilizing the longitudinal growth measurements available in the *Indefatigable* dataset. Figure 6 presents the height velocity data slightly differently than the previous two figures. Rather than showing how the velocity of children at each age changed across birth cohorts, it shows how the growth velocity of children within one birth cohort changed across various ages. The left panel shows the birth decade cohorts 1900 and before, and the right shows the birth decade cohorts 1900 and after, with 1900 repeated as a reference across the two graphs.

⁴⁹ Harris, *Health*, p. 88; idem, 'Height'.

The pattern from figure 6 is surprising and clear. In the birth cohort decades 1900 and before, growth velocity between ages 12 and 17 was relatively low at between four and five centimetres per year, and there was no marked pubertal growth spurt as the growth velocity was similar across these ages. However, beginning in the 1910s birth decade cohort, growth velocity increased and a clear pubertal growth spurt appeared with children in a narrow range of ages experiencing a higher growth velocity than children at later ages.⁵⁰ With some imagination, one can also see a decline in the age at peak pubertal growth velocity in the right-hand panel. Children born in the 1910s, 1920s, and 1930s experienced higher velocities at age 15.5 than children born in the 1940s and 1950s. This corresponds to the shift toward earlier maturation that has occurred in the past 100 years.⁵¹ Thus, plainly read, the evidence suggests that boys on the *Indefatigable* did not experience a pubertal growth spurt before the 1910s. This finding is corroborated by longitudinal evidence from schools in London and Boston, Massachusetts at the end of the nineteenth and early twentieth century, which show flat growth velocity across puberty.⁵² The empirical strength of this finding and its implications will be queried in considerable detail in the next three sections.

Finally, figure 7 shows the change in height-for-age Z-score that occurred for children of a certain midpoint age across birth cohorts. This figure displays how closely children in the past were growing relative to the modern reference. If children in a particular birth cohort were growing on average along the modern reference, then all ages would be tightly clustered around zero because the change in height-for-age Z-score would be zero. Thus, the fact that the change in height-for-age Z-score is decidedly not clustered around zero in the nineteenth century suggests that the boys were not following the modern growth pattern. In the nineteenth century, boys whose midpoint age in the institution was age 12 to 13 fell behind modern standards during their time on the ship because they experienced normal, slow growth as the children in the modern reference experienced their pubertal growth spurt. Fourteen-year-olds fell behind to a lesser degree because the growth velocity in the reference was beginning to fall. Finally, 15-, 16-, and 17-year-olds caught up relative to modern standards as they experienced higher growth velocities than children in the modern reference, even if these velocities did not approach those associated with a pubertal growth spurt on average. This pattern was remarkably consistent through the 1900s birth decade cohort, but then rapidly shifted for children born in the 1910s and 1920s. By the 1920s, 14-, 15-, and 16-year olds were growing relatively close to modern standards, experiencing only slightly faster growth than children in the modern reference. This faster growth is greatest in the 1920s and falls until the 1950s, suggesting that the timing of the pubertal growth spurt may still have been delayed relative to the modern reference. Thus, it appears that there was a rapid shift in the growth pattern of the children in the 1910s and 1920s that shifted their pattern closer to that of the modern one.

⁵⁰ Online app. section S3c presents results of estimating the velocity curves based on admission and discharge age rather than midpoint age, as well as a specification that includes both admission and discharge age dummies. These results confirm the general findings presented in the text.

⁵¹ Schneider, 'Children's growth'; Tanner, *Growth at adolescence*, pp. 152–5; Brundtland and Walløe, 'Menarcheal age'.

⁵² Schneider, 'Health', p. 335.

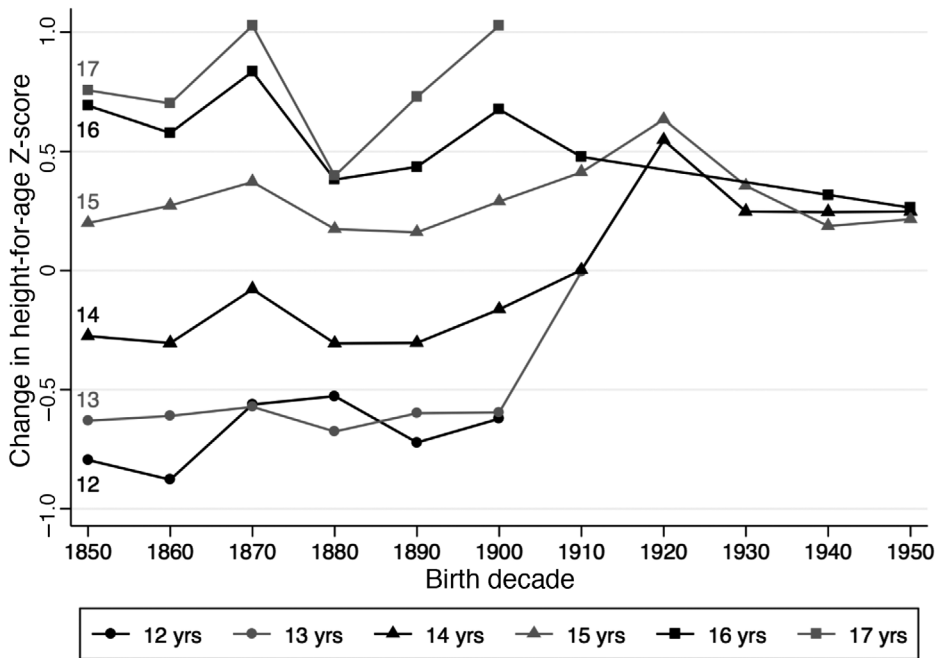


Figure 7. *Adjusted change in height-for-age Z-score by birth decade and midpoint age for Indefatigable boys, 1850–1950*

Notes: Ages are one-year binned midpoint age categories. The change in height-for-age Z-scores reported are predicted from a regression controlling for all observable characteristics. See online app. S3 for more detail.

