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The Growth Pattern of British Children, 1850-1975[1]

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Abstract:

This paper 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 1970s. Based on a unique dataset gathered from the records of the training ship *Indefatigable*, we analyse the mean heights of boys at admission and their longitudinal growth using regressions that control for observable characteristics. We find a secular increase in boys' mean height over time, and the 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 that there was no marked pubertal growth spurt like that which occurs in modern populations. However, for boys born in the 1910s and later, higher growth velocities associated with pubertal growth appeared for boys in a narrow range of ages, 14 to 16. 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 and improved hygiene mattered more for the changing growth pattern than improvements in nutrition that occurred before the 1910s.

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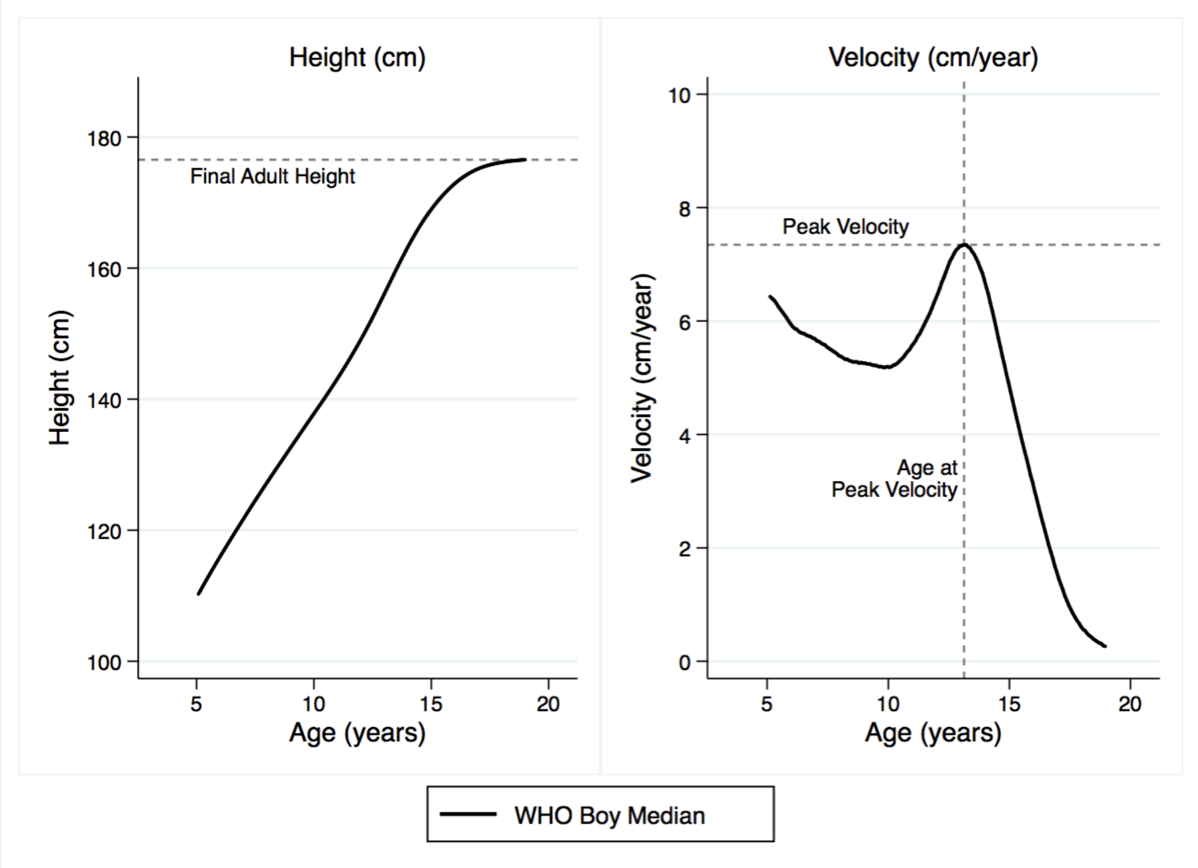
1. Introduction

Economic historians have long used anthropometric measures such as height and BMI to track economic development and living standards over time. Most of the existing research has focused on adults, using records from military enlistment and conscription, prisons, ship manifests and many other types of records.[2] These studies find that there has been a secular increase in adult mean stature since the mid-nineteenth century, reflecting improvements in nutrition and the disease environment over the same period. This increase has occurred in almost every country in the world over the past 100 years, although with large variations between countries: mean height in some African countries has only increased by one or two cm whereas mean height gain in Japan, Korea and Iran was between 16 and 20 cm.[3]

These findings have fundamentally changed our understanding of how living standards and health have changed over time and varied across space. However, they have also left some open questions that cannot be directly answered by looking at 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 twenty or more years of growth, but studies of adult stature tell us only one component of the growth pattern, adult size. They cannot reveal the timing of the pubertal growth spurt, the velocity of growth at different ages or the length of the growing years. Figure 1 illustrates these constituent parts of the growth pattern using the 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 velocity curve. This paper utilizes a unique dataset to assess how the growth pattern of children changed over time, focussing primarily on the pubertal growth spurt, the rapid increase in growth during puberty visible in the right panel of Figure 1.

[2] Floud, Wachter, and Gregory, *Height*; Komlos, 'The Secular Trend'; Komlos, 'Further Thoughts'; Nicholas and Oxley, 'Living Standards'; Johnson and Nicholas, 'Male and Female'; Cinnirella, 'Optimists or Pessimists'; Horrell, Meredith and Oxley, 'Measuring misery'; Humphries and Leunig, 'Cities'; Steckel, 'Height'.
[3] NCD Risk Factor Collaboration, 'Century'.

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



Sources: Data from https://www.who.int/growthref/tools/en/.

Studying the growth pattern directly is important for a number of reasons. First, the growth pattern reveals important information about the health of children. A delayed pubertal growth spurt and extended growing period into the early twenties (delayed maturation) are indicative of nutritional deprivation and/or a sustained disease burden during the growing years.[4] 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. Studying child growth and the growth pattern directly can also provide further evidence on the age periods in human development where health conditions matter most, so-called critical windows. Development economists and some nutritionists have highlighted the importance of the first thousand days from conception to age two. This is the period where most growth faltering, slower

[4] Schneider, 'Children's Growth', p. 23-4.

growth leading children to be stunted or too short for their age, occurs, and at the population level, there is little catch-up to modern growth standards after this period.[5] However, more recent historical and modern studies have highlighted the importance of shocks and interventions on the growth pattern that occur outside this thousand-day window. Schneider and Ogasawara find that health shocks at ages 6-11 were more important in shaping child growth than shocks in early life.[6] Likewise, Depauw and Oxley show that the most significant negative effects of the mid-nineteenth century potato blight in Belgium on adult stature occurred for cohorts who experienced the famine as teenagers rather than toddlers.[7] Finally, modern analyses of cohort studies from developing countries have also shown that catch-up growth between mid-childhood and adulthood is possible.[8] Studying how the growth pattern changed over time is essential for understanding critical windows because changes in growth may have made some of these critical windows more important in the past than today.

There is a great deal of preliminary evidence that suggests that components of the growth pattern have changed through history. Cameron has shown that children in London at the beginning of the twentieth century had their pubertal growth spurt at later ages than modern children, and Steckel and later Cole showed that this was a general pattern.[9] A'Hearn *et al.* show that the age at which Italian men stopped growing declined at the end of the nineteenth century at the beginnings of the secular increase in height.[10] 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.[11] However, aside from the case of Japan, few studies

[5] Victora, 'Worldwide'.
[6] Schneider and Ogasawara, 'Disease'.
[7] Depauw and Oxley, 'Toddlers'.
[8] Prentice *et al.*, 'Critical'; Stein *et al.*, 'Growth Patterns'.
[9] Cameron, 'Growth'; Steckel, 'Growth Depression'; Cole, 'Secular Trend'.
[10] A'Hearn *et al.*, 'Height'.
[11] Ali *et al*, 'Secular'; Cole and Mori, 'Fifty'; and Schneider *et al.*, 'Effects'.

have been able to track changes in the growth pattern across the secular increase in height.

This paper is the first to trace 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 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.[12] 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. 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.[13] 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 nineteenth century than today. Our findings suggests 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 mattered more for the changing growth pattern than improvements in nutrition.

[12] Hatton, 'Infant'; Hatton, 'How'.
[13] Tanner, *History*, p. 134.

2. The Indefatigable Dataset

This paper is based on records of boys admitted to the training ship *Indefatigable* between 1865 and 1995. 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.[14] The boys entered the ship at age 10 to 14 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 and Education Department.[15] 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 occupational distribution. 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 in the river Mersey near Liverpool, giving the ship ready access to clean water, fresh food and medical care.[16] The boys lived on the ship with living quarters on the lower decks. The first *Indefatigable* was 186 feet long and 54 feet wide and could accommodate over 200 boys.[17] The boys occasionally took the ship out into the broad river to practice sailing, but they did not go on long-distance voyages. The *Indefatigable* was based in 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 Las Llanfair, Anglesey in 1945.[18]

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

[14] 'First Annual Report [1866]', pp. 5-7.
[15] Only after the 1970s did tuition fees from parents become an important part of the ship's income.
[16] 'First Annual Report [1866]', p. 8.
[17] Evans, *Indefatigable*, p. 16, citing an article in the *Liverpool Review* on 21 January 1888.
[18] 'Seventy-Sixth Annual Report [1941]', pp. 4-5; 'First Annual Report [1945]', p. 3.

history of the *Indefatigable* from annual reports of the institution (1865-1990), monthly Chairman's reports to the executive committee (1939-43 and 1956-58) and recollections of former *Indefatigable* boys collected in Bob Evans's book *The Indefatigable*.[19] The information available in these sources is not as detailed as for other institutions studied in the literature;[20] however, we are confident about four facts about 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.[21] 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.[22] Second, the physical development of the boys was closely monitored and cared for by the staff.[23] The captain regularly emphasized the physical training of the boys in the annual reports, expressing his worries or satisfaction on the boys' physical development.[24] For a time, they even tracked the boys' weights at more frequent intervals than admission and discharge.[25] There was also a weekly medical inspection carried out by medical officers, and boys with illness were sent to hospital for further treatment.[26]

Third, the boys were always fed sufficient and wholesome food, even if the variation and taste of the food was limited.[27] Unfortunately, the information on

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[19] See reference list for full details.
[20] Schneider, 'Health'.
[21] 'First Annual Report [1866]', p. 9; 'Centenary', p. 22-24.
[22] 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', p. 19; A'Hearn *et al.*, 'Height', p. 2.
[23] 'Third Annual report [1868]', p. 13.
[24] 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. 'Annual reports [1901-34]'; 'Annual reports [1940-90]'
[25] 'Chairman's reports to the executive committee [1940]'
[26] 'Chairman's reports to the executive committee [1939]'
[27] 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

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 boys to grow: information on the boys' diet is presented in Appendix D. Likewise, evidence on real food expenditure per boy shows that expenditure was more or less constant over time, though there was a dip in expenditure during the 1940s and 1950s (see Figure 8 below). Fourth, with 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 am and asleep by 8:30 – 9:00 pm.[28] The boys' physical workload remained similar before and after the *Indefatigable* moved on shore in 1941 and later to Anglesey in 1945.

2.1 Key variables and the 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 heights and weights at admission and discharge. For certain sub-periods of time, they recorded additional information such as the child's school, the income of his parents, the ages of his brothers and sisters among other things, but this data was 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 Appendix Table A1).

As mentioned above, 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, 1933-1941 and after 1974, when height and weight were not recorded at discharge, which introduces gaps into our longitudinal data (see Appendix Figure A1). These gaps and their effect on our

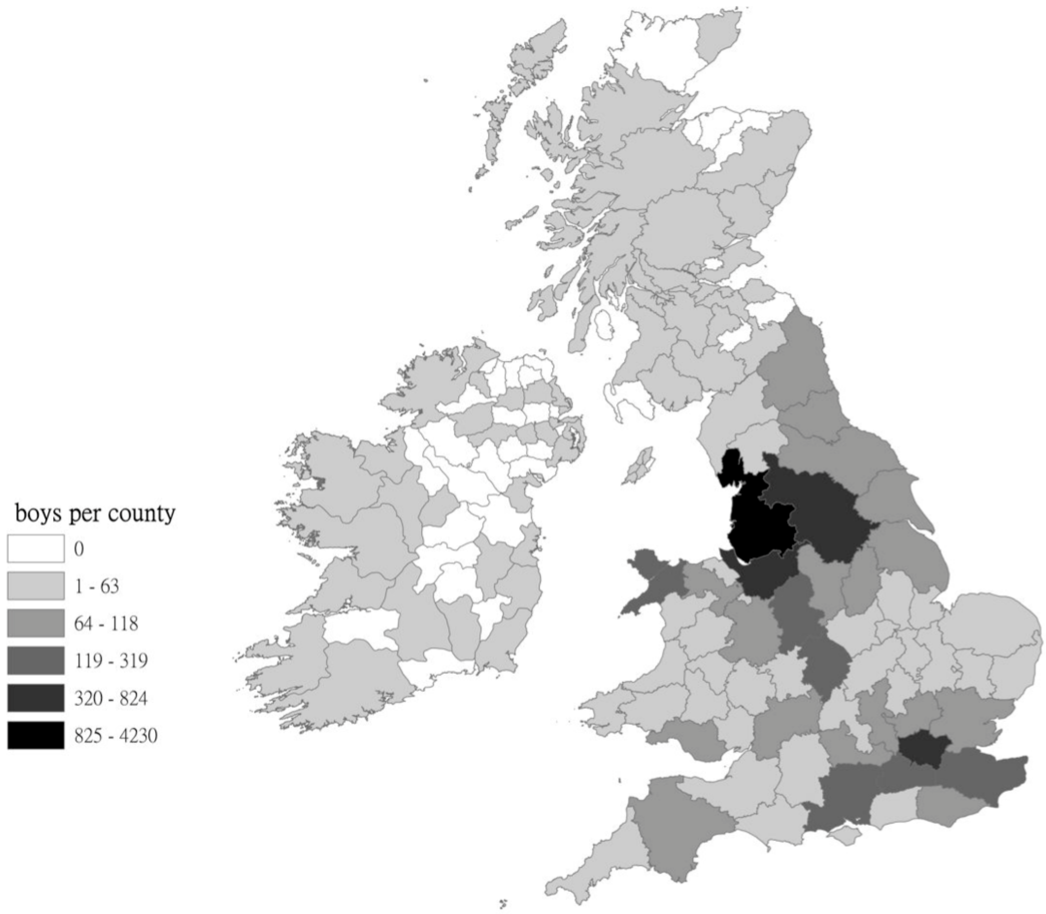
Committee shall deem expedient. The provisions shall be well dressed and served at stated hours' from 'Third Annual report [1868]', p. 13.

[28] 'Annual report [1924]', p. 5; Evans, *Indefatigable*, pp. 26, 32, 64.

understanding of the growth pattern of children will be discussed at length later in the paper in section 5.1. Thus, 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 large time period over 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 Southeast. The ship also drew a lot of boys from North Wales after it was relocated there in 1941.

