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Human capital and long run economic growth: Evidence from the stock of human capital in England, 1300-1900

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Human capital and long run economic growth:
Evidence from the stock of human capital in England, 1300-1900[1]

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Abstract

Did human capital contribute to economic growth in England? In this paper the stock of total years of schooling present in the population between 1300 and 1900 is quantified. The stock incorporates extensive source material on literacy rates, the number of primary and secondary schools and enrolment figures. The trends in the data suggest that, whilst human capital facilitated pre-industrial economic development, it had no role to play during the Industrial Revolution itself: there was a strong decline in educational attainment between ca. 1750 and 1830. A time series analysis has been carried out that confirms this conclusion.

Keywords: Human capital, Industrial Revolution, economic growth, England

JEL Codes: N13, N34, J24, O10.

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1. Introduction

Economic models of the Industrial Revolution increasingly emphasize the key role of human capital in promoting economic growth (Becker et al 2011, Galor 2011), and empirical studies have shown that education is a strong predictor of per capita GDP (Barro 2001, Cohen and Soto 2007, Sunde and Vischer 2011). The logic behind this is that human capital facilitated technological adoption and innovation (cf. Nelson and Phelps 1966, Schultz 1975). Contrary to the theory and evidence, however, economic historians have described the role of human capital in the English Industrial Revolution as minor (Mokyr 1990, Mitch 1993, Crafts 1996, Clark 2005). Literacy rates were at best mediocre. Around 1800, literacy rates were about 60% for males and 40% for females (Cressy 1980). Reis (2005) has shown that this was slightly higher than France, but significantly lower than the Netherlands, Sweden and Germany. For instance, Sweden was fully literate by the early 19th century.[2] There was not much improvement in literacy during the Industrial Revolution itself: male literacy rates fluctuated around 60% between 1750 and 1850 (Mitch 1993). Similar conclusions can be drawn from school enrolment figures. Out of the male population in the age bracket between 5 and 14, 28% were enrolled in schools in 1830. In 1850, by the end of the first Industrial Revolution, it had increased to 50%, but this was equal to France (51%) and considerably less than Prussia (73%) (Lindert 2004).

The conclusion that human capital did not play an important role in the British Industrial Revolution draws upon records of school enrolment and literacy.[3] Literacy rates are likely to underestimate the level of human capital as they only proxy primary schooling (reading and writing abilities) and enrolment rates do not take into account the age structure of the population. What is more, by largely focussing on the period after 1750, these measures are expected to understate the growth of literacy, and that of schooling in general, which occurred in the centuries leading up to the Industrial Revolution.[4] The recent studies of Baten and Van Zanden (2008) and Boucekkine et al. (2007) introduce more comprehensive measures of human capital formation such as book production and the number of (secondary) schools and even trace their evolution back to the medieval period. What these studies show is that the growth of human capital was far greater than previously assumed and that it significantly contributed to pre-industrial economic growth.[5]

In this paper the stock of human capital for England over the long run (1300-1900) is quantified. The human capital stock incorporates extensive statistical evidence on literacy rates, the number of primary and secondary schools and their average class sizes, and

[2] Sandberg (1979) argues that Sweden became Europe's 'impoverished sophisticate'. Although literacy rates were round about 100%, its industrialization was relatively late.
[3] Notably the records of school enrolment of Flora et al (1983) and the literacy rates of Schofield (1981) and Cressy (1980).
[4] An important exception stems from Kelly and Ó Gráda (2014) who acknowledge a steady increase in human capital between 1500-1750.
[5] Allen's (2003) regressions however suggests that 'literacy was generally unimportant for growth' between 1300 and 1800 (pp. 433). This non-result might be explained by his estimates of literacy: for 1500, his estimates are based on the urbanization ratio, which assumes that 23% of the urban and 5% of the rural population was literate (pp. 415). What is more, most of the estimates between 1500 and 1800 are based on intrapolation.

matriculations to the University of Cambridge, Oxford and London. Demographic key figures, such as survival rates of individuals, are applied to estimate average years of education present in the total population. An additional distinction is made on the basis of gender (years of education of males and females) and of level (formal primary, secondary and tertiary education). It is shown that the stock of years schooling can be quantified rather well. The estimates presented in this paper are therefore able to give a far more coherent picture on the evolution of formal schooling in the long run.[6] In that way, it becomes possible to examine the formation of human capital before as well as during the Industrial Revolution.

Some interesting conclusions stand out. The years of schooling measure began to increase at a fast rate after the 1530s. Between 1530 and 1700, secondary education accounted for over half of the share of the education stock of males. One out of six boys went up to the secondary level by the turn of the 17th century. A pronounced shift occurred after 1700 as indicated by stagnation in average years of primary schooling and a vast decline in attainment levels of secondary and tertiary schooling. Only one out of thirty boys went up to the secondary level in the second half of the 19th century. The educational attainment levels of females were well below those of males, although it is the only stock that shows consistent growth until 1800. Over the course of the 19th century, females rapidly caught up with males in terms of average years of primary schooling. Overall, from the evidence on the evolution of the stock of human capital, it can be concluded that the first Industrial Revolution coincided with a pronounced decline in formal secondary schooling levels of males.