Sources: *Indefatigable* dataset (see n. 21 and online app. S1).

V. Did health conditions on the ship influence the growth pattern?

The most striking result presented above was that the *Indefatigable* boys born in the nineteenth century and first decade of the twentieth century did not seem to experience a strong pubertal growth spurt as we might normally expect. This is quite puzzling since the pubertal growth spurt is now an established part of adolescent development. We argue that the relative flatness of the velocity curve experienced by birth cohorts before the 1910s reflects real lower velocities of growth for these children. However, there are several alternative explanations that need to be addressed, and these will be covered in the next three sections.

One possible explanation for the changing growth pattern of children is that health conditions on the *Indefatigable* changed over time, perhaps benefiting children born from the 1910s onward when we see changes in the growth pattern. Proving that this is not the case is complicated because the surviving institutional records for the *Indefatigable* are less detailed than those of other institutions.⁵³ In particular, we are concerned that there may have been changes in health conditions when the *Indefatigable* was relocated from the river Mersey to a land-based facility in North Wales in 1941. It is important to note that the relocation of

⁵³ *Ibid.*, pp. 312–30.

the school would have influenced boys born in 1927 and later, so any improvement in health conditions associated with the relocation cannot explain the change in the growth pattern for children born in the 1910s. To test whether health conditions changed significantly with the relocation, ideally we would check whether the boys' longitudinal growth was similar before and after the relocation. Unfortunately, we cannot analyse changes around this date directly because the crew did not record discharge heights for boys between 1933 and 1941 (see online appendix figure S1 for more detail). Thus, because we cannot look at the immediate effects of relocating the school directly, we proceed with a careful study of the qualitative evidence to see whether there were substantial changes in health conditions that would have affected the 1910s birth cohort onwards or that were associated with the relocation of the school.

The little evidence that we have about health conditions on the ship does not indicate that there were drastic changes during the interwar period. Figure 8 presents data on the real expenditure per boy in a number of categories that could have influenced the children's well-being. In order to simplify the interpretation of these figures, the x-axis shows the year in which the expenditure occurred. However, the vertical dashed grey lines show the corresponding birth decade cohorts for the years of expenditure so that we can relate expenditure to the experience of specific birth cohorts. Figure 8a shows that real expenditure per boy on provisions declined for birth decade cohorts from the 1880s and 1890s to the 1930s. The same pattern is present in clothing expenditure and medical expenditure which is more or less flat before declining for birth decade cohorts after the 1930s when the ship began benefiting from the newly formed NHS. Total ordinary expenditure, expenditure excluding one-off repairs or purchases of new ships, also declined for birth decade cohorts from the 1890s to the 1930s. Thus, it does not seem likely that greater spending on day-to-day care and nutrition can explain the change in the growth pattern that we observe beginning in the 1910 birth decade cohort. If anything, conditions were worsening, especially during the Second World War when the captain-superintendent had difficulty obtaining fuel and food for the ship.⁵⁴

In addition to expenditure, we also looked for mentions of the diet in the boys' memoirs quoted at length in Evans.⁵⁵ Online appendix table S9 documents the descriptions of the diet by the boys between the 1880s and the 1960s. Although the types of food changed and the diet seemed to worsen during wartime periods, it is difficult to find dramatic changes in the diet, especially between boys enrolled in the 1920s and the 1940s on either side of the change in the pubertal growth spurt and the relocation of the school. There may have been more meat in the diet in the 1940s, but without an idea of portion sizes and the quantities of meat and milk provided, it is difficult to make conclusive judgements. Interestingly, there are strong descriptions from both the 1920s and the 1940s about how terrible the food was and how the boys were 'always hungry'.⁵⁶ Perhaps this just highlights the high energy requirements of teenage boys whether growing rapidly or not. Thus, the anecdotal evidence is difficult to interpret but seems to concur with the

⁵⁴ NML, MAL, D/IND/1/4/1, *Indefatigable* and National Sea Training School for Boys, annual reports of the *Indefatigable* (1940–90), 'Seventy-sixth annual report [1941]', p. 4.

⁵⁵ Evans, *Indefatigable*.

⁵⁶ *Ibid.*, pp. 35–7, 61, 63, 114, 144.