Figure 2: Number of *Indefatigable* boys born in each county, 1850-1979



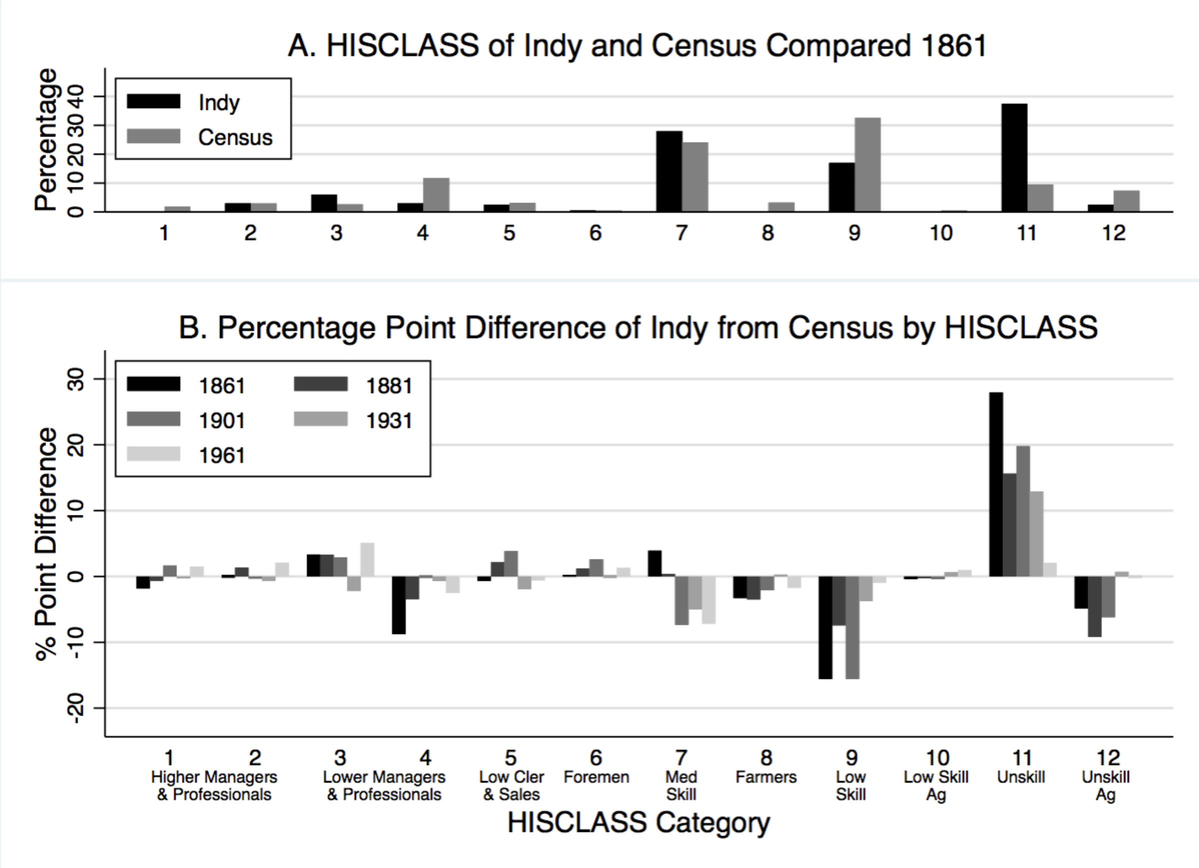
Notes: Dark shades correspond to a larger number of boys. Counties are based on 1851 borders. 89.9 per cent of cases had a recorded and identifiable birth county.
Sources: Indefatigable dataset, see Appendix A.

We have also analysed the parental occupations available in the data to understand the class background of *Indefatigable* boys. The percentage of boys whose father 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 Appendix Figures A2 and A3). 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.[29] In the early years, the vast majority of the boys were of working class backgrounds, but this share fell over time, especially after WWII (see Appendix Figure A2).

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 Indy sample from the census, showing the percentage point difference between the two. Surprisingly, the upper HISCLASS groups were overrepresented in many decades. Medium-skilled and low-skilled workers tended to be underrepresented and unskilled workers tended to be overrepresented. In general, agricultural workers were underrepresented. 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.

[29] van Leeuwen *et al.*, *HISCO*; van Leeuwen and Maas, *HISCLASS*.

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



Notes: We use the HISCO classifications in I-CEM for the 1861, 1881 and 1901 censuses, and we reclassified occupations from the 1931 and 1961 censuses into the HISCLASS system to make comparisons with the *Indefatigable* data.
Sources: Indefatigable dataset, see Appendix A; HISCO codes for the 1861, 1881 and 1901 censuses were drawn from http://icem-nesstar.data-archive.ac.uk/webview/; 1931 census: 'Census of England and Wales, 1931. Occupation Tables', pp.15-22; 1961 census: '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.[30] 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.[31] This is especially true since Schneider has highlighted a number of ways in which sample-selection bias might influence the

[30] Bodenhorn *et al.*, 'Sample-Selection'.
[31] Komlos and A'Hearn, 'Decline'; Zimran, 'Does Sample-Selection'.

growth pattern of children in various datasets, mostly through selection on age into the sample.[32] Selection on age is less of an issue for this dataset since we observe 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.[33]

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, local children's society or local authority. Beginning in the 1940s, the ship began collecting some tuition fees from families who could afford to pay for 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 ship.[34] 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 below, 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

[32] Schneider, 'Sample Selection'.
[33] 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.
[34] Indefatigable Annual Reports, various years.

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.

3. Methodology

Before presenting the results graphically below, 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.[35] 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 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 last birthday, i.e. their age rounded down to the nearest year, rather than their 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. Appendix B 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 profiles changed over time. Thus, we implement a series of OLS regressions that control for all observable characteristics to ensure that compositional changes in our sample are

[35] 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 Appendix A.

not driving any changes in the growth pattern. We control for parent's HISCLASS category, birth county, whether the child was born in several categories of urban districts, and whether the child was an orphan or had been deserted.[36] 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 Appendix C for those who are interested.

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 of time were more likely to either be given the same height measurement (rounded down) or 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.

[36] Urban population from Bennett *et al.*, *Urban*.

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 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 they 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 mid-point 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 mid-point. Appendix B 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 mid-point age bin, this does not strongly influence the velocity age profile nor bias our results.

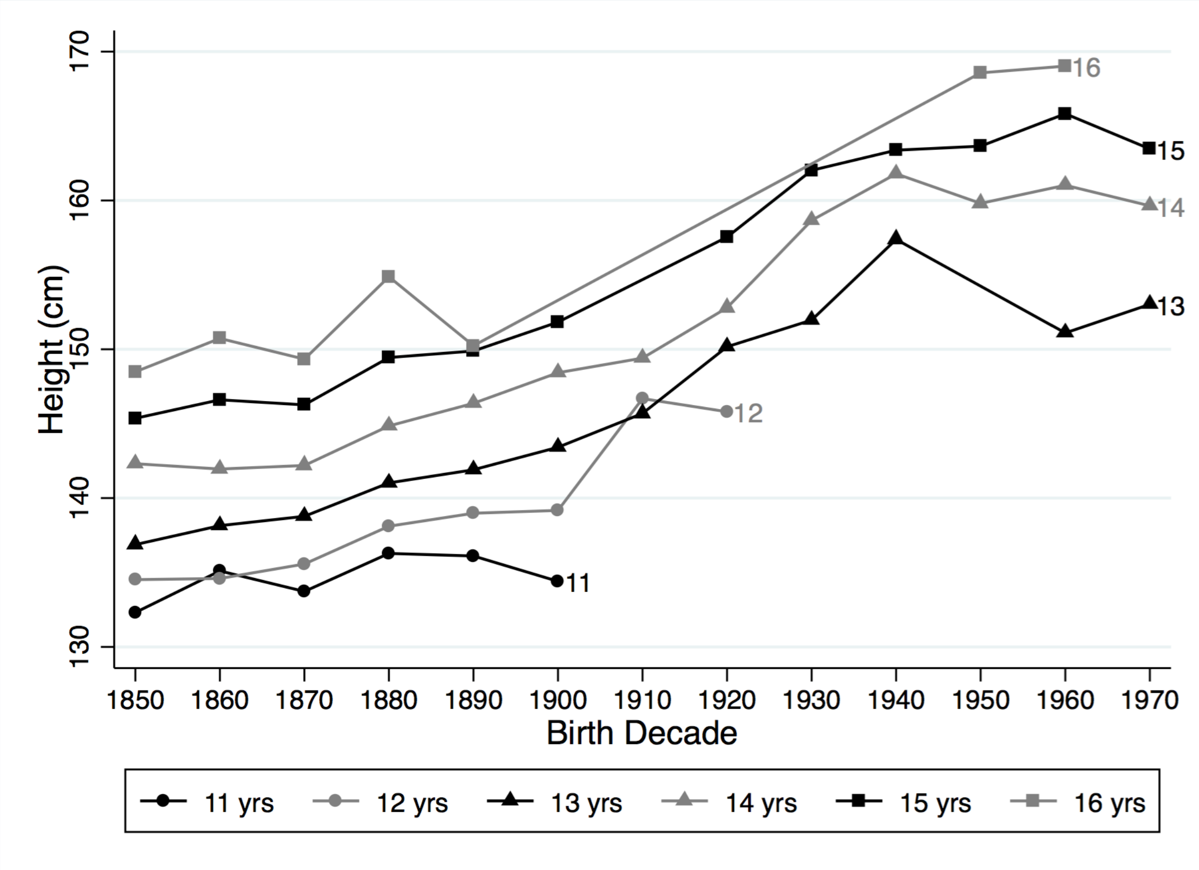
A final consideration for all indicators is whether the relationship between each of the covariates and the outcome variables changed across the decades. By including, for instance, a mother dead variable in a regression on the full sample, we are assuming that the influence of having a mother dead on 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. Appendix C presents the parameter stability checks in detail.

Rather than presenting the regression tables, we have instead provided graphs below 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.

4. Main Results

This section explores the changes in the growth pattern using the four different indicators discussed above. 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,

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 Appendix C for more detail.
Sources: Indefatigable dataset, see Appendix A.

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.[37] 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 through the 1970s. Thus, it appears that the interwar period was the fastest period of improvement in

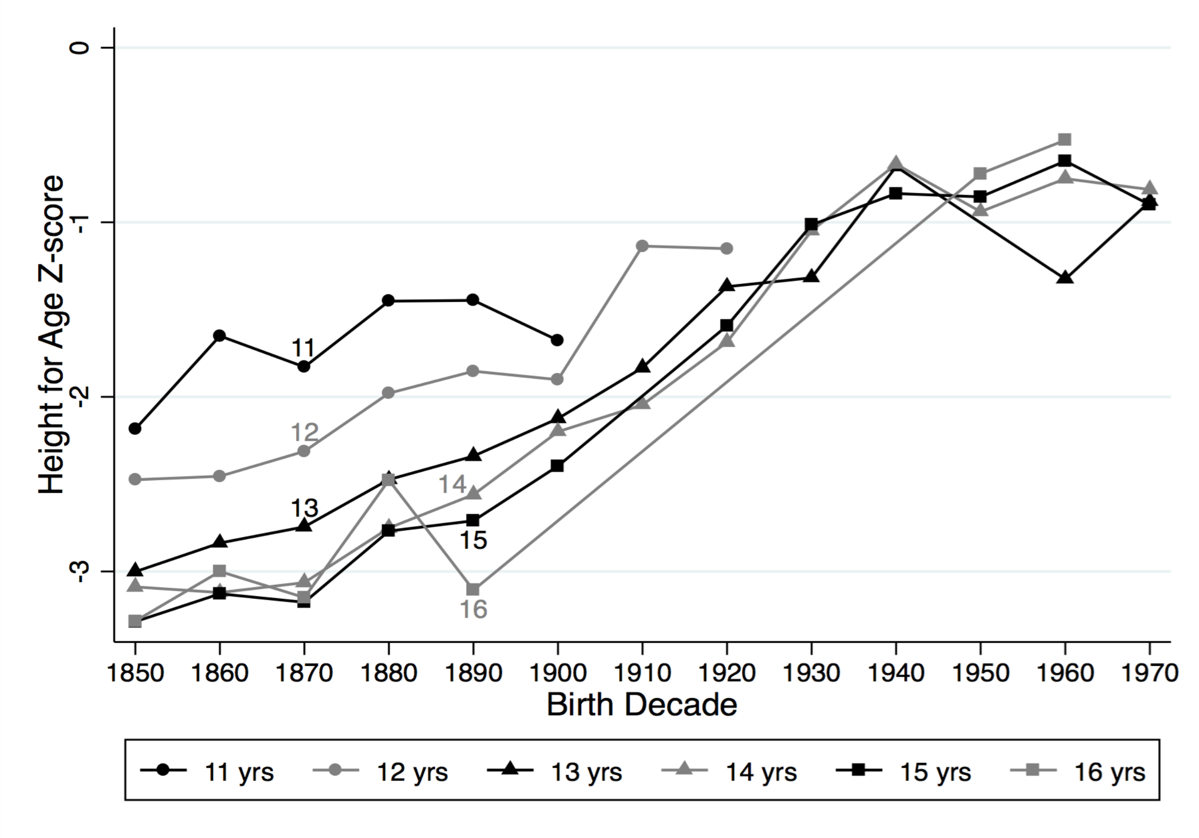
[37] We have focused on ages 13 and 14 because these two age groups have consistently large sample sizes across nearly all birth cohorts over the period studied.

children's admission heights, corroborating evidence collected across Europe showing a similar trend for adult heights.[38]

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?

[38] Hatton, 'How'.

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 Appendix C for more detail.
Sources: Indefatigable dataset, see Appendix A.

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 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.[39] 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 the problem would arise at different ages for boys and girls, who experience the pubertal growth spurt before boys. Thus, in the future, best practice should be either to control explicitly for age-related differences or to avoid the problem

[39] Harris, *Health*, p. 88; Harris, 'Height'.

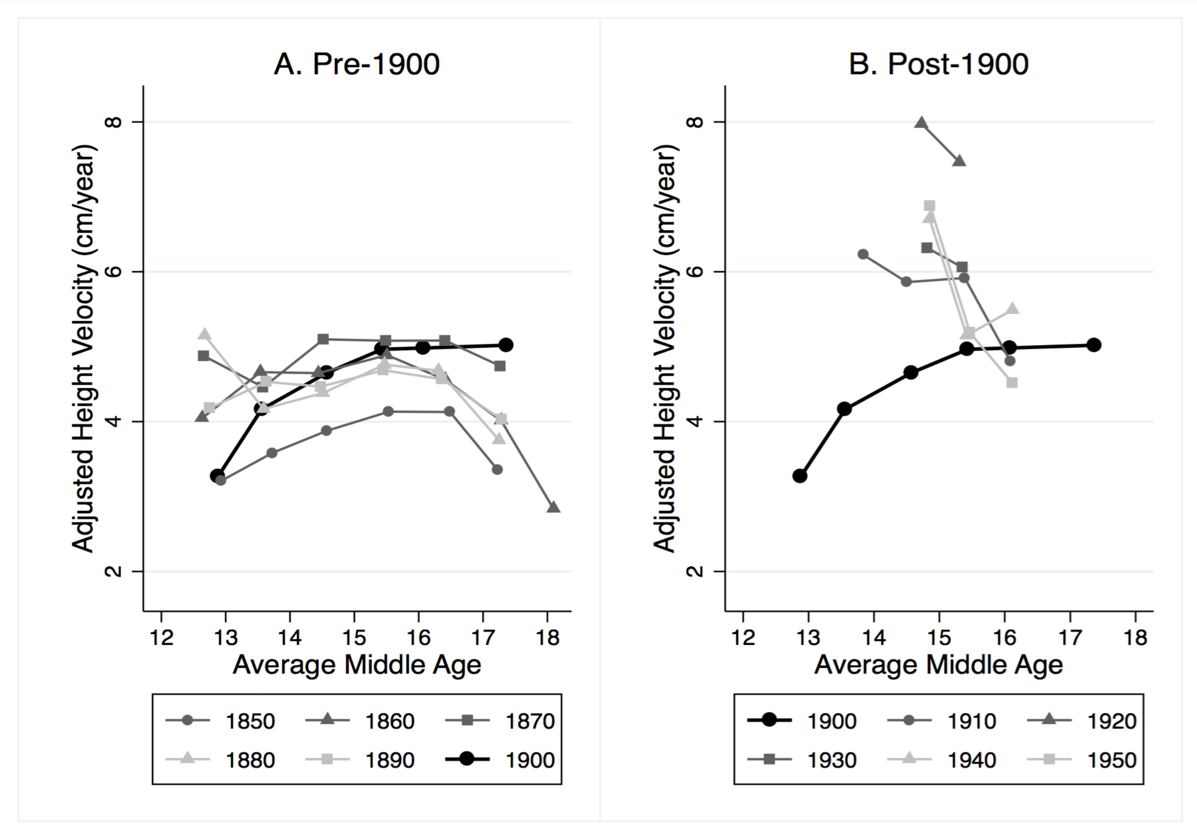
altogether by only analysing younger children with centiles or Z-scores of modern references.