To formally test the relation between human capital and economic growth, a time series analysis is conducted. Johansen tests of cointegration are performed to test the possibility of a long-term relationship among educational attainment and per capita GDP (Johansen 1995).[7] In the cases where cointegration is found, bivariate cointegrated VAR models are estimated. The model omits other relevant determinants of per capita GDP, so the results must be interpreted with some care. It is however possible to interpret the cointegrating relationship as robust correlation coefficient, because underspecification does not affect the consistency of the estimated cointegrating vectors (see Pashoutidou 2003). The overall results suggest a positive educational attainment to per capita GDP relationship in the 17th century. During the 18th and early 19th centuries, the relationship was clearly negative.

The results presented in this paper are in line with Baten and Van Zanden (2008) and Dittmar (2011) who show that book production and book printing significantly contributed to pre-industrial economic growth. The finding of a negative human capital to growth relationship during the age of cotton and steam provides further evidence to the predominant view that formal education did not contribute to England’s early industrialisation (Nicholas and Nicholas 1992, Mitch 1993). Relative to this literature several contributions are made. First of

[6] The information available forces me to focus on formal education. It thus ignores the part of the stock of human capital the acquisition of which did not involve formal schooling but which could have been important for the productivity of workers, such as apprenticeships or on the job learning (see: Humphries 2003, Wallis 2008 and Mokyr 2009).

[7] The analysis uses the latest estimates on per capita GDP of Broadberry et al (2015).

all, previous conclusions are derived from the observation of a pause in the growth of male literacy between 1750 and 1850. Evidence from the trends in the stock of primary education of males indeed suggests that this must have been the case. However, the movement away from formal secondary and tertiary schooling on the eve of the Industrial Revolution is a factor that should not be overlooked. It demonstrates that the decrease in human capital was more pronounced than the evidence on the spread of literacy alone would suggests, and therefore it may indicate that the reduction in the demand for educated (male) workers was more severe than previously assumed by scholars. Secondly, and related to the above, the regression results demonstrate that formal education constrained per capita GDP growth. This finding may support McCloskey's (2010) notion that investment in human capital can be massively misallocated and therefore have a negative impact on economic development.

The remainder of the paper is organised as follows. Section 2 presents the data on the stock of human capital, and discusses the assumptions underlying the estimates. Section 3 presents the main empirical results following the time series analysis. Section 4 concludes by discussing the implications of the findings for the debate on the nature of human capital formation in England, and that for the relation among human capital and economic growth more generally. The conclusion also proposes avenues for future research on the topic.

2. Data on the stock of human capital

The stock of human capital is computed in 'physical' units - that is as years of formal education present in the population.[8] In that way, the estimate of the human capital stock is a very direct application of the concept, since human capital is directly linked to individuals. Assuming the lifetime of humans (and therefore the lifetime of their human capital) to be finite, it is possible to apply the perpetual inventory method to compute the stock of human capital.[9] This is essentially the same way as building stocks of physical capital. An individual's human capital (the number of years of schooling) enters the stock when he/she finishes school and leaves the stock at time of death depending on his/her life expectancy. To estimate the annual flow of years of primary, secondary and tertiary schooling entering the human capital stock, statistical source material on literacy rates, the number of primary and secondary schools, and enrolment figures are used. The current section describes the procedure and discusses the outcomes.

2.1 *Primary education*

To estimate the annual flow of years of primary education entering the human capital stock between 1550 and 1900, existing statistical evidence on literacy rates are combined. Literacy rates are measured as the capacity of individuals to sign their names on documents. The estimates of literacy are derived from church and secular records for the period prior to 1754

[8] The method applied in this paper is originally developed by Clemens et al (1996).
[9] It is required to make this assumption to estimate the initial 1300 stock. From the mid-14th century onwards (i.e. roughly one asset life on), the estimates of the stock of human capital are independent of the initial assumption.

and marriage contracts for the years thereafter. The statistics on literacy of Cressy (1980, 1981) are used for the years 1550 to 1754; those of Schofield (1981) for the years 1754 to 1840; those of Stephens (1987) for the years 1840 to 1885; and, finally, those of Cressy (1980) for the years after 1885. All details regarding the availability of literacy rates can be found in Appendix I.