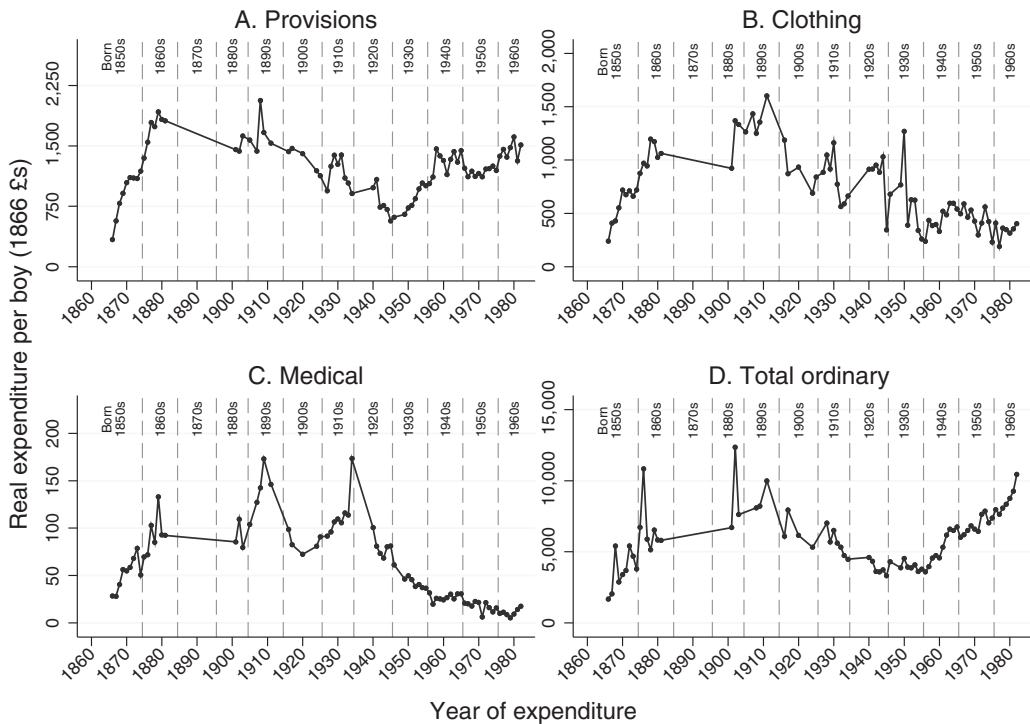


Figure 8. *Expenditure per boy in various categories, 1860s–1980s*

Notes: Total expenditure in each category was first divided by the number of boy-years lived on the ship in each year and then deflated by the Bank of England consumer price index to show real expenditure in 1866 pounds. The x-axis shows the year of expenditure, but the dashed vertical grey lines demarcate birth decade cohorts. The stock of boys on the ship was calculated from the data using the admission and discharge dates to calculate the precise number of boy-years lived on the ship in each year. Ordinary expenditure was spending on normally budgeted items such as the items listed in figs. 8a–c but excludes extraordinary expenditure on repairs, purchasing new ships, and so on. Missing data are driven by a lack of primary evidence on these forms of expenditure.

Sources: Expenditure data drawn from NML, MAL, D/B/115N/1, *Indefatigable* and National Sea Training School for Boys, annual reports of the *Indefatigable* (1865–81); D/CC/IND/1/1–2 (1901–34); D/IND/1/4/1 (1940–90). The stock of boys in the school was constructed from the *Indefatigable* dataset described in online app. S1. The consumer price index was drawn from Bank of England, 'A millennium of macroeconomic data', tab. A.47, <https://www.bankofengland.co.uk/statistics/research-datasets> (accessed on 16 Feb. 2018).

expenditure evidence that there were not radical improvements in the diet across the birth cohorts where the growth pattern changed.

We might also worry that the boys' physical workload changed after the *Indefatigable* moved on shore, but this does not appear to have been the case. The staff were fully aware that moving on land might potentially lower the boys' physical activity, so more sports activities were added to the timetable and the boys practised sailing and navigation during 'outward bound' sea school or on local rivers. They were also still responsible for cleaning their quarters and performing other domestic tasks.⁵⁷ Thus, we are very confident that the change in growth pattern experienced

⁵⁷ NML, MAL, D/IND/1/4/1, *Indefatigable* and National Sea Training School for Boys, annual reports of the *Indefatigable* (1940–90), 'Annual report [1943]', p. 3; 'Annual report [1946]', p. 4.

by birth cohorts from 1910 onwards was not driven by improvements in health conditions on the ship.

VI. Does dispersion in the timing of pubertal growth flatten mean growth velocity?

Another possible explanation for lower growth velocities and a lack of a distinctive pubertal growth spurt in the nineteenth century is that there may have been greater variation in the timing of the pubertal growth spurt in the past than in the twentieth century. If children experienced the pubertal growth spurt across a wide age range, then on average the velocity-age profile would be flatter because the high velocities of children experiencing pubertal growth at a given age would be cancelled out by the low velocities of children who had already experienced their pubertal growth spurt or who were yet to achieve it. Thus, the result we presented above could simply be ecological fallacy, that is, spuriously attributing a pattern at the group level to individuals. This is a real possibility in our data, and is especially important to consider given that all of the historical longitudinal growth curves that have been analysed to date show a strong pubertal growth spurt. These include the first longitudinal growth curve produced by de Montbeillard of his son in the mid-eighteenth century.⁵⁸ In addition, the longitudinal measurements of boys in the Carlschule in Stuttgart in the late eighteenth century also confirmed that these boys experienced a pubertal growth spurt. Worryingly, the lower-class boys also had greater dispersion in their age at peak velocity than the upper classes.⁵⁹ Finally, longitudinal data collected from family members of the pioneer auxologist Henry Pickering Bowditch in the mid-nineteenth century also show a strong pubertal growth spurt when analysed with the SITAR growth model.⁶⁰ Thus, it is necessary to consider whether greater dispersion in the timing of the pubertal growth spurt in the past may be driving our results.

It is difficult to test for this directly in the *Indefatigable* data. Because we only observe the boys' heights twice, we cannot determine where each boy was in his development. Therefore, we conduct a series of simulations that predict complete growth curves for simulated individuals and use the results to cross-validate our findings in the *Indefatigable* dataset. Unfortunately, there is not sufficient space here to provide the full explanation and justification for the simulations, but we provide these details in online appendix S5 for those who want to understand the exercise fully.