We can expand upon this discussion of change in admission heights over time by utilising 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.

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 between four and five cm per year, and there was no marked pubertal growth spurt as the growth velocity was similar across these ages. However, beginning in the birth decade cohort 1910s, 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. 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, 20s and 30s experienced higher velocities at age 15.5 than children born in the 1940s and 50s. This corresponds to the shift toward earlier maturation that has occurred in the past 100 years.[40] 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 century, which show a flat growth velocity across puberty.[41] The empirical strength of this finding and its implications will be queried in considerable detail in the next section.

[40] Schneider, 'Children's Growth'; Tanner, *Growth*, pp. 152-55; Brundtland and Walløe, 'Menarcheal Age'.
[41] Schneider, 'Health', p. 335.

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

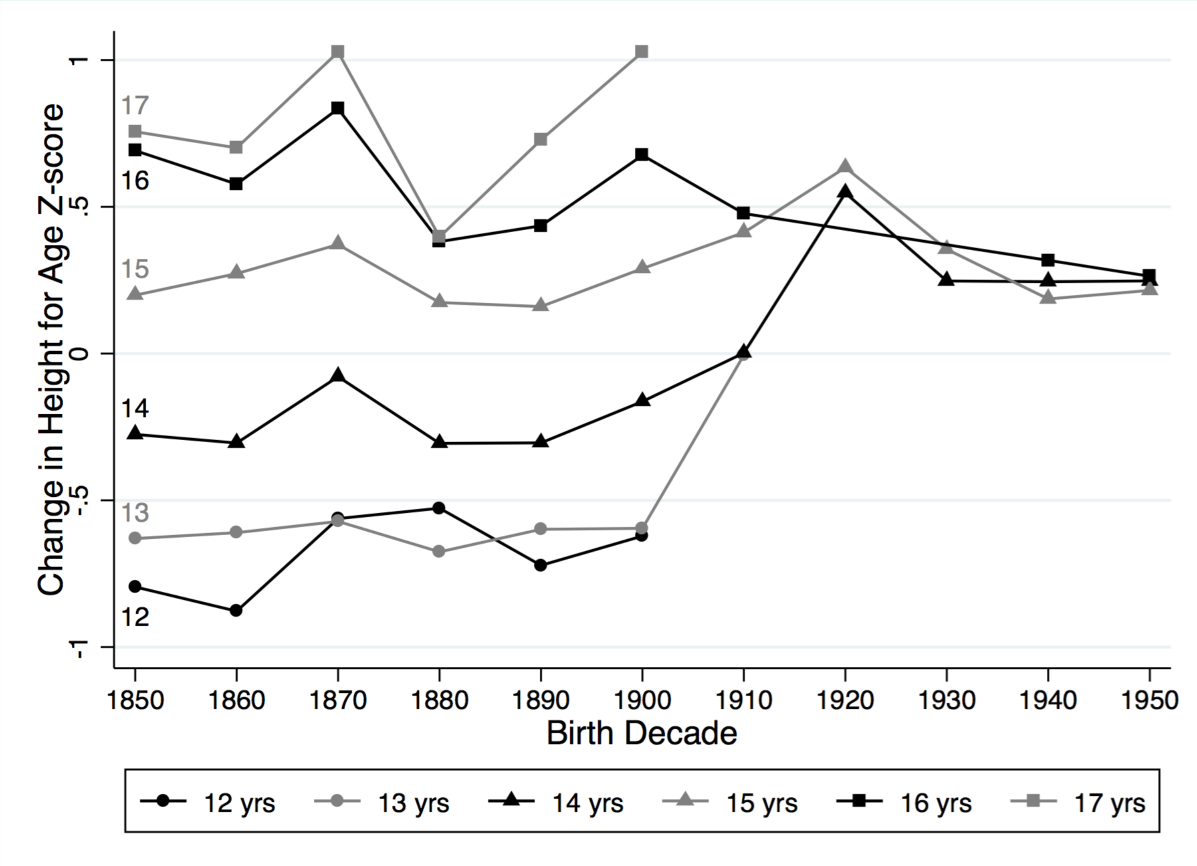


Notes: Ages are one-year binned midpoint age categories. The velocities reported are predicted from a regression controlling for all observable characteristics. See Appendix C for more detail.
Sources: Indefatigable dataset, see Appendix A.

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 graph 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 of the ship because they experienced normal, slow growth as the children in the modern reference experienced their pubertal growth spurt. 14-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. This pattern was remarkably consistent through the birth decade cohort 1900s, 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. 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.

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 Appendix C for more detail.
Sources: Indefatigable dataset, see Appendix A.

5. Explaining the Absence of the Pubertal Growth Spurt before 1910

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, several alternative explanations are possible, and we will refute each in this section.

5.1 Alternative 1: Better nutrition and less workload on the Ship?

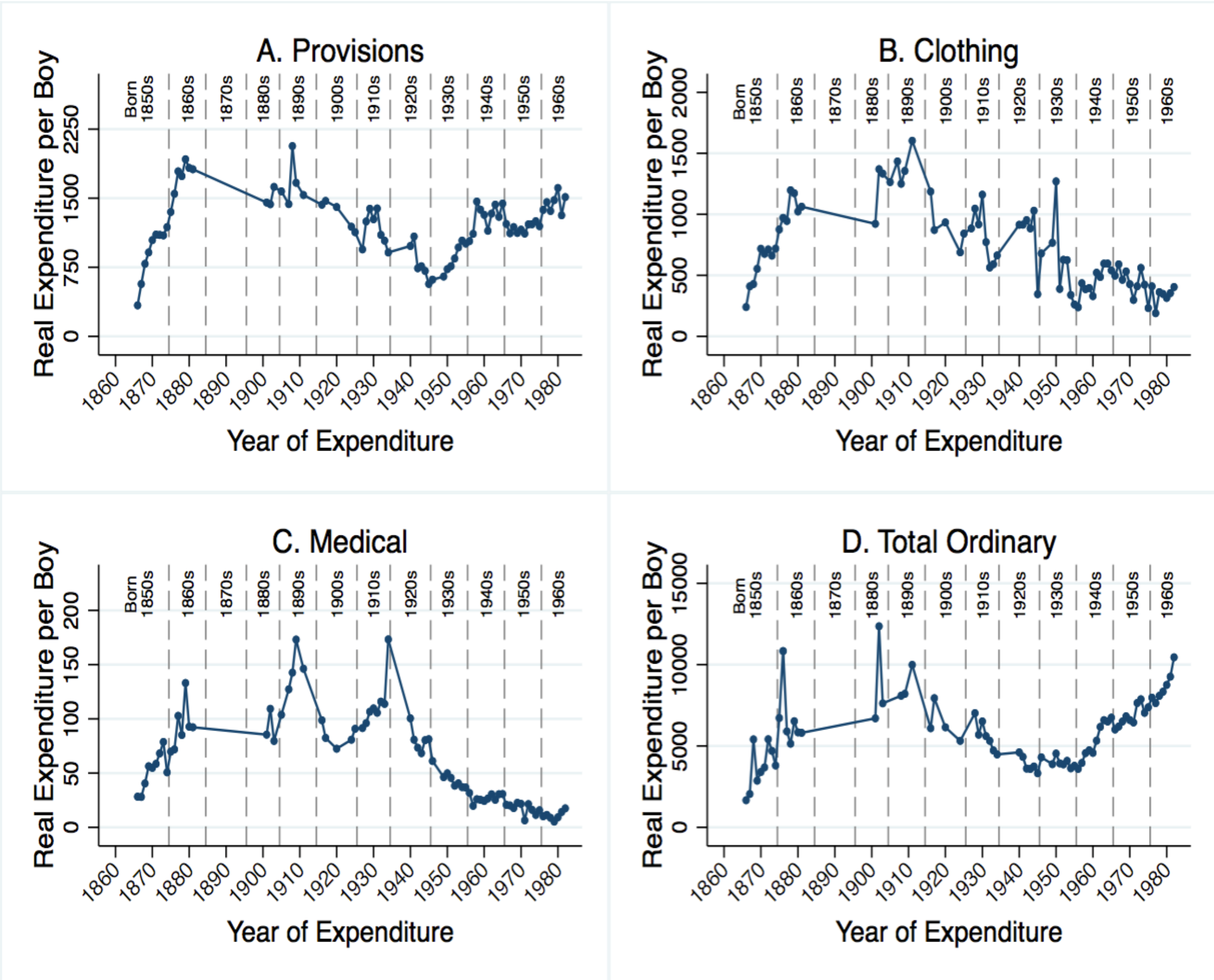
One possible explanation for the changing growth pattern of children is that health conditions on the *Indefatigable* changed over time, perhaps benefiting children born from the 1910s onward where we see changes in the growth pattern. Proving that this is not the case is complicated because the surviving institutional records for the *Indefatigable* are less detailed than those of other institutions.[42] 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 the ship 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, it would be nice to 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 Appendix Figure A1 for more detail). Thus, because we cannot look at the immediate effects of relocating the ship 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 ship.

[42] Schneider, 'Health', pp. 312-30.

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 10 presents data on the real expenditure per boy in a number of categories that could have influenced the children's wellbeing. 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 10A 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 benefitting 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.[43]

[43] 'Seventy-Sixth Annual Report', p. 4.

Figure 8: Expenditure per boy in various categories, 1860s-1980s



Notes: Total expenditure in each category was first divided by the number 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 Figures 8A-C but excludes extraordinary expenditure on repairs, purchasing new ships, etc. Missing data are driven by a lack of primary evidence on these forms of expenditure.
Sources: Expenditure data drawn from the annual reports of the *Indefatigable*: 1865-81 Merseyside Maritime Museum, D/B/115N/1; 1901-34 Merseyside Maritime Museum, D/CC/IND/1/1-22; 1940-90 Merseyside Maritime Museum, D/IND/1/4/1. The stock of boys in the school was constructed from the Indefatigable dataset described in Appendix A. The consumer price index was drawn from Bank of England, 'A Millennia of Macroeconomic Data for the UK', Table A.47, downloaded 16 February 2018 from https://www.bankofengland.co.uk/statistics/research-datasets.

In addition to expenditure, we also looked for mentions of the diet in the boys' memoirs quoted at length in Evans.[44] Appendix Table D1 documents the descriptions of the diet by the boys between the 1880s and 1960s. Although the

[44] Evans, *Indefatigable*.

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 1940s on either side of the change in the pubertal growth spurt and the relocation of the ship. 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 1940s about how terrible the food was and how the boys were 'always hungry'.[45] 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 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 in the timetable and the boys practiced sailing and navigation during the "outward bound" sea school or on local rivers. They were also still responsible for cleaning their quarters and performing other domestic tasks.[46] Thus, we are very confident that the change in growth pattern experienced by birth cohorts from 1910 onwards was not driven by improvement in health conditions on the ship.

5.2 Alternative 2: Duration of Stay on the Ship

It is also possible that the differences in longitudinal growth velocity could be related to changes in the amount of time the boys spent on the ship. There was a substantial decrease in the duration of stay over time with the average duration of stay decreasing from 2.39 years in the pre-1910 period to 1.33 years afterward. As mentioned above, larger intervals between measurements could lead to an understatement of the longitudinal velocity because high velocities in one year

[45] Evans, *Indefatigable*, pp. 35-37, 61, 63, 114, 144.
[46] 'Annual report [1943]', p. 3.; 'Annual report [1946]', p. 4.;

may be averaged out by lower velocities in subsequent years. We discuss how duration of stay might influence our ability to observe a pubertal growth spurt in more detail in Appendix E and find that differences in the average length of stay would not produce the flat growth pattern we observe in the nineteenth century.

5.3 Alternative 3: Greater Dispersion in the Age at Peak Velocity during Puberty

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 than in the twentieth century. If different children experienced the pubertal growth spurt across a wide age range, then on average the velocity-age profile would be flatter because the children experiencing pubertal growth at high velocities at a given age would be cancelled out by children who had already experienced their pubertal growth spurt or who were yet to achieve it growing more slowly. This theory may be true to some extent, but our main findings cannot be entirely explained by it.

We attempt to address this concern first by looking at the individual-level data directly to see what share of boys were experiencing rapid pubertal growth and whether this percentage changed between the pre- and post-1910 birth cohorts. Determining a threshold for pubertal growth is somewhat difficult, but we use the WHO reference to give us a rough guide. The construction of the thresholds is discussed at length in Appendix F, but essentially we use the 75th percentile of the WHO median velocity measured at 16 month intervals for the post-1910 period and the -2 standard deviation WHO velocity measured at 30 month intervals for the pre-1910 period. These different levels and intervals account for changes in the growth pattern and measurement interval over time so that the threshold for pubertal growth is lower in the pre-1910 period at 5.45 cm/year than in the post-1910 period at 5.98 cm/year. Using these thresholds, we find that only 23.67 per cent of boys in the pre-1910 period experienced rapid pubertal growth whereas this percentage was 43.52 in the post-1910 period. Appendix Table F1 presents the differences in the means and quartiles of velocity and length of stay of the slow- and fast-growing groups as well.

To test whether pubertal growth was widely dispersed across ages in the early period, we then look at the share of boys experiencing rapid pubertal growth at each age in each period. Table 1 shows that there was a small but consistent share of children experiencing rapid growth from ages 12 to 17 in the pre-1910 period. This does suggest the possibility that the dispersion in the age of the pubertal growth spurt could have been wider, but this interpretation is limited by two factors. First, some of this growth, especially in the nineteenth century, may have been catch-up growth. Children who experienced very poor health conditions before entering the ship may have experienced faster-than-normal growth once they received more wholesome and regular meals on the ship.[47] Second, the percentage of boys experiencing rapid pubertal growth is higher at all overlapping ages in the post-1910 period. Thus, although the variation in the percentage in the post-1910 period is greater, it is difficult to determine if there was actually greater dispersion in the earlier period. Because the ages listed are mid-point ages, all we can see is that, for instance, 28.85 per cent of boys entering the ship born before 1910 around age 14 and leaving around age 16 experienced rapid pubertal growth between those ages. Thus, the rows are not additive. The fact remains that rapid pubertal growth was much rarer in the earlier period even when accounting for differences in the duration of stay on the ship. Thus, the relative flatness of the velocity curve in the pre-1910 period seems more likely to be driven by children growing at lower velocities for a longer period of time rather than children with typical growth curves reaching their peak velocity during puberty at different ages.

In conclusion, the change in the growth pattern that appears with the 1910 birth cohort cannot be explained away by changes in the food consumption or workload on the ship, changes in the variance in the timing of the pubertal growth spurt or by changes in the length of time between height measurements. These changes are real and reflect actual changes in the way boys were growing.