Preference for literacy rates is for a variety of reasons. To begin with, the capacity to sign documents is said to give a fair indication of the share of the population that could read at an advanced level, as well as a certain ability to handle writing materials.[10] Unlike nowadays, reading and writing were taught in separate and successive periods of about two to three years at a time. Signature evidence is therefore argued to proxy a relatively sustained and prolonged effort of learning in primary schooling (Schofield 1968, Reis 2005). Secondly, it has the merit of being fairly homogeneous across space (Albers 1997). With respect to the history of schooling in England, there were different ways for children to learn basic reading and writing skills. Children could have learned to read and write at churches, at work, or informally at home (Williams 1961, Schofield 1981). If children were sent to school, then there were different types of elementary schools were they could choose from: ABC-, song-, reading-, writing-, and petty schools. Even more types of school started to emerge after 1700. Examples of these include Sunday-, charity-, monitorial-, industrial-, and workhouse schools. It is not only uncertain how skills of basic and reading and writing were learned, there were also differences in the learning objectives of the schools. ABC-, song-, and reading schools were concerned with reading, whilst charity- and Sunday schools taught moral and religious courses (Jewell 1998). The use of signature evidence has the advantage of making it possible to assume a certain level of primary education that ignores the way in which these skills were obtained in the first place. Finally, and related to the above, it would be practically impossible to proxy primary schooling covering the whole of England without the use of evidence on literacy rates. The charity schools are relatively well documented in the records (see Boucekkine et al 2007): London and Westminster had 54 charity schools teaching about 2000 pupils in 1704, which had increased to 179 schools teaching 7108 children in 1799. Unfortunately, no such detailed evidence exists for the number of other types of primary schools and their average class sizes.[11]

Statistical evidence on literacy rates for the medieval period is harder to come by. What is known from qualitative studies is that around 1300 literacy was mainly restricted to the clergy. Following the Black Death, however, lay literacy gradually started to increase. The English economy became more commercialised and economic specialisation rose: for instance, over the course of the 15th century, England became a significant producer of finished cloth (Lawson and Silver 1973). Centralisation of the state stimulated the growth in royal administration and common law. Both developments required more educated laymen,

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[10] Literacy rates do however overestimate the share of the population with advanced writing skills (see discussion below).

[11] A limitation of the use of literacy rates is that it does not capture improvements in the quality of schooling across time that were clearly there. One may therefore expect a year of schooling obtained in say, 1500, to be of lower quality than a year's schooling in 1900. As I discuss in more detail in Section 2.3, allowance is made for increases in years of schooling when estimating the stock.

leading to human capital formation. On top of this, church controlled education started to decline after 1400, which made it appealing for middle class children to enter the schooling programme (Leach 1915). Due to these three (to some extent interrelated) factors, literacy spread among the upper- and middle classes. There is even evidence of growing literacy among groups of lower social status. For instance, Graff (1987) shows that male literacy was as high as 40% in London during the 1460s, of which craftsmen formed a significant group of literate people.[12]

Statistics provided by Hoeppner Moran (1985) allow for an estimation of the annual flow of years of primary education during the medieval period. Hoeppner Moran (1985) traces the evolution of schooling in the Diocese of York between 1300 and 1548 by quantifying the number of primary schools (song- and reading schools) and the number of secondary schools (notably Latin grammar schools). The results are presented in Figure 1 and illustrate that the trends in the number of schools compare rather well with what we know from the more qualitative studies on the spread of literacy, in particular the rise in school foundations over the course of the 15th century. Based on the increase in the number of primary schools, Hoeppner Moran estimates the average literacy rate to have been around 15% in the 1530s. Her estimate is higher than Cressy's (1980) figure of 8.2% for this period.[13] In order to quantify the stock of primary schooling, it is important to make the two datasets comparable. Therefore I now turn to the two reasons accounting for the disparities in the numbers – the applied definition of literacy and the slight underestimation of the spread of literacy by Cressy.

[12] Buringh (2014) furthermore shows that the price of information (measured by the price of books) sharply fell in the years following the Black Death. He therefore concludes that schooling became much cheaper for large groups within the society.

[13] According to Moran, 22.5% of the males and 7.5% of the females were literate. Following Cressy (1980), this was round about 13.6% and 2.8% respectively.

Figure 1. The growth in elementary and secondary (grammar) education in York diocese, pre-1300 to 1548
Source: Hoeppner Moran (1985, p. 118).

About two-thirds of the difference can be attributed to the applied definition of literacy.[14] Whereas the literacy estimates of Cressy are quantified from evidence on signatures, those of Hoeppner Moran are derived from the growth in the number of song- and reading schools. Since song- and reading schools were mainly concerned with teaching pupils on how to read, Hoeppner Moran concludes that her estimates are likely to capture 'reading-literacy' rather than 'signature-literacy' as those of Cressy do (see Hoeppner Moran 1985, pp. 225).