We start with a growth curve for the Bowditch longitudinal data for mid-nineteenth-century Boston mentioned above. This was predicted using the SITAR growth model and reflects the average individual-level growth curve for this group. As shown in online appendix figure S16, the Bowditch mean curve has a very strong pubertal growth spurt with growth velocity increasing from 4.4 cm per year at the beginning (take-off) of the pubertal growth spurt to 8.0 cm per year at the peak of the growth spurt.

⁵⁸ Tanner, *History*, pp. 104–5.

⁵⁹ My thanks to Tim Cole for pointing me toward the data for this source. Komlos, Tanner, Davies, and Cole, 'Growth'.

⁶⁰ Data from Tanner, *History*, pp. 186–7. SITAR analysis conducted by the authors using Cole, 'Super imposition'; and R Core Team, 'R'.

The simulation takes the Bowditch individual-level mean curve and uses the insights of the SITAR growth model to predict individual-level growth curves. It does this by adjusting the mean curve in three ways: it shifts the height curve up or down influencing the final adult height of the individual (size); it shifts the height curve left or right changing the age at peak velocity during the pubertal growth spurt (timing); and it stretches the age scale to account for differences in the speed of maturation across individuals (intensity). These three parameters—size, timing, and intensity—explain differences between individual curves and the mean curve in the SITAR model.

We simulate the individual curves under four sets of assumptions, which vary the dispersions of and correlations between the three parameters. The dispersions and correlations underpinning each set of assumptions are drawn from the analysis of two datasets using the SITAR growth model. The first, the Christ's Hospital School dataset from the mid-twentieth century, is analysed by Cole et al. and provides assumptions for modern children.⁶¹ The second dataset is the late eighteenth-century Carlschule dataset described earlier.⁶² We analysed this dataset for all boys and for a sample of lower-class boys to understand the potential differences across social groups. The fourth and final set of assumptions simply increased the dispersion of the timing parameter for the Carlschule lower class assumption to produce the maximum possible amount of variation in the timing of the pubertal growth spurt. Online appendix table S10 presents the assumptions behind each simulation, but what is most important is that across the simulations the standard deviation of the timing parameter increases from 0.97 under the Christ's Hospital School assumptions to 1.87 for the Carlschule lower class assumptions. Thus, the simulation allows us to test how expanding the dispersion in the timing of the pubertal growth spurt would affect the mean velocity at each age across individuals while holding the underlying individual-level mean curve constant.

Online appendix figure S18 shows the results, which confirm that as the variation in the timing parameter increases across the simulations, the mean velocity at each age, similar to our earlier prediction in figure 6, becomes flatter and flatter. As mentioned above, this is while holding the underlying individual mean curve constant, so this pattern is driven entirely by the dispersion of the growth pattern parameters. Under the Christ's Hospital School assumption, we would observe an increase in velocity between the take-off and the peak of pubertal growth of 1.5 cm per year, but this falls to 0.3 cm per year for the fourth simulation with much greater dispersion in the timing parameter. Thus, the simulation confirms that our results above may simply be driven by the greater dispersion in the timing of the pubertal growth spurt in the nineteenth century.

However, the story is not so simple. The simulation has proven that ecological fallacy could lead one astray when trying to infer individual-level growth patterns from grouped data, but this does not mean that the simulation is consistent with the pre-1910 *Indefatigable* data. What is clear from the simulated individual-level velocity curves in online appendix figure S17 is that large shares of individuals were experiencing rapid pubertal growth above 6.2 cm per year, the midpoint velocity between the velocity at the take-off and the peak of the pubertal growth spurt in

⁶¹ Cole, Donaldson, and Ben-Shlomo, 'SITAR', p. 1562.

⁶² Komlos, *Carlschule students*.

the Bowditch individual-level mean curve. Measuring this formally, at least 30 per cent of simulated boys aged 13 to 17 were experiencing growth above the threshold. If we calculate the same share for the pre-1910 *Indefatigable* data, far fewer boys were experiencing rapid pubertal growth: only between 10 and 16 per cent of boys between ages 13 and 16 experienced growth above the threshold.⁶³ Thus, the Bowditch individual-level mean curve does not reflect the individual-level mean curve of the *Indefatigable* boys.

To find an individual-level mean curve that would be compatible with the *Indefatigable* dataset, we create alternative versions of the Bowditch individual-level mean curve by slowing the intensity (speed of maturation) of the curve. This means that growth takes place more slowly over a longer period of time and the pubertal growth spurt becomes less pronounced. We adjust the Bowditch curve by one and two standard deviations of the Christ's Hospital School intensity parameter and then re-run all of the simulations using the adjusted Bowditch curve as the new mean curve in the simulation. These adjusted curves also have lower thresholds for pubertal growth since the pubertal growth spurt is less pronounced. In the end, the Bowditch curve adjusted downward two standard deviations in intensity most closely matches the *Indefatigable* dataset in shares experiencing rapid pubertal growth. However, this is a curve with a much less pronounced pubertal growth spurt than the original Bowditch curve.