[47] Schneider, 'Children's Growth'; Boersma and Wit, 'Catch-up Growth'.

Table 1: Share of *Indefatigable* boys experiencing rapid pubertal growth

	Born Pre-1910		Born Post-1910	
Mid-point Age	% High Vel.	N	% High Vel.	N
11	0.00%	2		
12	15.00%	100		
13	15.54%	650	83.33%	6
14	24.23%	1300	51.27%	472
15	28.85%	1196	42.52%	2079
16	24.69%	478	26.83%	41
17	14.15%	106		
18	0.00%	6		
19	0.00%	2		

Notes: Velocities are calculated for boys who were on board the *Indefatigable* for more than four months. Mid-point age refers to the midpoint age between admission and discharge from the ship. See Figure F1 and Table F1 for an explanation of how the velocity thresholds were determined.
Sources: Indefatigable dataset, see Appendix A.

6. Why do Nineteenth-Century, Cross-Sectional Data Sources Show Pubertal Growth?

Our finding that the growth velocity curve was much flatter in the nineteenth century is also surprising because it contradicts earlier studies of human growth including the studies of 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.[48] Thus, it is necessary to consider a range of possibilities for why the pubertal growth spurt appeared in these cross-sectional studies but is

[48] Tanner, *History*, pp. 134, 179, 192.

conspicuously 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.

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.[49] Because most school samples are based on cross-sectional data, i.e. 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 and 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.[50]

The question then is whether Roberts's studies 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 age 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 height of boys entering the military reduces the bias in the data and argues that there is still strong evidence for a pubertal growth

[49] Schneider, 'Sample Selection'.
[50] Schneider, 'Sample Selection'.

spurt.[51] 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 15 and 16 where it increases and then falls again. 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.[52] The committee built off of Roberts's work described above 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 they carried out their labour indoors or outdoors.[53] This classification system contained six classes, but the committee only had sufficient data to analyse the 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 class for which there was 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-class individuals: it seems likely that the sons of many semi-skilled working-class individuals are categorised in class 4.[54]

[51] Tanner, *History*, pp. 177-78.
[52] Anthropometric Committee, 'Final Report', p. 253.
[53] Anthropometric Committee, 'Final Report', p. 281-83.
[54] Anthropometric Committee, 'Final Report', p. 282, 287.

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).[55] 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.[56] Boys in class 3 experienced an interval of nearly 10 cm/year at age 15, far above plausible average levels of growth that should appear in cross-sectional data.[57] 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, Massachusetts and Japan.[58] Thus, Nineteenth-century data that suggests a strong pubertal growth spurt is far more problematic than previously acknowledged.

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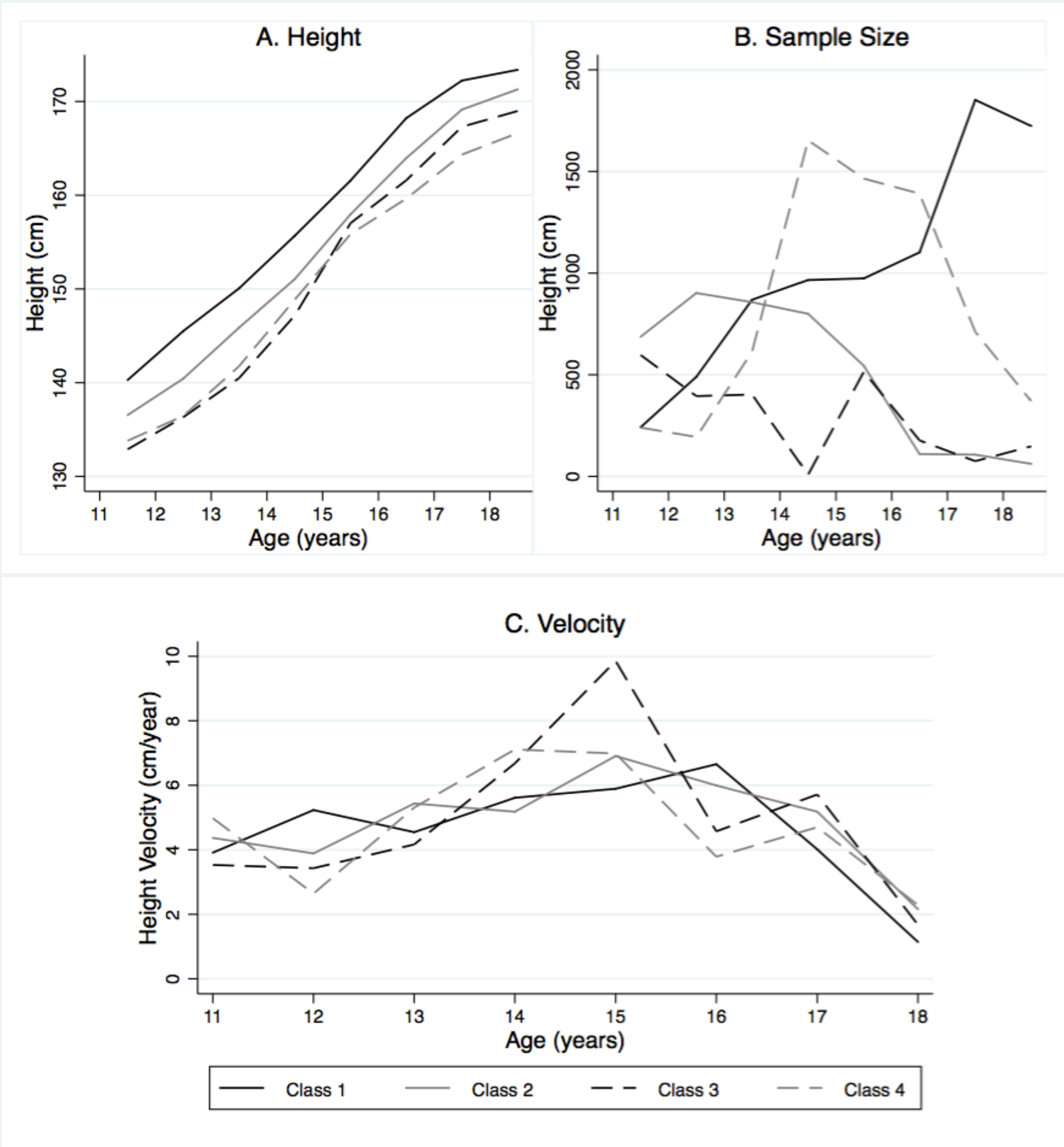
[55] de Pleijt, 'Human Capital', p. 112.
[56] Steckel, 'Growth Depression', p. 127; Cole, 'Secular'.
[57] Because cross-sectional data averages across individual-level variation, it understates velocities: see Tanner *et al.*, 'Standards', p. 458.
[58] Schneider, 'Sample Selection'.

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



Notes: Class 1 contains the upper class and professionals (4.46 per cent of workers by their classification of the 1870 census). Class 2 contains commercial classes like clerks and shopkeepers (10.36 per cent). Class 3 contains labourers working in rural areas such as agricultural labourers and miners (47.46 per cent). Class 4 contains urban artisans such as engravers, printers, and 'workers in wood, metal, stone, leather and paper' (26.82 per cent). 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 per cent of 1870 workers) because there was not enough data.
Sources: Anthropometric Committee, 'Final Report', pp. 287-90.

7. Conclusion

This paper shows 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 was more sudden. Boys born in the 1910s and later began to show a pronounced pubertal growth spurt that was not apparent in the earlier period. 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. Thus, the longitudinal evidence presented in this paper offers a truly unique and vital perspective on how children's growth has changed over time.

However, our study is not without weaknesses. We have no data for girls, which means that we cannot determine whether girls followed a similar pattern to that for boys. In cross-sectional studies, girls have a much flatter pubertal growth spurt than boys, so it might be more difficult to assess changes in the pubertal growth spurt for girls. However, understanding whether this pattern also holds for girls 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.[59] Another weakness is that our data, like most historical data, is far from perfect. We have tried to show that changes in observable characteristics such as birth county, urban or rural, orphan status, occupational class and length of stay on the ship do not drive our results, nor are our results vulnerable to changes in health conditions on the ship at the critical junctures. However, there is always some uncertainty in these interpretations, and we encourage future researchers to seek to corroborate or reject our findings.

This paper also does not reveal the causes of the change in the growth pattern. These causes are difficult to identify because the 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

[59] Osmani and Sen, 'Hidden'; Horrell and Oxley, 'Gender Bias'; and Schneider, 'Children's Growth'.

shift a child from the growth pattern determined *in utero* and in early life.[60] Separating the influence of different critical windows 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.[61] 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. Thus, it is only by combining the linear growth of a large number of children at different ages that we are able to observe changes in growth across different ages.

Although we are not able to precisely identify the causes of changes in the growth pattern, the sudden shift beginning with children born in the 1910s can help us to narrow the list of potential factors. 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,[62] whereas infant mortality, a proxy for the disease environment and hygiene, did not decline in Britain until the early twentieth century with most of the decline occurring by 1950.[63] 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 affected young children's health but led to fewer deaths outside of infancy.[64] Thus, a sudden change in the growth pattern beginning with the 1910s birth decade cohort suggests that morbidity may have been more important than nutrition in changing the growth pattern.

Our results also speak to the literature in development economics, human biology and economic history about critical windows in human development where health

[60] Schneider, 'Children's Growth', pp. 4-9.
[61] Schneider and Ogasawara, 'Disease' provide an example of the former while Depauw and Oxley, 'Toddlers' and Schneider *et al.*, 'Effect' are examples of the latter.
[62] Floud *et al.*, *Changing Body*, p. 167; Gazeley and Horrell, 'Nutrition'.
[63] Woods, *Demography*, p. 253.
[64] Sharpe, 'Explaining'; Hatton, 'Infant Mortality'; Schneider and Ogasawara, 'Disease'; Bailey *et al.*, 'Atmospheric Pollution'.

shocks may matter more for growth. Our finding of a weak pubertal growth spurt does not contradict recent work finding that shocks outside of the first 1,000 days and especially in puberty may influence heights.[65] 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.[66] 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. Firstly, is there evidence from longitudinal growth measurements of a strong pubertal growth spurt in other historical populations before the onset of the secular increase in height? We do not know 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 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. Finally, this research needs to be extended to girls so that we can understand whether similar changes in the growth pattern occurred for them. 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 finding these sources is vital for understanding the secular increase in height and change in the growth pattern.

[65] Prentice *et al.*, 'Critical'; Schneider and Ogasawara, 'Disease'.
[66] Depauw and Oxley, 'Toddlers', pp. 14-16.

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Web Appendix

Appendix A: Data Sources and Construction

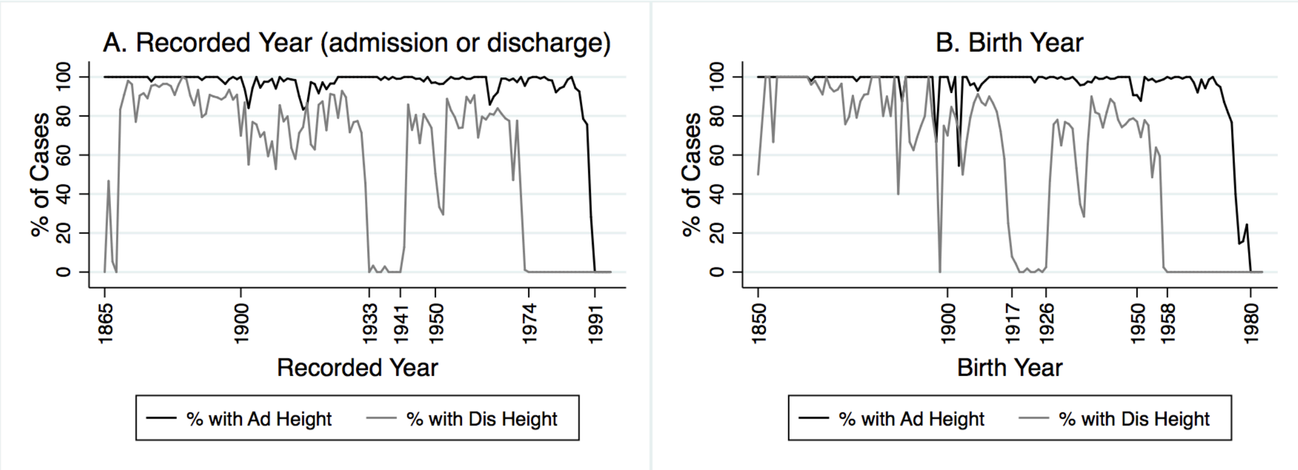
The main dataset used in this paper is the Cadet Records for the training ship *Indefatigable*, held at the Maritime Archives and Library (MAL) in Liverpool. The Cadet Records contain information about 11,548 boys who were admitted to the *Indefatigable* between 1865 and 1995. The data used in this paper will so be available in the UK Data Archive. The deposit includes detailed information about the data, transcription process and variables. The following are the key variables in our analysis: each boy's height at admission and discharge, length of stay on the ship, age, orphan status, parental occupation, and place of birth and residence. Table A1 presents descriptive statistics of our main variables of interest by birth decade. The section below describes how the original data was adjusted and categorised to produce our results.

Anthropometric measurements

We are mainly interested in height and height growth in this paper. After the original data were transcribed, we performed a series of tests to ensure high quality in these measures. We verified all height and weight measurements in the original records if the measurement in the transcribed dataset met one of the following conditions: 1) the values were out of the correct range (0-11 inches, 0-13 lbs when stone were used); 2) the discharge height was lower than the admission height; 3) the measurement was implausibly high or low; or 4) if the computed WHO Z-score was implausibly high or low. If one of the first two errors were verified in the original, we excluded the boy from the sample. However, we did not exclude boys that had verified high or low heights unless it was clearly implausible, i.e. a 13-year-old with a height of 7 feet. These steps lead us to exclude 74 cases or 0.6 per cent of the total data.

Unfortunately, although heights at admission were routinely recorded, heights at discharge were not recorded as frequently. Figure A1 reports the percentage of each one-year admission or birth cohort with admission or discharge heights included. Obviously, there were a few periods where the staff on the ship stopped recording discharge heights: discharge years 1933-41 and after 1974. Excluding periods where no discharge height information was measured, recording height at discharge is uncorrelated with any individual characteristics except the duration of stay oo the ship with boys with short stays less likely to have their heights recorded. This effect may have been driven by boys absconding and evading the formal discharge procedure or by the administrators deciding not to record heights for boys who had only been on the ship a short period of time, but it is unlikely to cause substantial bias.

Figure A1: Anthropometric data available at admission and discharge in the Indefatigable dataset by recorded year and birth year



Sources: Indefatigable dataset, see Appendix A.

We have also converted the heights in our dataset into height-for-age Z-scores relative to the 2007 WHO reference for school-aged children using the Stata macro available from the WHO website.[67] This allows us to compare how the children in the past were growing relative to a modern reference population.

Age

Age in the Cadet Records was recorded in three ways: age at last birthday in years (rounded down age), age in years and months, and birthdate from which we can calculate a precise age to the day from the admission and discharge dates. The missing exact ages might prove problematic for calculating height-for-age Z-scores

[67] Available to download at the following link: https://www.who.int/growthref/tools/en/.

and for calculating the midpoint age on the ship, so we discuss how we dealt with this issue at length in Appendix B.