In order to make them comparable, the next step is to convert reading-literacy into signature-literacy for which it is required to combine the length of the primary schooling programme with the estimates on literacy. As explained at the beginning of this section, signature-literacy gives a fair suggestion of the share of the population that could read easily. Certainly more people were able to read than could sign their name on a (marriage) contract, so the capacity to sign a document is likely to underestimate the share of the population that could read at a basic level (see the discussion in Schofield 1968 and Stephens 1987). The official length of the primary schooling programme was 3 years at the time, during which children first learned how to read and thereafter how to write at an advanced level (writing was taught at a later stage than reading) (Stone 1964). The ability of an individual to sign a (marriage) contract does not infer anything about the writing capabilities of that person. Whereas signature-

[14] Converting the reading-signature estimates of Hoeppner Moran into signature-literacy gives the following results: 7.6% of the population was literate in 1500 (11.4% of the males and 3.75% of the females). In 1530 this had increased to 11.3% (16.9% of the males and 5.6% of the females). The estimates of Cressy (1980) suggest a literacy rate of 5.5% in 1500 (10% of the males and 1% of the females), which had increased to 8.2% (13.6% of the males and 2.8% of the females) by 1530. Comparing the estimates implies that round about 58% to 65% of the difference can be explained by the applied definition of literacy. See Appendix I for more details.

evidence is said to underestimate reading capabilities, it is very likely to overestimate advanced writing skills. Hence, the share of the population able to sign documents must have been higher than the share able to write at a reasonable level. Since it is known that children learned to read in about 1.5 years (Jewell 1998), reading-literacy is set equal to 1.5 years of primary schooling. Signature-literacy is likely to capture more advanced reading skills, whereas at the same time it is unclear whether the individuals were able to write. It is thus not plausible to set signature-literacy equal to the length of the primary schooling programme (3 years), but it is fair to give it 2 years of education.

Combining the years of schooling with the estimates on signature- and reading literacy indeed removes the largest part of the difference.[15] There is still one third of the disparity that cannot be explained by the applied definition of literacy. This implies that either Hoeppner Moran's figures are too optimistic, or those of Cressy are too pessimistic. The study of Hoeppner Moran shows that the 15th century expansion of song- and reading schools was followed by an increase in the number secondary schools: from 25 in 1500 to 68 in 1548 (see Figure 1). As discussed in Section 2.2 about the growth in secondary and tertiary schooling, scholars tend to agree on the extraordinary expansion of higher education over the 16th and 17th century, which was labelled the 'educational revolution in higher education' by Stone (1964) (see also Jordan 1959 and Simon 1960). Unfortunately the studies do not explain where the demand for secondary and tertiary schooling came from, but the onset and magnitude of the revolution squares rather well with the trends that Hoeppner Moran sets out for the York Diocese: the growth of song- and reading schools over the 15th and early 16th century, in which 50 schools were founded between 1400 and 1500, and 54 more between 1500 and 1548, must have paved the way for an expansion in grammar schooling.[16] In other words, the enthusiasm for higher education in the 16th and early 17th centuries would have been unlikely without enough primary schools to feed them, and the revolution in secondary and tertiary schooling can therefore be better understood given the preceding developments.

Taking the trends in secondary and tertiary schooling into account, it is suggested here that Cressy slightly underestimates the spread of literacy by the early 16th century.[17] On top of this, it might well be that Hoeppner Moran (1985) slightly underestimates the magnitude in the growth of (secondary) schooling - most probably caused by the focus on trends at the level of the York diocese. The evidence on the number of secondary schools as documented by Orme (2006) cover the whole of England during the medieval period and indicate that the growth of secondary schools must have been twice as high as the results of Hoeppner Moran

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[15] See calculations in footnote 12.

[16] The focus of the studies of Jordan (1959) and Simon (1960) is on the period after 1500, which may help to explain why they do not consider where the growth in secondary and tertiary education came from.

[17] Converting the literacy rate of Cressy for 1500 into enrolment in primary schooling and comparing it to the enrolment figures in secondary education of Orme (2006), suggests that as many children were sent up to the secondary level as were able to read and write – a results that seems very unlikely. This finding once more suggests that Cressy slightly underestimates the spread of literacy by the early 16th century. For the period after 1550, Cressy's estimates correspond well with the figures of Stone (1969, pp. 101) and Schofield (1981).

suggest.[18] Hence, if the expansion of secondary and tertiary schooling was indeed fed by the growth in primary schooling, then it is even possible that the estimates of reading-literacy underestimate the growth in literacy between 1300 and 1530.[19]

The reading-literacy rates of Hoeppner Moran (1985) are projected backwards in time by taking the growth in primary schools into account (i.e. the trends as set out in Figure 1).[20] In order to make it comparable with the evidence for the period after 1550, 'reading-literacy' is converted into 'signature-literacy' using the assumption about the attainment levels, i.e. reading-literacy is equal to 1.5 years of education and signature-literacy is equal to 2 years of education. The calculations can be found in Appendix I. Table 1 reports on the results.[21]

Year	Men	Women
1300	2.0	0.7
1400	3.3	1.1
1500	11.4	3.8
1600	25	9.3
1700	42	24
1750	56	36
1800	64	42
1850	69	54
1900	95	94

Table 1. Literacy rates, 1300-1900

Notes and sources: See main text. Percentages are rounded up to the nearest digit.