Taking these findings together, we cannot rule out that the *Indefatigable* boys were experiencing a pubertal growth spurt of some kind, but the growth curve that is consistent with the growth observed in the *Indefatigable* data is still very different from the other longitudinal growth curves predicted from historical data. The peak velocity during puberty of the matching intensity-adjusted Bowditch curve is 5.9 cm per year, which is far lower than the peak velocity of the Bowditch mean curve at 8.0 cm per year and both of the Carlschule curves which peak at 8.3 cm per year and 8.6 cm per year for the complete sample and lower-class sample respectively. Tanner and Whitehouse's British longitudinal height standard from the 1960s shows a peak velocity during puberty of around 9.5 cm per year for the 50th percentile, which is at least one standard deviation in intensity above the Bowditch mean curve.⁶⁴ Thus, if the pre-1910 *Indefatigable* boys were experiencing a pubertal growth spurt, it would be three standard deviations in intensity below modern standards with peak velocity during puberty around 3.6 cm per year lower. This is consistent with our argument that there was not a strong pubertal growth spurt in the pre-1910 period.

The simulation results also help to reveal the nature of the sudden change in the growth pattern between the pre-1910 and post-1910 periods. The fact that changes in the mean velocity across individuals appear for these cohorts in figure 6 suggests that there was a substantial reduction in the dispersion of the pubertal growth spurt for the later cohorts, perhaps because health disparities across individuals were becoming smaller due to improvements in income and nutrition and public health interventions. In addition, when looking at the post-1910 period as a whole, a far greater share of boys were experiencing rapid pubertal growth (see online appendix

⁶³ We compute the simulated velocities with 2.4 years between measurements, the mean length of stay on the ship in the pre-1910 period, so that differences in the increment between measurements do not influence the results.

⁶⁴ Tanner and Whitehouse, 'Clinical longitudinal standards', p. 175.

figure S20), which suggests that there was also a shift to a growth curve with a faster rate of maturation and thus greater average growth velocity. This shift fits well with Cameron's earlier work on Britain and the larger literature on changes in the growth pattern over time.⁶⁵

Thus, the simulation points toward a novel way in which the growth pattern has changed since the mid-nineteenth century: there has been a reduction in the dispersion of the timing of the pubertal growth spurt over time as growth began to follow a more uniform pattern. This reduction in dispersion occurred alongside a reduction in the age at peak velocity during the pubertal growth spurt. This is an important observation to consider for those analysing worldwide variation in the growth pattern and the evolutionary underpinnings of human growth.⁶⁶

VII. Why do cross-sectional nineteenth-century sources show pubertal growth?

Having resolved the differences between longitudinal growth curves showing a pubertal growth spurt and the *Indefatigable* data, we still must reconcile our results with earlier, cross-sectional studies of human growth including the studies by contemporaries in the nineteenth century that found a clear pubertal growth spurt in their data. In fact, the presence or absence of a pubertal growth spurt was a topic of great interest in the nineteenth century. Quetelet was the first to produce a cross-sectional growth curve from the heights of children at different ages in 1831, and he conspicuously did not find a pubertal growth spurt. Later authors such as Roberts and Bowditch writing in the 1870s challenged Quetelet's results, finding evidence of a pubertal growth spurt in their data.⁶⁷ Anthropometric historians have also found considerable evidence of pubertal growth spurts in historical settings from Steckel's original work on slaves to his later work comparing slaves to other historical populations, to more recent work by Quanjer and Kok on Dutch boys.⁶⁸ Thus, it is necessary to consider a range of possibilities for why the pubertal growth spurt appeared in these cross-sectional studies but is absent in our individual-level, longitudinal data. In order to do this, we will focus on Roberts's study of child growth in the UK in the 1870s since this is more comparable to our data than Bowditch's study of Boston children.⁶⁹

The largest problem with the data arises from sample selection bias. Using the Bowditch data and data drawn from school records in Japan, Schneider has highlighted how selection on unobservables can bias estimates of the timing and velocity of the pubertal growth spurt in school samples.⁷⁰ Because most school samples are based on cross-sectional data—that is, the growth curve is drawn from the average height of children measured in the same year at different ages—any positive selection related to age would bias the mean height upward and exaggerate the growth velocity between ages. Selection on unobservables occurs because enrolment rates in primary school were near universal in most western countries

⁶⁵ Cameron, 'Growth'; Cole and Mori, 'Fifty years'.

⁶⁶ Wells, 'Worldwide'.

⁶⁷ Tanner, *History*, pp. 134, 179, 192.

⁶⁸ Steckel, 'Peculiar population'; idem, 'Growth depression'; Quanjer and Kok, 'Tall boys for tall ships?'

⁶⁹ Anthropometric Committee, *Final report*, pp. 287–90.

⁷⁰ Schneider, 'Sample-selection biases'.

and in Japan at the end of the nineteenth century, but enrolment in secondary school was much lower. Thus, school datasets that draw from the population of children in school may suffer from selection on unobservables if children in secondary school were positively selected on height. It is important to note that controlling or reweighting for social class may not be enough to account for these effects. Even within a social class, if children who attend secondary school are positively selected relative to other children in their class, the growth and velocity curves will be biased.⁷¹

The question then is whether Roberts's studies of British children in the 1870s also feature these types of biases. As Tanner discusses, in Roberts's earlier work he used data drawn from school children to obtain heights up to the age of 15 but then used the heights of boys recruited into the army or navy from 16 to 25. This change in sampling led to a sharp increase in velocity between ages 15 and 16 since boys joining the military were subject to minimum height requirements. Tanner argues that taking the modal rather than mean values of the height of boys entering the military reduces the bias in the data and argues that there is still strong evidence for a pubertal growth spurt.⁷² This is optimistic. Whether the modal value of height in a truncated distribution is a good proxy for the population mean is determined by where the truncation occurs in the distribution and whether other selection mechanisms could make the sample unrepresentative. Tanner's adjustment of Roberts's original work shows a flat velocity curve until the interval between ages 15 and 16 where it increases and then falls again.⁷³ Thus, the only evidence of a pubertal growth spurt occurs for the age group when the data source changes.