Table A1: Table of descriptive statistics for main anthropometric and age variables

Birth Decade	1850	1860	1870	1880	1890	1900	1910	1920	1930	1940	1950	1960	1970
Observations	496	818	889	964	1013	772	610	893	1079	1121	1220	1075	507
Obs. containing longitudinal height	78.63%	95.23%	88.75%	78.53%	67.62%	78.24%	56.23%	26.76%	65.25%	79.57%	44.75%	0.00%	0.00%
Mean age at admission (years)	13.78	13.74	13.58	13.82	13.73	13.66	13.80	14.23	14.77	14.79	14.93	15.13	13.83
Mean midpoint age (years)	14.98	15.07	14.91	14.85	14.80	14.68	14.85	14.85	15.21	15.32	15.47	15.72	14.96
Mean age at discharge (years)	16.18	16.40	16.24	15.89	15.88	15.70	15.91	15.48	15.65	15.84	16.00	16.31	16.00
Mean height at admission (cm)	138.93	139.82	139.62	142.79	143.62	145.68	148.07	153.89	161.44	164.05	163.34	166.35	157.86
Mean height at discharge (cm)	148.22	151.86	152.19	151.73	152.59	155.27	159.05	166.55	167.72	169.93	168.86	-	-
Mean admission height-for-age Z-score	-2.92	-2.75	-2.67	-2.39	-2.26	-1.98	-1.79	-1.36	-0.8	-0.48	-0.66	-0.39	-0.54
Mean discharge height-for-age Z-score	-3.21	-2.77	-2.67	-2.6	-2.54	-2.16	-1.77	-0.69	-0.55	-0.38	-0.54	-	-
Mean height velocity (cm/year)	3.81	4.48	4.69	4.27	4.28	4.45	5.23	8.46	7.00	5.09	5.71	-	-
Mean change in height-for-age Z-score	-0.24	-0.01	0.00	-0.20	-0.22	-0.13	0.13	0.53	0.28	0.11	0.22	-	-
Mean duration of stay on the ship (years)	2.43	2.69	2.71	2.15	2.23	2.16	2.20	1.34	0.97	1.12	1.14	1.23	2.15

Notes: Mean values are calculated for reliable ages and height measurements as described in the appendix text above.
Sources: Indefatigable dataset, see Appendix A.

Occupations

The Cadet records also include parental occupations so that we can understand how the class composition of the sample changed over time. The document mostly recorded one parental occupation per boy. When the father was alive and had not deserted the child, the occupation tended to be the father's occupation. However, if the father was absent or dead, the document either listed the mother's occupation or the child's stepfather's occupation. We have used whatever occupation was provided to analyse how the class composition of the sample changed over time. Unfortunately, occupations were not recorded for a minority of the sample and so we have added an unknown occupation category to our analysis so that we do not lose large numbers of individuals in a few decades.

In order to simplify the occupational information, we have classified 3,495 occupations into 674 HISCO codes following the rules set out by van Leeuwen *et al.*[68] For instance, shop workers, grocer's assistants, sales assistants and 44 other occupations that appeared in the *Indefatigable* records were condensed into HISCO Code 45130, which includes all retail trade salespersons. We then placed the HISCO codes into their respective HISCLASS category following van Leeuwen and Maas, grouping the occupations into 12 classes based on four criteria: manual/non-manual, skill level, supervision and agricultural (see Table A2 for details).[69]

Figure A2 shows the occupational composition of the sample by HISCLASS groups over time including those with unknown occupations or where the occupation could not be classified. However, Figure A3 shows the composition excluding unknown occupations and those that could not be classified, showing that despite significant changes in the percentage of the sample with unknown occupations across birth decades, there were not sudden or large changes in the composition of occupations that were classified. The occupational distribution is compared to five censuses in the main text to gauge representativeness over time (see Figure 3).

[68] van Leeuwen *et al.*, *HISCO*.

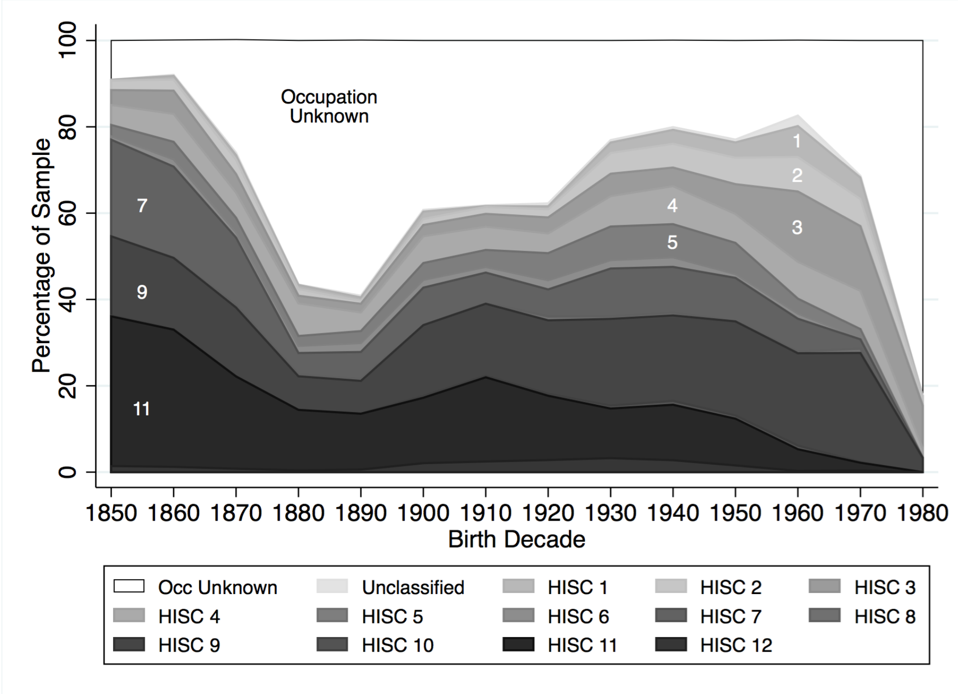
[69] Van Leeuwen *et al.*, *HISCLASS*.

Table A2: Description of HISCLASS categories used in our analysis

Class Number	Label	Manual/Non-manual	Skill Level	Supervision	Sector
1	Higher managers	Non-manual	High	Yes	Mainly other
2	Higher Professionals	Non-manual	High	No	Other
3	Lower managers	Non-manual	Medium	Yes	Mainly other
4	Lower professionals, and clerical and sales personnel	Non-manual	Medium	No	Other
5	Lower clerical and sales personnel	Non-manual	Low	No	Other
6	Foremen	Manual	Medium	Yes	Other
7	Medium skilled workers	Manual	Medium	No	Other
8	Farmers and fishermen	Manual	Medium	No	Primary
9	Lower skilled workers	Manual	Low	No	Other
10	Lower skilled farm workers	Manual	Low	No	Primary
11	Unskilled workers	Manual	Unskilled	No	Other
12	Unskilled farm workers	Manual	Unskilled	No	Primary

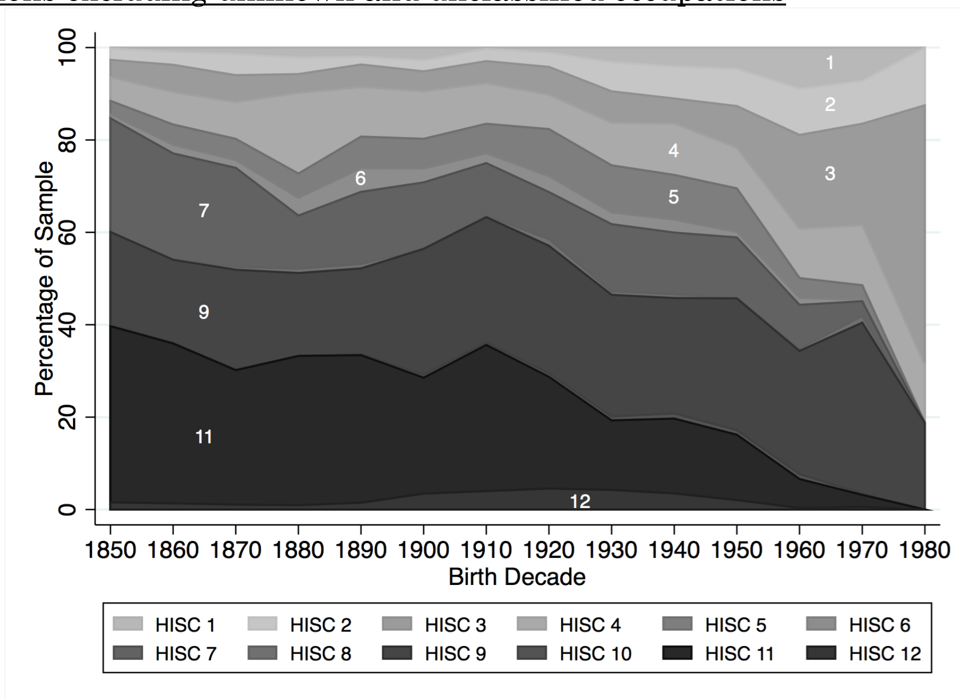
Source: van Leeuwen and Maas, *HISCLASS*, p. 57.

Figure A2: HISCLASS composition of *Indefatigable* boys based on parental occupations



Notes: HISC refers to the HISCLASS categories. See Table A2 for details.
Sources: Indefatigable dataset, see Appendix A.

Figure A3: HISCLASS composition of *Indefatigable* boys based on parental occupations excluding unknown and unclassified occupations

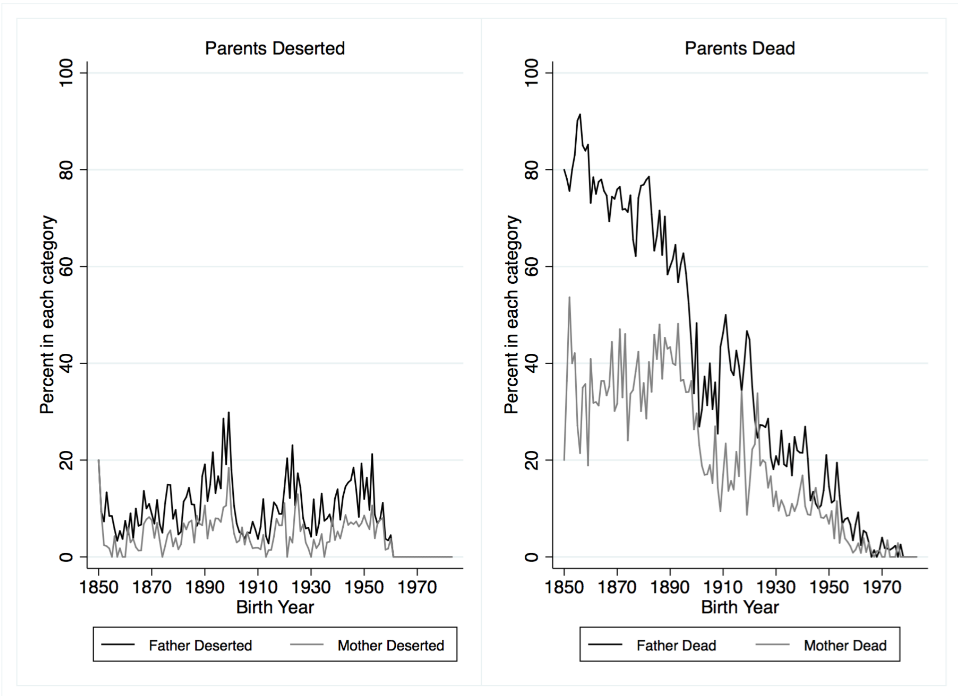


Notes: HISC refers to the HISCLASS categories. See Table A2 for details.
Sources: Indefatigable dataset, see Appendix A.

Orphan Status

The cadet records also noted when a boy's mother or father had died or when the mother or father had deserted the child. Figure A4 shows the share of boys in each of these categories across birth cohorts. Note that the same boy could be counted in more than one category if for instance his father was dead and his mother deserted him. The large declines in the share of orphan children around 1900 pre-date the shift in the growth pattern.

Figure A4: Share of Indefatigable boys with parents deserted or dead, 1850 - 1970



Location of Birth and Last Residence

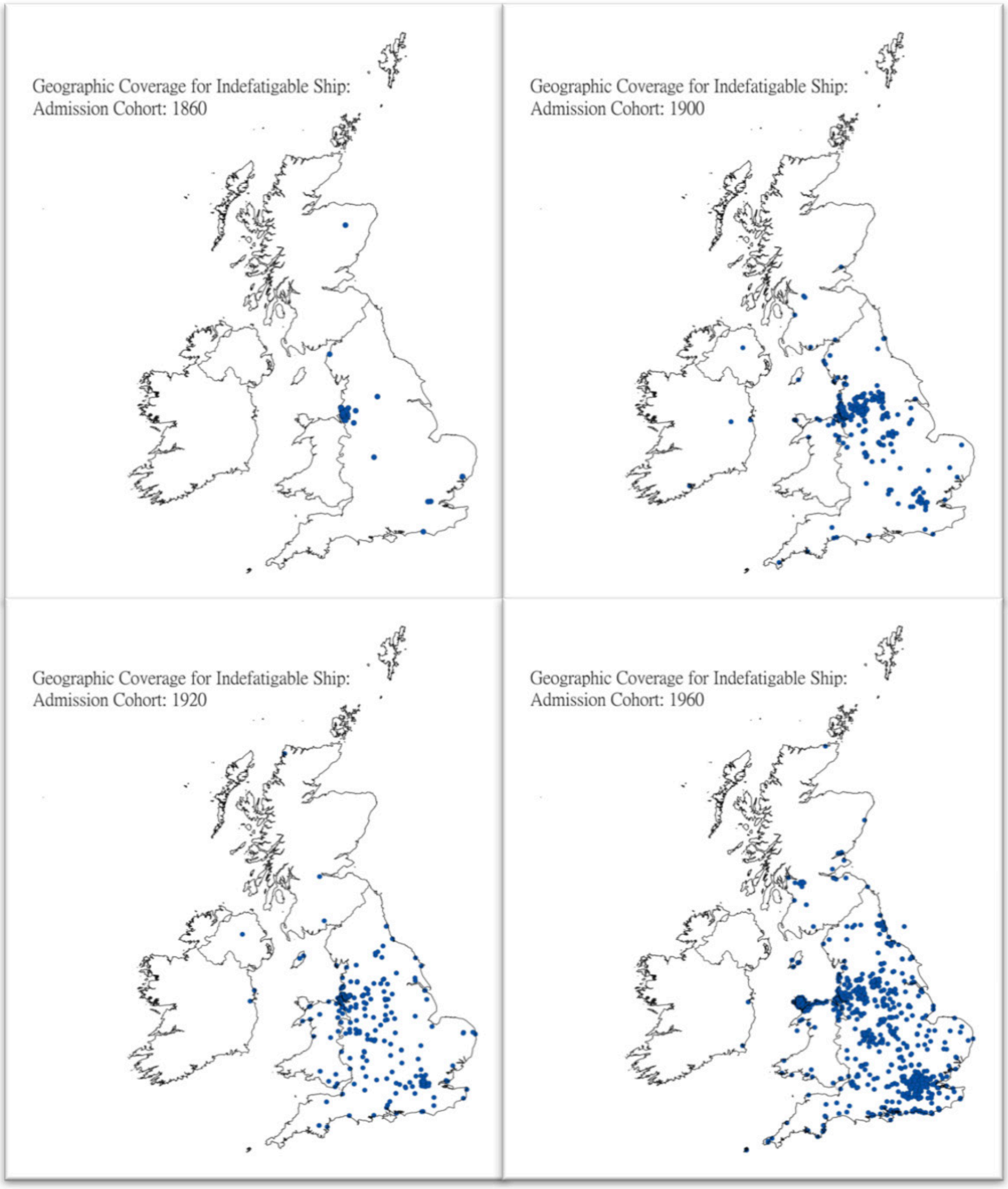
The Cadet Records also included information about each boy's birth location and location of last residence. Birth place is recorded for most of the boys, but for the ones whose birth county and city were not clearly reported, we use their last permanent address to assign them to a county. When the boy entered the ship from a poor law union or workhouse, the location refers to the workhouse of the poor law union which we found in Higginbotham.[70] When a precise address could not be found, we used context from other variables such as school location to assign

[70] Higginbotham, *Workhouse*.

a location in a local area. We convert this address information into latitude and longitude and overlay this with the county map of 1860 to determine the boy's birth county. Figure 2 in the paper is constructed based on this information.