Equation (1) is used to convert literacy into primary school enrolment, h_t^1. Schooling opportunities opened up around the age of 5 and closed again as children entered the labour market around the age of 15 (Cressy 1980). Since 72% of the spouses were in the age bracket between 20 and 29 when signing their marriage contracts, a lag of 15 years is employed to control for the time difference between schooling and marriage (Schofield 1968). h_t^1 thus is a function of literacy in $t+15$ (l_{t+15}). The next step is to calculate the absolute number of children that enrolled in year t. Wrigley et al. (1997) provide estimates on the share of the English population that was in the age bracket between 5 and 14 for the period 1541 to 1871: $\gamma_{(5\text{-}14),\,t}$. The share is quite constant over time: it had only slightly increased from 21% in the 16th century to 22% in 1871. It is therefore assumed that 21% of the population was in the age

[18] Orme (2006) shows an increase of 69% in the number of secondary schools between 1500 and 1548. The estimates of Hoeppner Moran suggest this was round about 37%.

[19] The literacy rates worked with in this paper are therefore a lower bound.

[20] It would of course be better to use the trends at the national level to project the literacy rates backwards in time. Unfortunately, to follow Orme (2006), whilst secondary schools are well recorded in the records, evidence on the number of primary schools is relatively scant.

[21] It is possible to perform a robustness-check for the level of literacy in the 14th century. Lawson and Silver (1973) state that there were around 30,000 ordinary clergy, about 15,000 monks, canons and friars, and 7,000 nuns. If all these people were literate, then they comprised up to 1.5% of the population. Including part of the lay civil servants, lay judges and some common lawyers, a part of the magnates, knights and leading burgesses, merchants and craftsmen, brings the figure up to round about 3%. This corresponds rather well with the estimates as set out in Table 1: Taking the average of male and female literacy implies that 1.4% of the population was literate in 1300. In 1400 this had increased to 2.2%.

bracket between 5 and 14 before 1541 and 22% of the population after 1871. These shares are then multiplied by the latest population figures of Broadberry et al (2015), n_t, and divided by 10 (we need one year instead of 10) to calculate primary school enrolment.[22]

$$h_t^1 = l_{t+15} \frac{\gamma_{(5-14),t}}{10} n_t \quad (1)$$

2.2 Secondary and tertiary education

Regarding secondary education, Orme (2006) provides a very detailed list of (endowed) schools between 1300 and 1530. All of the secondary schools that he includes are coupled to a specific date at which the institution was first encountered in the records. Following the statistics derived from the appendix of Orme, there were 156 grammar schools in 1480 and 234 of such schools by the early 1530s. About 50% of the secondary schools recorded by Orme became endowed in the last two decades of the 15th century, and nearly all schools were still in existence by the 1530s. Not only do these findings correspond with the picture that Hoeppner Moran depicts for the York Diocese, it is also illustrates the continuing and long-lived tradition of the secondary schools stressed in the literature (Stone 1964, Vincent 1969, Jordan 1959).[23]

Detailed statistics on the growth of secondary schooling after 1530 are available from the report of the School Inquiry Commission (Henceforth SIC) that was published in 1868. The SIC examined the quality of all endowed secondary schools between 1864 and 1868. The report includes the number of schools founded per decade between 1480 and 1860. The statistics not only include classical Latin grammar schools, but any endowed institution that offered education beyond the elementary level (Owen 1964). This is important to note, in particular because Vincent (1969) argues that the focus on Latin grammar schools alone would underestimate the growth of secondary schooling (see also Stone 1964). England had many private fee-paying institutions in the early modern period: as many as 857 grammar schools, 301 private schools, and 63 private tutors sent boys up to the four Cambridge colleges between 1600 and 1660. A possible disadvantage coming from the use of the SIC statistics is that it only reports on those schools that were still in existence by the 1860s. It is thus likely to underestimate the increase in the number of secondary schools when moving backwards in time. The number of secondary schools is therefore slightly adjusted upwards to control for this possibility (see discussion in Appendix I).

Figure 2 plots the number of recorded secondary schools by the SIC in 1868. The data shows that the growth in the number of new school foundations slowed down between 1660 and 1720. Strikingly, there is a strong decline in the growth rate that sets in after this date, and to

[22] The population estimates of Broadberry et al. (2015) cover the period up to 1870. They concern annual estimates for sub-period 1540-1870; for the period before 1540 point estimates are available. The estimates of Maddison (2003) are used to cover the years after 1870.