We can also look at Roberts's later work which was expanded as a part of the Anthropometric Committee of the British Association for the Advancement of Science.⁷⁴ The committee built upon Roberts's work just described but also collected more data on children's growth from a wide variety of schools. The children were then grouped into occupational groups meant to capture various environmental conditions that might influence growth, namely, the expected income of an occupation and the sanitary conditions in the place where the child was living. The sanitary categories divided children between urban and rural areas and whether their fathers carried out their labour indoors or outdoors.⁷⁵ This classification system contained six classes, but the committee only had sufficient data to analyse four. Class 1 contained the upper classes and professionals. Class 2 contained the urban commercial classes such as clerks and shopkeepers. Class 3 contained workers in the countryside including agricultural labourers and miners. Class 4 contained urban 'artisans' described as engravers, printers, and workers in wood, metal, stone, leather, and paper. The fifth and sixth classes for which there were not sufficient data covered urban factory workers on the one hand and soldiers, policemen, and criminals on the other. However, these four classes still provide considerable variation and a fair number of urban working-

⁷¹ Ibid.

⁷² Tanner, *History*, pp. 177–8.

⁷³ Ibid.

⁷⁴ Anthropometric Committee, *Final report*, p. 253.

⁷⁵ Ibid., pp. 281–3.

class individuals: it seems likely that the sons of many semi-skilled working-class individuals are categorized in class 4.⁷⁶

If we look at the growth and velocity curves for each class reported by the Anthropometric Committee, we see some very puzzling results. First, although classes 3 and 4 start out far behind class 2, these lower classes experience strong convergence to class 2 between ages 13.5 and 15.5, the exact ages when boys left primary school and gained statutory rights to work (figure 9a).⁷⁷ The convergence at these ages is suspicious and may suggest positive selection on unobservables. Second, boys in classes 3 and 4 experienced earlier and more pronounced pubertal growth spurts than boys in the higher classes (figure 9c). The peak of pubertal growth occurred two years earlier for boys in class 4 than boys in class 1. This pattern contradicts what we know about the change in the growth pattern over time, and the class differences in the growth pattern in other datasets.⁷⁸ Boys in class 3 experienced an interval of nearly 10 cm per year at age 15, far above plausible average levels of growth that should appear in cross-sectional data.⁷⁹ In fact, this very high velocity seems to be an artefact of a very small sample size in class 3 at age 14.5 followed by a return to a larger sample size at age 15.5, signalling a shift in the composition of the sample (figure 9b). Because the Anthropometric Committee did not report the individual means for every school separately, it is not possible to account for these changes in composition in the data, let alone any selection on unobservables.

Although there is not quite a smoking gun, all of the evidence presented here suggests that unobservable selection correlated with age accentuated the pubertal growth spurt in the Roberts and Anthropometric Committee data. This finding is corroborated by data from Boston and Japan.⁸⁰ Thus, cross-sectional, nineteenth-century data that suggest a strong pubertal growth spurt are far more problematic than previously acknowledged.

VIII. Conclusion

This article has shown that the secular increase in mean adult stature was also associated with a fundamental change in the growth pattern of children. Unlike the secular increase which saw improvements in height across a large number of years, the change in the growth pattern occurred more suddenly. Boys born in the 1910s and later began to show a pronounced pubertal growth spurt that was not apparent in the earlier period. Simulation results suggest that this change in the growth pattern was probably caused by both a reduction in the dispersion of the timing of the pubertal growth spurt and by an increased speed of maturation and thus higher growth velocity. This sudden change would not have been predicted from a biological perspective or from the existing analysis of changes in the growth pattern, mainly from cross-sectional evidence. For instance, Cameron finds a general increase in size and the speed of maturation in twentieth-century London,

⁷⁶ *Ibid.*, pp. 282, 287.

⁷⁷ de Pleijt, 'Human capital', p. 112.

⁷⁸ Steckel, 'Growth depression', p. 127; Cole, 'Secular trend'.

⁷⁹ Because cross-sectional data averages across individual-level variation, it understates velocities; see Tanner, Whitehouse, and Takaishi, 'Standards', p. 458.

⁸⁰ Schneider, 'Sample-selection biases'.