Figure A5 further presents changes in the geographic coverage of the *Indefatigable* overtime. At its foundation, most boys came from Liverpool and Lancashire but quickly admission expanded to a much wider range of the country. London and the Southeast featured quite prominently, and after the ship moved to North Wales during World War II, the proportion of children from North Wales increased as well.

Figure A5: Locations of *Indefatigable* boys admitted from the 1860s to 1960s.



Urban Categories

In order to identify whether the birth place of a boy was in a rural or urban area, something that has been found to influence height in the previous literature, we collected data on urban population by registration district from Bennett *et al.*[71] We then created the urban variable from information about the size of the urban population in each registration district in 1851 as four

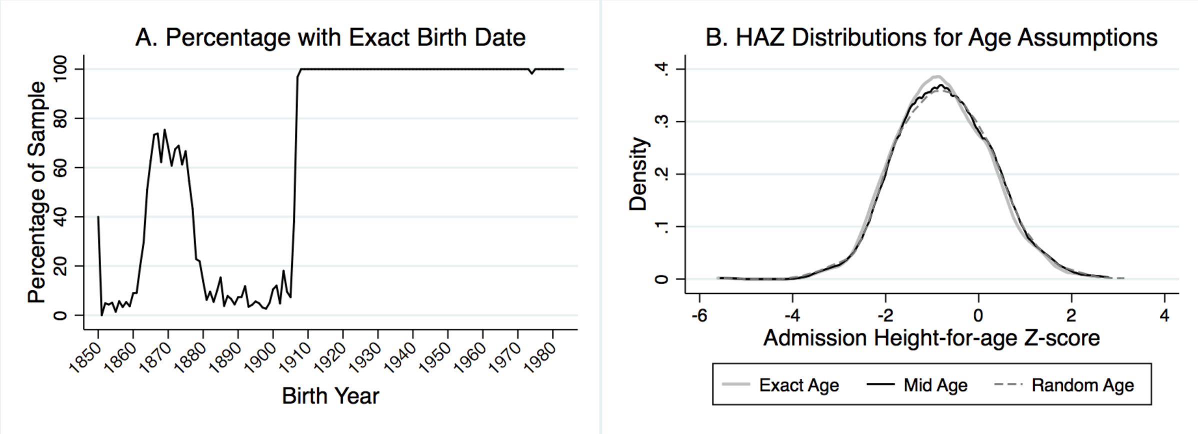
[71] Bennet *et al.*, *Urban.*

categories: rural, small town (10,000-25,000 people), small city (25,000-50,000 people) and large city (more than 50,000 people). The urban population in each district was very highly correlated with urban population in 1881, 1901 and 1911 (greater than 0.97), so we believe that the four categories created for 1851 will capture urban disamenities associated with larger cities in the nineteenth and early twentieth century.

Appendix B: Precision of Age Measurements

One potential issue with the data that deserves further discussion is that we do not have precise birth dates for children for most of the birth cohorts of the nineteenth century (Figure B1.A). Unfortunately, for many boys the only information given about their age is their age at last birthday upon admission to the ship. This imprecision in age is not a problem when we compare how the admission heights of boys have changed over time because we group all boys into age bins based on their age at last birthday. However, the imprecision could affect our analysis in two respects: it could create distortions in the height-for-age Z-scores calculated for each child since these are based on their age in months and it could also lead us to miscalculate the child's age at discharge and middle age in the institution. We will deal with each of these in turn.

Figure B1: Percentage of boys with an exact birth date and the height-for-age Z-scores of 14-year-olds born in the 1930s with different age assumptions



Notes: In the right figure (B), exact age is determined by subtracting the admission date from the birth date. Mid(-point) age assigns all boys of age at last birthday a, $a + 0.5$. Random age assigns all boys of age at last birthday a, $a + r$ where r is a uniformly distributed random variable varying between 0 and 1.
Sources: Indefatigable dataset, see Appendix A.

First, in order to calculate height-for-age Z-scores from the WHO growth reference, we needed to assign an exact age to all individuals who only had their age at last birthday recorded. We considered two possible methods for doing this. One was to assign all individuals in a given one-year age bin the mid-point age, i.e. 12-year-olds were all assigned to be 12.5. Another possible method was to generate random ages in the one-year age bin so that individuals were assigned ages across the distribution. To test the efficacy of these two methods, we took *Indefatigable* boys born in the 1930s, for whom we have an exact birth date and admission height, and who were admitted to the ship between ages 14.00 and 14.99 as our base sample. We then pretended that we did not know their precise ages and generated new ages for the boys based on the two rules above. The new ages were then used to calculate the height-for-age Z-scores of the boys. Finally, we compared the height-for-age Z-scores calculated with the generated ages with the original distribution calculated with the precise ages.

Table B1: Comparison of height-for-age Z-scores of 14-year-old boys born in the 1930s calculated with different age assumptions.

	Admission Height-for-age Z-score			Admission Age (years)		
	Exact Age	Mid Age	Rand Age	Exact Age	Mid Age	Rand Age
Mean	-0.789	-0.730	-0.731	14.589	14.500	14.517
Standard Deviation	1.012	1.034	1.053	0.246	0.000	0.287
Min	-5.610	-5.550	-5.480	14.004	14.500	14.000
Max	2.600	2.790	3.130	14.998	14.500	15.000

Notes: Exact age is determined by subtracting the admission date from the birth date. Mid(-point) age assigns all boys of age at last birthday a, $a + 0.5$. Rand(om) age assigns all boys of age at last birthday a, $a + r$ where r is a uniformly distributed random variable varying between 0 and 1.
Sources: Indefatigable dataset, see Appendix A.

Figure B1.B and Table B1 show the results. The distributions for the exact age, middle age and random age height-for-age Z-scores are very similar. The random age distribution would obviously change depending on the random draw of ages, but the distribution was always fairly similar. Looking at the summary statistics in Table B1, we can see how well the age assumptions proxy the real age distribution. Both the middle age and random age assume that the mean age of boys entering in a one-year age bin is the middle age, but in the case of 14 year olds born in the 1930s, the average age was slightly above this at 14.59. This means that the mean height-for-age Z-score is slightly lower than those calculated via the other methods. However, the difference in the means and standard deviations was very small. In the end, we decided to set the exact age to the mid-point age for all boys without a precise birthdate, and all of the estimations and evidence in the paper are based on this methodology. This assumption should not matter unless the mean (unobserved) precise age of a one-year age bin is not equal to the midpoint. In that case, the height-for-age Z-scores would be biased. However, this is only likely to occur at the extreme admission ages in our sample such as 10 or 11 or 16 and 17 and would not affect children admitted at ages 12 to 15. Thus, admission height-for-age Z-scores should be treated with a bit of caution for the early and later ages.

The second way that imprecise ages could affect our analysis is by leading us to miscalculate the actual discharge age and middle age on the ship for boys. Because the administrators did not record the boys' ages at discharge, the only way to know their discharge age is to add their duration of stay on the ship, which we observe precisely, to their admission age. This could create error in the discharge age that would lead us to assign some boys to the wrong one-year discharge age bin. For instance, consider a 13-year-old who remains on the ship for 5 months. Because we do not have a precise birth date and admission age for the child, we assume that he is 13.5 years old. This means that both his admission and discharge one-year age bin would be 13. However, if the child was actually 13 years and 11 months old at admission in reality, his discharge bin would be 14, and we would have incorrectly assigned him to the wrong bin. The scale of these incorrect assignments is important because it could help to explain why the growth curve is flatter in the nineteenth century.

Rather than testing this problem using the 1930s data, we turn to the nineteenth century data itself since we would like to know the effect of admissions policies and in the period and whether growth velocities are affected. Fortunately, as seen in Figure B1.A, there was a period between 1864 and 1876 when at minimum 50 per cent of the boys had a precise birthdate listed, i.e. either a birth month listed or an age in years and months. Thus, we can use this subsample with accurate ages in the nineteenth century to understand whether our age estimating procedure leads us to place boys in the incorrect age bins. Table B2 presents the results. We break the sample at each age into three groups: those where the estimated age (Age_{est}) is lower than the exact age (Age_{exact}), i.e. children are mistakenly put in a lower age bin that they ought to have been; those where the estimated age is equal to the exact age, i.e. our method correctly assigns the boys; and those where the estimated age is greater than the exact age, i.e. children are mistakenly put in a higher age bin. We show these both for discharge age bins and for mid-point age bins (the mid-point age between admission and discharge). For discharge ages 11.3 per cent of all cases were mistakenly placed in a lower age bin and 12.8 per cent were mistakenly placed in a higher age bin, an error rate of 24.1

per cent. When looking at the middle age bins, 15.0 per cent of cases were incorrectly placed in a lower age bin and 13.5 per cent were mistakenly placed in a higher age bin yielding an error rate of 28.5 per cent. The error also varied across the age bins. The degree of error presented here is troubling since assigning boys to the incorrect age bin could potentially reduce the volatility in the age pattern of growth velocity.

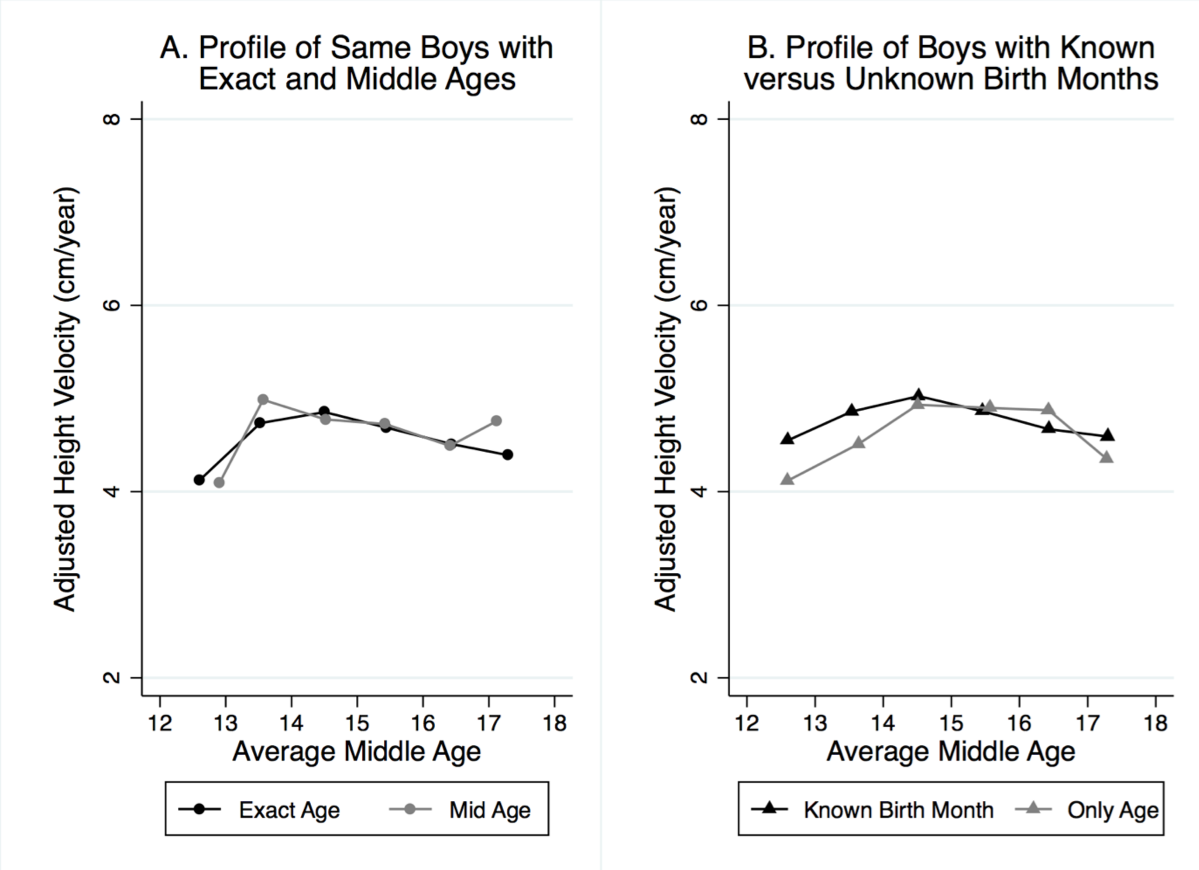
Table B2: Number and percentage of cases where the estimated age and exact age of children born between 1864 and 1876 do or do not match

One-year Age Bin	Number of Cases			Percentage at Each Age		
	Age_{est} < Age_{exact}	Age_{est} = Age_{exact}	Age_{est} > Age_{exact}	Age_{est} < Age_{exact}	Age_{est} = Age_{exact}	Age_{est} > Age_{exact}
Discharge Age						
11		1		0.0%	100.0%	0.0%
12	1	3		25.0%	75.0%	0.0%
13		17	5	0.0%	77.3%	22.7%
14	2	78	17	2.1%	80.4%	17.5%
15	17	155	25	8.6%	78.7%	12.7%
16	31	158	28	14.3%	72.8%	12.9%
17	17	99	15	13.0%	75.6%	11.5%
18	11	30	1	26.2%	71.4%	2.4%
19	2	5	1	25.0%	62.5%	12.5%
Total	**81**	**546**	**92**	**11.3%**	**75.9%**	**12.8%**
Mid-point Age on Ship						
11		2		0.0%	100.0%	0.0%
12	2	19	11	6.3%	59.4%	34.4%
13	17	106	28	11.3%	70.2%	18.5%
14	26	148	32	12.6%	71.8%	15.5%
15	33	154	16	16.3%	75.9%	7.9%
16	20	69	10	20.2%	69.7%	10.1%
17	10	14		41.7%	58.3%	0.0%
18		2		0.0%	100.0%	0.0%
Total	**108**	**514**	**97**	**15.0%**	**71.5%**	**13.5%**

Notes: This table analyses a subsample of boys with known exact ages born between 1864 and 1876. To understand the bias created by imprecise ages, we take these cases with known ages and assign them estimated ages using the mid-point year (12-year-olds are 12.5) estimation strategy described in the text. The columns show the number and percentage of cases where the estimated ages and exact ages do or do not differ. We present these for one-year discharge and middle age bins. The middle age on the ship is the midpoint between the admission and discharge age.
Sources: Indefatigable dataset, see Appendix A.

To determine whether the measurement error in the middle age bins is responsible for the flattened growth pattern that we observe in the nineteenth century, we conduct two tests. First, using the subsample with precise ages born between 1864 and 1876, we estimated the same regressions as in Figure 6 in the main text (Equation C2 as described in Appendix C) to draw a velocity profile based on the precise ages of the boys and on the estimated ages with the error presented above (Figure B2.A). While there are some differences between the two curves, especially at ages 13 and 17, they are more or less the same despite the substantial error introduced by the mid-point age estimation strategy. Thus, the 28.5 per cent error in the middle age in the institution does not significantly alter the growth pattern. In addition, if we compare the velocity profile of those born between 1864 and 1876 with known birth months and those with only age at last birthday reported (Figure B2.B), we see that there is actually more variation in velocity across age for boys with imprecise ages than for boys with precise ages. The differences between the two groups were also statistically insignificant at all ages. We do not see a clear pubertal growth spurt pattern as we do in the post-1910 period among boys with precisely measured ages. Thus, both of these tests suggest that imprecise ages do not drive the flattened velocity profile that we observe in the nineteenth century. This pattern appears to have been a true reflection of the data.