[23] Of the grammar schools listed by Orme (2006), 35 out of 156 of them were endowed in 1480, which had increased to 116 out of 234 by the 1530s. This might also highlight the increase in demand for secondary education by the turn of the 16th century. The closing date of 14 schools from the list is unknown. It is assumed that these schools existed for 100 years. Omitting them from the dataset does not change the results.

follow the report of the SIC, the 18th and 19th centuries saw a further decay in schooling. 799 secondary schools were of direct concern to the commission in 1868. 500 of these schools were more than two centuries old and were supposedly classical grammar schools, but a mere 27% taught Greek and/or Latin, and fewer than 40 sent boys up to Oxford and Cambridge (Owen 1964).[24] The trends in the growth of schooling as depicted in Figure 2 are very similar to those as set out by Vincent (1969). His careful analysis of the Cambridge student body shows that, between 1660 and 1720, the number of grammar schools and private schools sending boys up to the four Cambridge colleges had fallen from 857 to 738 and from 301 to 201 respectively. The real deterioration sets in after this date, when it had decreased further to 406 and 130 in 1800.

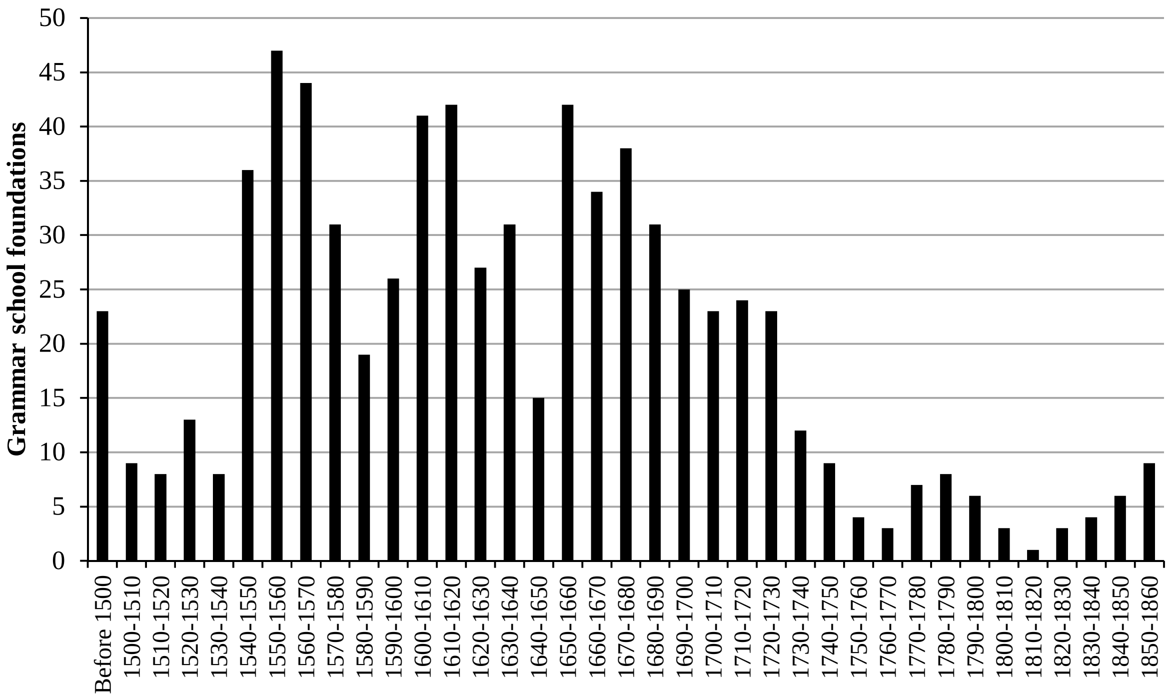

Figure 2. Number of secondary schools found per decade, 1500-1860
Notes and sources: Boucekkine et al (2007, pp. 214). The statistics summarize those of the Schools Inquiry Commission (1868a, 1868b).

The number of secondary schools from the SIC report as set out in Figure 2 are added to the data derived from the study of Orme (2006). The results suggest that there were 776 secondary schools by the 1660s and 842 by the 1720s. Following the results of the SIC, the number of schools for boys had fallen to 786 in 1868. The investigations of the SIC furthermore revealed the poor provision of secondary education, the uneven geographical distribution of schools, the misuse of endowments, and that there were only 13 secondary

24 Although it is a lower bound estimate, it is possible to perform a robustness-check: If 500 of the schools were more than 200 years old by the 1860s, then it implies that there were at least 500 schools by the 1660s. Interpolating the growth in the number of schools for boys between 1660 and 1868 (from 500 to 786) gives similar results: i.e. there is still a decline in the educational attainment level of males during the classic years of the Industrial Revolution.