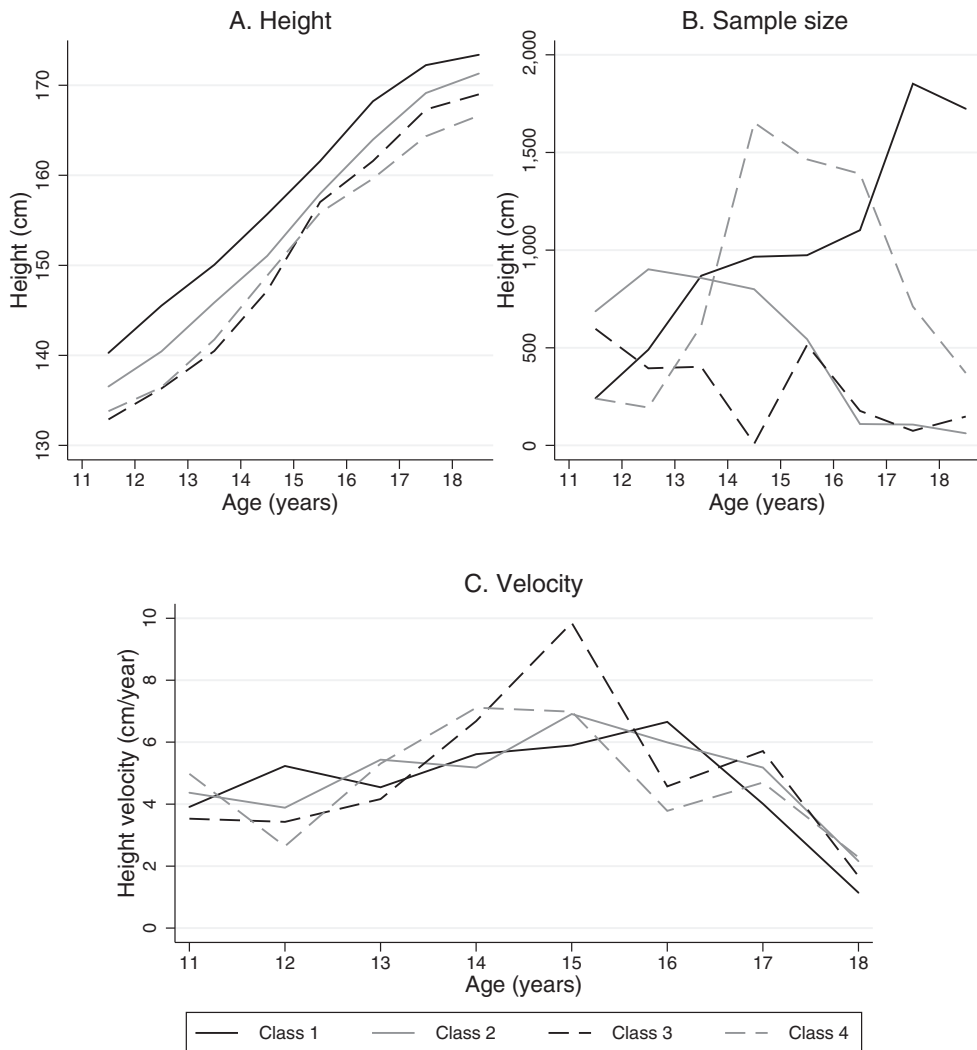


Figure 9. *Growth pattern of Roberts's British boys by social class, c. 1860s–70s*

Notes: Class 1 contains the upper class and professionals (4.46% of workers by their classification in the 1870 census). Class 2 contains commercial classes like clerks and shopkeepers (10.36%). Class 3 contains labourers working in rural areas such as agricultural labourers and miners (47.46%). Class 4 contains urban artisans such as engravers, printers, and 'workers in wood, metal, stone, leather and paper' (26.82%). This includes a fair number of semi-skilled workers in the manufacturing sector. The committee did not report data for their class 5, the industrial classes, which contained 'factory operatives', tailors, and shoemakers (10.90% of 1870 workers), because there were not enough data.

Sources: Anthropometric Committee, *Final report*, pp. 287–90.

but not such a sharp change.⁸¹ Thus, the longitudinal evidence presented in this article offers a truly unique and vital perspective on how children's growth has changed over time.

Unfortunately, this study is not able to identify precisely the causes of the change in the growth pattern. These causes are difficult to identify because the growth

⁸¹ Cameron, 'Growth'.

pattern is influenced by health conditions around birth that set the biological process of development and maturation but is also influenced by changes in conditions at later ages that may shift a child from the growth pattern determined *in utero* and in early life.⁸² Separating the influence of health shocks and interventions in different critical windows during development is difficult and requires either carefully specified empirical models that can remove the influence of conditions in one of the periods or health shocks that affect children in different birth cohorts at different ages.⁸³ In addition, it is difficult to identify individual-level patterns of growth in our data because the growth pattern is non-linear and our data only reveal linear growth between two ages.

Although we are not able to identify precisely the causes of changes in the growth pattern, the sudden shift beginning with children born in the 1910s and the boys' rapid growth during the interwar period help to narrow the list of potential factors.⁸⁴ First, improvements in nutrition were not likely to be the root cause of the sudden change in the growth pattern because most studies analysing change in British nutrition over time find that food was plentiful and of relatively high quality by the beginning of the twentieth century.⁸⁵ Survey evidence suggests that both urban and rural households had enough calories and protein, though they suffered from shortages of key micronutrients such as calcium and vitamin C.⁸⁶ Even the First World War did not substantially reduce nutrients available to the British working class.⁸⁷ Thus, improvements in nutrition do not coincide with the change in the growth pattern.

However, there was one change in nutrition that might have mattered: the introduction and expansion of the school meals and milk-in-schools programmes. Originally introduced in 1906 and expanded thereafter, the school meals programme provided free meals to poor and malnourished children while charging other better-off children for the meals. The policy was implemented by local education authorities and expanded and contracted throughout the interwar period, with the greatest expansion in the 1930s. Although the programme was limited with only 2–3 per cent of children receiving free solid meals, its targeted nature may have reduced nutritional inequality among children. In addition to the school meals policy, there was also an expansion of milk provided free or at reduced cost to schoolchildren so that by the late 1930s, 2.7 million children were receiving milk at school, of which 635,000 children received it for free.⁸⁸ The expansion of the milk-in-schools programme also coincided with the introduction of pasteurization of milk, which made milk a safe and rich source of nutrients.⁸⁹ These targeted nutritional interventions and especially the widespread provision of milk improved the nutrition of children and probably contributed to the shift in the growth pattern.⁹⁰

⁸² Schneider, 'Children's growth', pp. 4–9.