Figure B2: Tests showing that imprecision in ages does not affect the velocity profile



Notes: Figure A presents predicted values from a regression of velocity on the normal controls (see Equation C2) for a subsample of boys with known exact ages born between 1864 and 1876. The Exact Age line is the velocity profile of the boys based on their exact age, whereas the Mid Age line is the velocity profile of the boys with the mid-point age estimation strategy employed in the paper. Figure B looks at all boys born between 1864 and 1876 showing the differences in the velocity profiles between those with precise ages (a known birth month) and those where only the age at last birthday is provided.
Sources: Indefatigable dataset, see Appendix A.

Appendix C: Further Information on the Estimation Strategy

This appendix expands upon Section 3 in the main text to provide a detailed description of the regressions estimated to produce Figures 5-8. Again, these regressions are not meant to capture any causal effect of a particular variable on height or growth velocity but instead control for the changing composition of the sample across observable characteristics over time so that the estimated patterns of height and velocity are not influenced by composition effects.

For the cross-sectional analysis, we estimate two regressions to explain the absolute admission height or the height-for-age Z-score on admission. We estimate the following equation:

$$h_{i,t,a} = \alpha + \delta_t + \phi_a + \delta_t \times \phi_a + \chi_i \gamma + \varepsilon_{i,t,a} \quad \text{(C1)}$$

where $h_{i,t,a}$ is the height or height-for-age Z-score of boy i born in birth decade t entering the *Indefatigable* at age a. We include birth decade fixed effects (δ_t), age fixed effects (ϕ_a) and also allow the pattern of height by age to vary by birth decade by interacting the birth decade and age fixed effects. We also include individual-specific controls ($\chi_i \gamma$) to capture changes in the composition of the sample over time. These controls include dummies for whether the father died, father deserted, mother died or mother deserted the child; dummies for the 12 HISCLASS occupational categories as well as an occupation unknown category; dummies that capture the level of urbanisation in each boy's birth location in 1851; and county of birth dummies. In Figures 5 and 6, we hold the values of all of the individual-level controls ($\chi_i \gamma$) constant at their reference group level and predict the values of $h_{t,a}$ from the birth decade and age fixed effects and their interactions. The reference group refers to individuals with both parents alive and present in the household with the household head in HISCLASS group 11 (unskilled labourers) from large cities with an 1851 population greater than 50,000 and born in Lancashire. These controls are discussed in more detail in Appendix A.

For the longitudinal analysis, we estimate another two regressions to explain the absolute velocity of growth and the change in height-for-age Z-score. We estimate the following equation:

$$v_{i,t,a} = \alpha + \delta_t + \phi_a + \delta_t \times \phi_a + \beta_1 \frac{1}{d_i} + \frac{1}{d_i} \times \delta_t + \chi_i \gamma + \varepsilon_{i,t,a} \tag{C2}$$

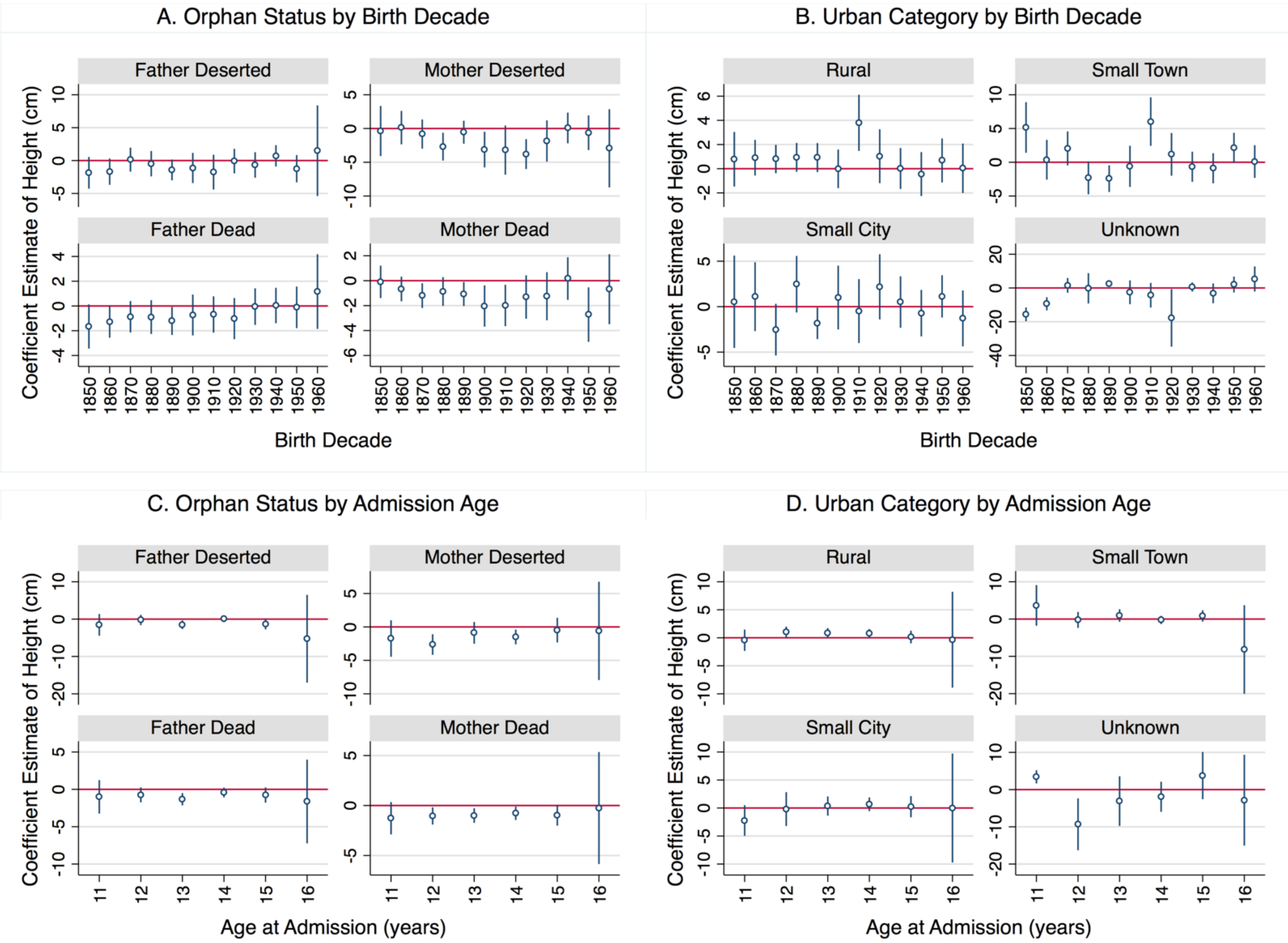
where $v_{i,t,a}$ is the velocity of growth or the change in height-for-age Z-score for boy i born in birth decade t with a mid-point age on the *Indefatigable* of a. Using the mid-point age helps ensure that we assign each boy's velocity to the one-year age bin that most directly captures his growth. We again include birth year and mid-point age fixed effects and their interaction to allow the pattern of velocity by age to change across birth decade cohorts. The same individual-level controls are included as in Equation C1 above and the predicted values plotted in Figures 7 and 8 refer to the same reference group. However, we add a new, very important individual control (d_i) which is the duration in years that the boy remained on the ship or the time between measurements. The reasons for including this variable are discussed at length in Sections 3 and 5.2 of the main text and in Appendix E. We interact the duration on the ship with the birth decade fixed effects because there is strong evidence that the effect of duration on velocity changed over time.

The estimation strategy presented in Equations C1 and C2 above will control for the changing composition of the sample. However, the equations will not correctly account for the changes in sample composition if the parameters on the control variables vary over time or across ages since the controls are individual specific. Thus, we need to check for parameter stability across the regressions. To do this we estimate Equations C1 and C2 for each birth decade and at each age. For the birth decade regressions, we estimate Equations C1 and C2 without the birth year fixed effects or their interactions. This allows us to see how the coefficients on the control variables change across birth decades. There might be change over time if, for instance, the influence of being in a rural area on height changed over time. For the age regressions, we estimate Equations C1 and C2 without the age fixed effects and without the duration on the ship and birth decade interactions. This allows us to check that the coefficients on the individual-level controls do not change across ages. These parameter stability tests obviously involve running a large number of regressions, so rather than reporting the findings in regression tables, we present graphs that plot the coefficients along with 95 per cent confidence intervals around them. We are less interested in whether the coefficients are statistically different from zero (the red line) than in whether the confidence intervals for the estimated parameters overlap. If the confidence intervals overlap, then it is ok to include a time or age invariant parameter in the regressions. We have checked these figures for all individual-level controls ($\chi_i\gamma$) and for all dependent variables, but we only report those for dependent variables admission height and growth velocity and the controls for orphan status and urban category here. We only report these two controls because the others have a large number of categories making them difficult to present and because we believe these variables would be expected as most likely to violate the parameter stability assumption. The results for the dependent variables height-for-age Z-score at admission and change in height-for-age Z-score are very similar to the results for the absolute measures of those variables admission height and velocity.

Looking first at the parameter stability of the orphan status and urban category controls on admission height by birth decades (Figures C1.A and C1.B), we see that in nearly every birth decade the confidence intervals for the parameter estimates overlap. There is certainly no systematic bias over time which would require interacting these controls with the birth decade fixed effects in Equation C1. Likewise, when looking at differences in the estimated coefficients across different admission age bins (Figures C1.C and C1.D), we see that nearly all of the confidence intervals on these coefficients overlap. The wide confidence intervals at admission age 16 reflect a small sample size in that age group and should not be taken as a serious problem for our estimation strategy. Similar plots for HISCLASS categories and counties of birth yield very similar results. Thus, there does not appear to be any problems of parameter stability for the admission height and admission height-for-age Z-score regressions.

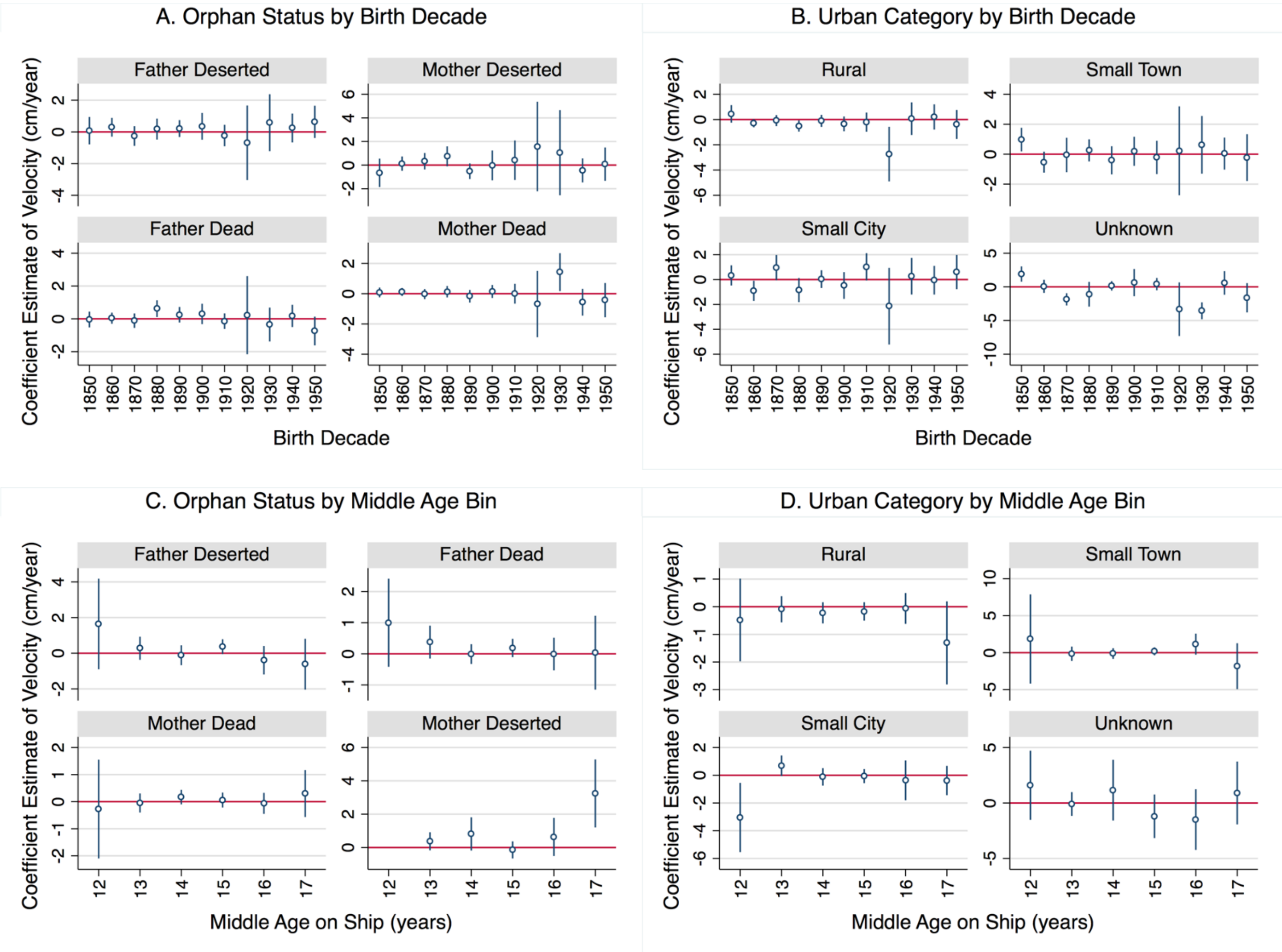
The story is very similar when looking at these same control variables for growth velocity. When looking across birth decade cohorts, the confidence intervals on the estimated coefficients almost always overlap (Figures C2.A and C2.B). There were some substantially lower values for rural and small cities in 1920, but the confidence intervals on these intervals were very large, and this decade was the only one that differed. When looking at differences in the estimated coefficients across age, we again mostly find parameter stability (Figures C2.C and C2.D). The somewhat discordant results at ages 12 and 17 are again driven by fairly low sample sizes at these ages. Again, we find similar results when looking at HISCLASS categories and county of birth. Therefore, we do not believe there are any major issues related to parameter stability related to the individual-level controls that are common in Equations C1 and C2.

Figure C1: Parameter stability checks for the influence of controls on admission height by birth decade cohort and age at admission



Notes: Figures A and B show the estimated coefficients with 95 per cent confidence intervals for each variable for each birth decade cohort. Figures C and D show the same but at each age. The wide confidence intervals and odd parameter estimates at age 16 are related to small sample sizes. In Figures B and D, the urban categories refer to the urban population in the registration district of birth for each boy. Rural registration districts are districts with an urban population of less than 10,000 in 1851, small towns are districts with an urban population between 10,000 and 24,999 people and small cities are districts with an urban population between 25,000 and 49,999 people. Large cities, districts with an urban population greater than 50,000 in 1851, are the reference category in the regression.
Sources: Indefatigable dataset, see Appendix A.