schools for girls in the country (SIC 1868b).[25] After 1868, most probably based on the alarming conclusions of the SIC regarding the quality of schooling at the time, government policies were implemented to enhance the quality of the educational system and to increase the number of schools. The policies were quite effective as indicated by a staggering increase in the foundation of secondary schools after 1868: there were as many as 1353 schools in 1905 (Bolton 2007).[26]

Equation (2) is used to calculate enrolment in secondary schooling, h_t^2. The number of boys entering secondary schooling in year t is a simple function of the number of schools, s_t, and the average population level of the schools, p_t. Following Stowe (1908), the average population level of these schools was 75 between 1500 and 1600. This corresponds with the estimates of Hoeppner Moran (1985) for the Middle Ages and the estimates of Vincent (1969) for sub-period 1660-1720. The average population level declined from round about 75 in 1720 to 50 by the 1860s (Vincent 1969). In 1868 there were on average 47 boys per school (Owen 1964).[27] Bolton (2007), working with official government statistics, estimates the average population level to be 178 by the year 1909. Since the official length of the secondary-schooling programme was 6 years (Stone 1964), the population estimates are divided by 6 to calculate annual enrolment in secondary education.

$$h_t^2 = \frac{P_t S_t}{6} \qquad (2)$$

To estimate the annual flow of years of tertiary education entering the human capital stock between 1500 and 1909, the analysis of Stone (1974) is used. His study includes statistics on the decennial averages of freshmen admissions to Oxford University and the University of Cambridge. As Stone points out, Oxford had two groups of students. The first group opted for a career in church or in teaching, whereas the second group studied for a career in commercial professions (e.g. secretary, accountancy, public politics, etc.). The latter group of students came to Oxford for about two years and used it primarily as a kind of finishing school. Stone distinguishes between the number of students that completed the bachelor programme (denoted h_t^3) and those that made it up to the masters' level (denoted h_t^4), which makes it possible to correct for those students who did not receive a degree (denoted h_t^5). On average 724 freshmen a year came to the University of Oxford or Cambridge during the late 16th century, of which a mere 25% actually graduated.[28] Although the share of graduates gradually

[25] Girls were not admitted to secondary and tertiary education before the 19th century (Stone 1969). The findings of the SIC show that there were 13 secondary schools for girls by the 1860s. Since it is unknown when these schools were established, I decided to not include it in the stock. In 1878 the examinations of the University of London opened up for women. The number of female graduates between 1878 and 1900 is however included in the stock. It is also assumed that these women had completed the secondary schooling programme. There was only a handful of women that made it up to the secondary and tertiary level: in 1878 only 4 female students graduated from the University of London, which had increased to 160 in 1900. Hence, the inclusion or exclusion of these estimates does not change the results.

[26] The growth in the number of secondary schools is added exponentially as it is reasonable to assume that it takes time for government policies to be implemented.

[27] The population figures of Owen (1964) are derived from the SIC report.

[28] The same set of weights is used for enrolment in the University of Cambridge. The contribution of tertiary education to the stock of human capital of males was very minor. In 1641, the year where the growth in tertiary

increased to round about 70% by the mid-19th century, the average number of matriculations had only slightly risen to 811. Considering the significant growth of the English population at the time (from ca. 4,0 to 17,3 million between 1600 and 1850), this reveals further that tertiary schooling had lost among its popularity over the centuries.[29]

No such detailed dataset exists for the period before 1500. It was not until the mid-15th century that provisions were made for what is known as matriculation. Freshmen were required to enter their names on a role of a master during the Middle Ages, but not a single example of such roll survived (Leader 1988). Population estimates for both universities are however available. Aston (1977) estimates the Oxford student body round about 1500 by the early 14th century, which had fallen in the centuries following the Black Death: to 1200 in 1400 and 1000 by the 1450s. Aston et al. (1980) provide estimates of the student body of Cambridge. This was about 500 in 1500, 400 in 1400 and between 755-810 in 1450. It is known that 20% of the student body was enrolled into tertiary education (Aston 1977), which makes it possible to calculate the student population. For both universities this was 250, 200 and 223 respectively. Only 20% of the students entering one of the universities graduated, and of those who did 40% left after obtaining the bachelor's degree and 60% went up to the master's level (Aston 1977). These shares are applied to convert population levels into annual matriculations. The annual number of matriculates was 115 in 1300. After the Black Death this had decreased to 92, though climbed back somewhat closer to its pre-plague level by the mid-15th century to 103.

There is not much evidence for the years between 1450 and 1500. Qualitative studies indicate that the universities benefited from the upsurge in grammar schooling between 1450 and 1530. This is especially apparent from the number of colleges founded, notably at Cambridge. Whereas Cambridge was only one third of the size of Oxford by the early 15th century, it approximated Oxford in size by 1530: Cambridge had 14 colleges and Oxford 13 colleges (Cobban 1988). The years between 1450 and 1500 are interpolated, where the growth in matriculations are added exponentially to match the trends as set out by the qualitative studies as well as the trends in the growth of secondary schooling of Orme (2006). Although tentative, the results imply that there was a staggering increase in the number of freshmen admissions: from 103 in 1450 to 238.[30]

2.3 Estimating the stock of average years of education

The estimate of the gross stock of human capital (H_t) is the weighted sum of past investment in human capital:

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education was fastest, it adds a mere 0.046 years to the stock. Hence, even if the assumption about the share of graduates at Cambridge is a rather crude one, it does not change the results presented in this paper.