⁸³ Schneider and Ogasawara, 'Disease', provides an example of the former, while Depauw and Oxley, 'Toddlers', and Schneider et al., 'Effect', are examples of the latter.

⁸⁴ Hatton, 'Infant mortality'; idem, 'Europeans'.

⁸⁵ Floud, Fogel, Harris, and Hong, *Changing body*, p. 167.

⁸⁶ Gazeley and Horrell, 'Nutrition'; Gazeley and Newell, 'Urban working-class food consumption'.

⁸⁷ Gazeley and Newell, 'First World War'.

⁸⁸ Harris, *Health*, pp. 120–6.

⁸⁹ Atkins, 'White poison?'.

⁹⁰ Baten and Blum, 'Agricultural production'; Headey, Hirvonen, and Hoddinott, 'Animal sourced foods'.

Beyond nutrition, there were also important reductions in child morbidity in the early twentieth century. Child mortality began declining from the mid-nineteenth century, but as many authors have argued, infant mortality may be a better proxy for chronic morbidity of children than child mortality. Infants often died of diarrhoea and respiratory infections that caused chronic illness in young children but led to fewer deaths outside infancy.⁹¹ Infant mortality did not decline at the national level in Britain until around 1900 with most of the decline occurring by 1950.⁹² Thus, the timing of the infant mortality decline suggests that reductions in child morbidity could have been key for the changes in the growth pattern observed in this study.

Our results also speak to the literature in development economics, human biology, and economic history about critical windows in human development where health shocks may matter most for growth. Many scholars emphasize the importance of the first thousand days from conception to the age of two years. This is the period where most growth faltering—that is, slower growth leading children to be stunted—occurs, and at the population level, there is little catch-up to modern growth standards after this period.⁹³ However, more recent historical and modern studies have highlighted the importance of shocks and interventions for the growth pattern that occur outside this thousand-day window.⁹⁴ Our finding of a weak pubertal growth spurt does not necessarily contradict findings that health shocks in adolescence may influence heights.⁹⁵ For instance, Depauw and Oxley find final adult height deficits of 1–2 cm for Belgian prisoners who experienced two economic crises in the mid-nineteenth century. This is a sizeable effect on adult stature.⁹⁶ However, 1–2 cm at adulthood is not large when considering that even in the nineteenth century the *Indefatigable* boys were growing at 4–5 cm per year from ages 13 to 17. Thus, puberty may be a critical window not because of the pubertal growth spurt but because children suffering health shocks in puberty have less time to recover at later ages.

Our findings also open interesting questions for future research. First, our results differ starkly from other historical longitudinal growth curves that show a very strong pubertal growth spurt.⁹⁷ This may be because these longitudinal data tend to come from elite populations that may not be representative of general historical populations in the eighteenth and nineteenth centuries. Thus, it is important to collect longitudinal growth measurements for other historical populations to see if there was a strong pubertal growth spurt before the onset of the secular increase in height and determine whether the pattern we have uncovered for British children is unique or a more widespread feature of the secular increase in height and change in the growth pattern. In addition, our finding that the growth pattern changed rather suddenly suggests that further research is needed to understand

⁹¹ Sharpe, 'Explaining'; Hatton, 'Infant mortality'; Schneider and Ogasawara, 'Disease'; Bailey, Hatton, and Inwood, 'Atmospheric pollution'.

⁹² Woods, *Demography*, p. 253.

⁹³ Victora, de Onis, Hallal, Blossner, and Shrimpton, 'Worldwide'; Wells, 'Worldwide'; Almond, Currie, and Duque, 'Childhood'.

⁹⁴ Prentice, Prentice, Ward, Goldberg, Jarjou, Moore, Fulford, and Prentice, 'Critical windows'; Stein, Wang, Martorell, Norris, Adair, Bas, Sachdev, Bhargava, Fall, Gigante, and Victora, 'Growth patterns'; Akresh, Bhalotra, Leone, and Osili, 'Impacts'.

⁹⁵ Prentice et al., 'Critical windows'; Schneider and Ogasawara, 'Disease'.

⁹⁶ Depauw and Oxley, 'Toddlers', pp. 14–16.

⁹⁷ Komlos et al., 'Growth'.

what factors influence the growth pattern and what stages of human development were critical windows where shocks or positive health interventions could make the most difference in the growth pattern. It also highlights yet again that the interwar years were a particularly crucial period for improvements in child health. However, despite its importance, there are relatively few studies focusing on changes in health during the interwar period. Finally, this research needs to be extended to girls so that we can understand whether similar changes in the growth pattern occurred for them. This should be a priority for researchers since women's health may not be perfectly correlated with men's health and is important for the intergenerational transmission of health.⁹⁸ Finding longitudinal growth measurements for girls in the long run will be difficult because there are fewer long-run historical sources upon which to draw, but discovering these sources is vital for understanding the secular increase in height and change in the growth pattern.

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⁹⁸ Osmani and Sen, 'Hidden penalties'; Horrell and Oxley, 'Gender bias'; Schneider, 'Health'.

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Supporting information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

S1. Data sources and construction

S2. Precision of age measurements

S3. Further information on the estimation strategy

S4. Further information on living standards on the ship

S5. Simulations to compare *Indefatigable* data with other historical longitudinal growth curves