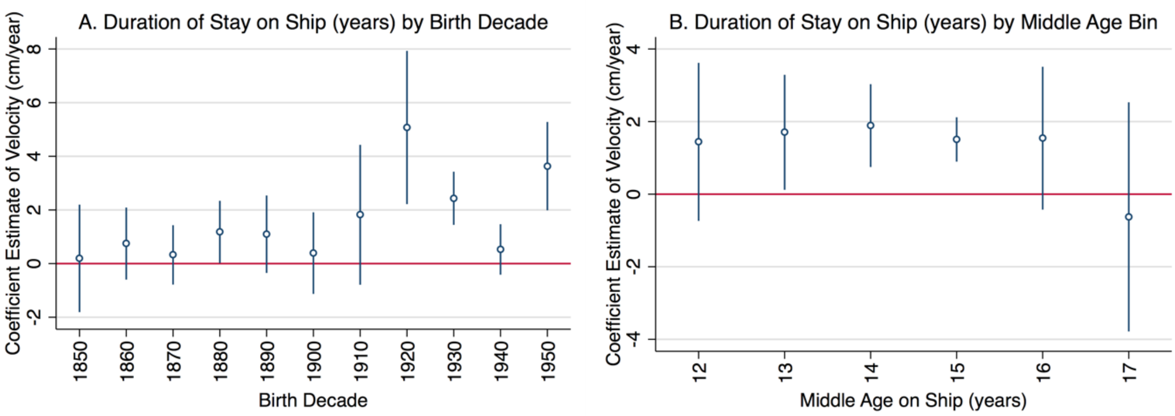
Figure C2: Parameter stability checks for the influence of controls on growth velocity by birth decade cohort and middle age on the ship



Notes: Figures A and B show the estimated coefficients with 95 per cent confidence intervals for each variable for each birth decade cohort. Figures C and D show the same but at each age. The wide confidence intervals and odd parameter estimates at age 12 and 17 are related to small sample sizes. In Figures B and D, the urban categories refer to the urban population in the registration district of birth for each boy. Rural registration districts are districts with an urban population of less that 10,000 in 1851, small towns are districts with an urban population between 10,000 and 24,999 people and small cities are districts with an urban population between 25,000 and 49,999 people. Large cities, districts with an urban population greater than 50,000 in 1851, are the reference category in the regression.
Sources: Indefatigable dataset, see Appendix A.

However, the duration of stay on the ship variable showed more systematic variation across birth decades with several birth decades having significantly different coefficients from one another and a general increase in the parameter magnitudes appearing in the 1920s and later (Figure C3). Thus, it seemed prudent to include interactions between the birth decades and duration of stay in equation C2. We also tried using only a post-1920 interaction, but the results were very similar, so it seemed fine to use the birth decade interactions. The change in the magnitude of the parameters on duration of stay on the ship over time could be caused by a number of factors related to measurement error and the uniformity of length of stay on the ship. The reason that we observe a reciprocal relationship between growth velocity and the duration of stay on the ship is because there is measurement error in the height measurements but relatively continuous variations in the duration of stay variable. Because of height measurements were often only measured to the nearest half inch, we observe specific changes in height, 1 inch, 1.5 inches, 2 inches. These height increments are divided by smooth increasing durations of stay producing a reciprocal look to the graphs. If height were measured very precisely, we would not expect this relationship. Thus, it is important to consider how the precision of measurement was changing over time.

Figure C3: Parameter stability checks for the influence of the reciprocal of duration of stay on the ship on growth velocity by birth decade cohort and middle age on the ship



Notes: Figures A and B show the estimated coefficients with 95 per cent confidence intervals for each variable for each birth decade cohort and middle age on the ship.
Sources: Indefatigable dataset, see Appendix A.

Table C1 shows the percentage of admission and discharge height measurements reported at the whole inch, half inch or quarter inch level. If height were precisely measured to the quarter inch, we would expect 25 per cent of cases to end on a whole inch, 25 per cent to end on half an inch and 50 per cent to end on one quarter or three quarters of an inch. However, height never seems to have been measured this precisely, and the precision seems to have declined over time rather than improving. The most precise measurements were those for boys born in the 1850s but by 1950, it seems the ship had given up on measuring boys to the nearest quarter inch. On the whole admission heights were measured more precisely than discharge heights as well, which could add to the error. The changes in measurement precision over time are compounded by the fact that the average duration of stay on the ship declined from the 1920s birth cohort onwards. Thus, the dispersion of velocities is higher for these birth cohorts since the rounding to the nearest half inch would increase the probability that boys experience zero growth or very rapid growth.

However, this is not a problem for our overall analysis for a number of reasons. First, as mentioned in the main text, we exclude boys who remained on the ship for less than four months to control for the greatest extremes in this error. In practice, the ship did something similar, recording discharge heights for only 17.4 per cent of boys who remained on the ship for less than four months compared to 74.0 per cent for boys who remained on the ship for more than four months.[72] Second, we control for the length of stay in the regressions and allow it to vary across birth decades, so any changes that may occur across birth decades will be captured in our methodology. Finally, we are comforted to see in the raw data that the high velocities we observe in the post-1910 period even occur at durations of stay on the ship that overlap with those in the pre-1910 period (see Appendix F). Thus, we do not believe that the change in the growth pattern observed is spurious.

[72] This is calculated for birth cohorts from 1850 to 1956 when discharge height was commonly measured, except for a few birth cohorts in the late 1910s and early 1920s.

Table C1: Percentage of admission and discharge heights reported to be a whole inch, half inch or one- or three-quarters inch by birth decade cohort

Birth Decade	Admission Height			Discharge Height		
	Whole Inch	Half Inch	Quarter Inch	Whole Inch	Half Inch	Quarter Inch
1850	31.70%	26.03%	42.27%	36.86%	23.71%	39.43%
1860	36.77%	27.23%	36.00%	51.35%	25.94%	22.71%
1870	38.31%	32.44%	29.25%	57.09%	27.59%	15.33%
1880	51.02%	32.47%	16.51%	58.53%	30.56%	10.91%
1890	54.19%	30.44%	15.37%	54.34%	29.38%	16.29%
1900	43.88%	26.14%	29.98%	54.66%	27.97%	17.37%
1910	44.67%	29.88%	25.44%	48.22%	35.21%	16.57%
1920	53.59%	34.18%	12.24%	38.82%	37.13%	24.05%
1930	41.84%	32.65%	25.51%	51.46%	34.84%	13.70%
1940	52.14%	37.38%	10.48%	55.83%	42.02%	2.14%
1950	63.36%	29.35%	7.29%	47.66%	51.40%	0.93%

Notes: Whole inch denotes a height measurement on a whole inch unit, i.e. 6.0. Half inch denotes a height measurement on a half inch unit, i.e. 6.5 but not 6.0. Quarter inch denotes a height measurement on a quarter inch unit, i.e. 6.25 or 6.75 but not 6.0 or 6.5. Since the precision matters most for individuals for which we observe longitudinal growth, the percentages in the table are only for individuals with both a recorded admission and discharge height. We also exclude cases that have been verified in the original source as transcription error such as when heights fell over time. See Appendix A for more detail.

Sources: Indefatigable dataset, see Appendix A.

To conclude, although there are some issues with the data, our estimation strategy allows us to control for the changing composition of the sample to understand how the growth pattern changed over time. Overall, the regression parameters are stable, and so it is possible to use Equations C1 and C2 to predict the age pattern of growth for each birth decade cohort.

Appendix D: Further Information on Living Standards on the Ship

Food

Both rich anecdotal evidence and the data on real food expenditure per boy suggest that there were no substantial changes in the boys' daily diet on the ship before the 1950s. Table D1 documents how the boys' diet changed between the 1880s and 1960s using oral histories of boys published in the Old Boys Society's publications and collected in Evans's book on the *Indefatigable* and other sources. Without quantities of overall food and especially of meat and milk, it is very difficult to gauge changes in nutritional quality over time. There is a shift from three meals per day to four meals per day that occurred by the 1940s, but the fourth meal was rather small and could have been easily balanced with a reduction in food at another meal. Looking at the period before and after the ship was transferred on land in 1941, the diet did not change dramatically. The children were given milk before and after the move on land although there may have been more meat in the 1940s than 1920s.

We have also noted some of the boys' own descriptions of food quality and their hunger in the 1920s and 1940s in Table D1. It is striking that these are so similar. In both cases the boys describe themselves as 'always hungry' and they unanimously thought the food was horrible. Thus, from the boys' perspectives there doesn't appear to have been a big change in the diet either. This gives us confidence that the change in growth pattern beginning with the 1910s birth cohort was not driven by improvement in food quality on the ship.

Workload

The main physical activities on the ship included practice of seamanship[73], sports exercise[74] and routine duties[75] on the ship. There is mixed evidence for a modest reduction in workloads after the critical time period, i.e. for boys born in the 1910s

[73] The practice of seamanship included 'practical instruction . . . in various branches of seamanship, including helm and compass, boat-work, boat pulling, boat sailing, knots and splices, signals, wireless telegraphy and etc.'; 'Seventy-Seventh Annual Report', p. 5.

[74] Boys were asked to engage regularly in various sports, including football, swimming, boxing, rowing and cricket.

[75] The routine duties of the ship involve the employment of boat's crews, motor boat's crew, tailor's shop boys, engineers, cooks and etc.

and later. The moving of the *Indefatigable* on shore to Calwdd Newydd between 1941 and 1945 may have reduced boys' physical activities, especially since they were no longer actively working on a ship. However, after the ship was moved on land, the instructors introduced more sport activities to the timetable and sent boys in batches to the "outward bound" sea school where the boys still practiced sailing small vessels. The annual report of 1942 indicates that all lessons and duties were resumed on a similar basis as the original routine on the ship before the *Indefatigable* was moved on shore.[76] After moving to Anglesey in 1945, the regular practice of navigation and rowing and sailing was resumed in the Menai Straits.[77]

Living conditions

The boys lived in modest conditions on the *Indefatigable*. Before the *Indefatigable* was moved on shore, boys slept in hammocks. Conditions actually worsened during World War II at the Clawdd Newydd camp because there were not always permanent dormitories for the boys to sleep in. At times they slept on bunks in unheated huts or in entryways to other buildings, making winters more difficult.[78] Major improvements took place after the school moved to Anglesey. New beds were installed in dormitories, and modernization work was carried out from late 1950s onwards: for instance, electronic re-wiring work was done in 1956, and beds and mattress were regularly renewed.[79] The records did not specifically mention when piped water was installed, but there was definitely running water and electricity in all of the land-based facilities.

Disease environment

From the very beginning, medical examinations of the boys were conducted regularly (weekly for most of the *Indefatigable's* history, and very sick children with infectious or chronic diseases were sent to hospitals onshore. After 1920, the

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[76] 'Seventy-Fifth Annual Report', pp. 4-5; 'Seventy-Seventh Annual Report', pp. 4-7; 'Seventy-Eighth Annual Report', pp. 4-7.
[77] 'Second Annual Report [1946]', p. 3.
[78] 'Chairman's Reports to the Executive Committee', 13 November 1941; 9 April 1942.
[79] 'Chairman's Reports to the Executive Committee', 29 November 1955; 18 January 1956; 8 May 1957; 30 April 1958.

annuals reports discuss a sick bay on the ship for boys who were sick. After the 1930s, dental surgeon's visits were arranged.

Although it is clear that conditions on the ship improved over time, in most cases the major improvements either pre-dated or post-dated the sharp change in the growth pattern suggesting that changes in the conditions on the ship are not driving our results.

Table D1: Daily diet recorded by boys on the ship, 1888-1960

Year	Description of the diet
1888	Sunday Breakfast: Cocoa, bread and butter Dinner: Roast beef, suet pudding Tea: Tea, bread and butter Monday Breakfast: Cocoa and biscuit Dinner: Beef, potatoes, vegetable soup Tea: Tea and biscuit Tuesday Breakfast: Oatmeal porridge and syrup Dinner: Beef, potatoes, vegetable soup Tea: Tea and biscuit Wednesday Breakfast: Cocoa and biscuit Dinner: Pork and pea soup Tea: Tea and biscuit Thursday Breakfast: Porridge and syrup Dinner: Beef and suet pudding Tea: Tea, bread and butter Friday Breakfast: Cocoa and biscuit Dinner: Beef, potatoes and soup Tea: Tea and biscuit Saturday Breakfast: Porridge and syrup Dinner: Beef, potatoes and soup Tea: Tea and biscuit
c. 1917	More meagre diet because of war rationing: Breakfast: two slices of bread and margarine, mug of cocoa or tea Dinner: a bowl of stew Supper: two slices of bread and margarine, mug of cocoa or tea
c. 1920s	Diet in early 1920s:

	Breakfast: a slice of thick bread with margarine, cocoa (with milk) Dinner: potato stew or cod (Fridays) or roast beef with potatoes (Sunday) Tea: a slice of thick bread with jam In winter, porridge and boiled rice were provided with breakfast and dinner respectively. Descriptions of hunger 1920: 'One abiding memory is being permanently hungry' (Evans, p. 61) 1925: 'The food was horrible; I shut my eyes to eat it, but I was always hungry' (Evans, p. 63)
c. early 1940s	Diet in 1944: Breakfast: porridge, chunk of bread and marge and tea Lunch: meat of some sort with potatoes and gravy with spotted dick cake for dessert Tea: pilchard (fish) pie, two half-inch chunks of bread and tea Supper: rock cake and half a mug of milk. Descriptions of hunger 1944: 'We were always starving. One day we refused to eat the stuff and in due course the chef was sacked' (Evans, p. 114) 1946-7: 'I think my main concern while I was in Inde [sic] was food. I always seemed to be hungry' (Evans, p. 144)
c. late 1960s	Menu from booklet advertising *Indefatigable* from the late 1960s: Breakfast Rice crispies and milk Sausage, bacon and egg Bread and butter Marmelade Tea Dinner Steak and kidney pie or chicken Fried or mashed potatoes Brussel sprouts or peas Coconut and jam pudding Custard Tea Bread and butter Jam Assorted cakes Tea Supper Beans on toast Squash or cocoa

Sources: Evans, *Indefatigable*, pp. 19-20, 32, 35-7, 61, 63, 114, 144; 'T.S. Indefatigable', p. 10.

similar in the two periods. However, there were substantial differences between the high velocity groups with higher velocities in the later group at the mean and first and third quartiles. All of this evidence suggests that there was substantial change in growth velocity between the two periods. These changes also cannot be easily explained away by the differences in duration of stay over time since the differences in duration of stay between the low and high velocity groups were relatively small (0.2 years or 2.4 months at the mean). Table 1 in the main text confirms these results by looking at these percentages across different ages. Thus, we are confident that there are real changes in growth between the pre-1910 and post-1910 periods.

Figure F1: Illustration of thresholds for rapid pubertal growth

Sources: Data from https://www.who.int/growthref/tools/en/.

Table F1: Growth velocity distribution for Indefatigable boys, pre-1910 vs. post-1910

	Born Pre-1910		Born Post-1910	
	Low Velocity	High Velocity	Low Velocity	High Velocity
	Growth Velocity (cm/year)			
Velocity Threshold	5.45		5.98	
Mean	3.64	6.74	3.69	9.02
P25	2.91	5.81	2.74	6.89
P75	4.61	6.91	4.93	10.00
N	2931	909	1490	1148
Percentage	76.33%	23.67%	56.48%	43.52%
	Duration of Stay (years)			
Mean	2.56	2.36	1.39	1.20
P25	2.17	2.01	0.91	0.84
P75	3.02	2.82	1.61	1.48

Notes: Velocities and lengths of stay are calculated for boys who were on board the *Indefatigable* for more than four months and exclude problematic cases described in Appendix A.
Sources: Indefatigable dataset, see Appendix A.