[29] The University of London was established in 1836. Harte (1986) provides the number of graduates (men and women) between 1839 and 1900, which are also included in the stock of human capital.

[30] Emden (1957, 1963) estimates the total number of alumni at 22,000 for the period before 1500 (7,000 at Cambridge and 15,000 at Oxford). The sum of all matriculates between 1300 and 1500 brings the number of students to 21,250, which is very close to the estimate of Emden.

$$H_t = H_{t-1} + IH_t - \delta H_t \quad \text{and} \quad H_{t-1} = \sum_{i=l-1}^{t-1} IH_i \tag{3}$$

where IH_t are investments in human capital, δH_t is the depreciation of human capital, and l the average lifetime of human capital.[31]

The next step is to apply a set of weights to the annual flows of primary (h_t^1), secondary (h_t^2) and tertiary schooling (h_t^3, h_t^4 and h_t^5) that enter the gross stock. As discussed in section 2.1, the estimates of attainment levels assume 2 years of education for primary education. It is however necessary to make three exceptions to the assumed number of years. First, the share of the boys entering one of the secondary schools had completed the primary schooling programme (Stone 1969). Since the length of the official programme was 3 years, it is reasonable to assume that the share of the boys that went up to the secondary level had followed 3 years instead of 2 years of primary schooling. Secondly, to follow Stone (1969 pp. 129), 'the 18th century was a period of growth rather than of stagnation, and the quality of literacy of a significant proportion of the population is evident in any comparison of the clumsy signatures in 1675 with the polished and flowing hands of 1775'. The increase in quality of signatures reflects the rise in basic educational opportunities that opened up during the 18th century (Schofield 1981, see also discussion in section 2.1). Therefore one additional year of education between the dates is allowed for.[32] Third, mass education became a nationwide concern in the 19th century. Several Factory Acts and Elementary Education Acts were implemented to reduce children's working hours and subsequently increase their school attendance. For instance, the 1860 Elementary School Code stipulated the leaving age at 12, and the 1870 Elementary Education Act introduced free and compulsory education for all children aged 5 to 13. As a consequence, school attendance, as well as the average years of schooling, increased significantly over the course of the 19th century: from 2.5 years in 1825 to 4.8 years in 1870.[33]

The length of the secondary schooling programme was 6 years (Stone 1964). The estimates of attainment levels therefore assume 6 years of education for secondary schooling. Regarding tertiary education, the proportion of the students that did not graduate at one of the universities stayed for about 2 years; those students obtaining a bachelor degree studied 2 more years; and finally, those who made it up to the master's level had 5 additional years

[31] The equation follows Albers (1997, pp. 3).

[32] Boys entering secondary education: increase from 3 to 3.5 years between 1675 and 1750, and 3.5 to 4 years between 1750 and 1775. Those that did not enrol in secondary schooling: increase from 2 to 2.25 years between 1675 and 1750, from 2.25 to 2.5 between 1750 and 1775, and from 2.5 to 3 between 1775 and 1825. This follows the phases in the increase in quality of signatures that Stone (1969) identifies. When keeping it constant to 2 years of education, the decline in the stock of human capital of males becomes more severe during the years of the first Industrial Revolution.

[33] Research points to further increases in the length of the primary schooling programme between 1825-1900. It indicates that years of schooling had increased from ca. 2.3 in 1805 (Sanderson 1995), to ca. 3.8 in 1850 (Sanderson 1995), to ca. 4.8 in 1870 (Lawson and Silver 1973), to 5.5 in 1905 (Lawson and Silver 1973). When keeping literacy equal to 2 years of primary schooling, there is still significant growth in schooling after ca. 1825, although the growth rate becomes smaller.

(Stone 1974). The estimates of attainment levels thus assume 2, 4 and 7 years of schooling respectively.

A final step is to estimate the average lifetime of human capital (*l*), for which life expectancy estimates are used. The data of Russel (1948), Hatcher (1986), Harvey (1995) and Jonker (2003) are used for the period before 1640; the data of Wrigley and Schofield (1981) for the years between 1640 and 1809; and, finally, the estimates of The Human Mortality Database for the years after 1809.[34] The estimates used refer to life expectancy at the age of 25 years.

Figure 3 depicts the stock of human capital per capita according to the attainment data, h_t^1 - h_t^5. The stock of total years of education is the average of males and females. Before 1878, the years of schooling measure of females is based on the development of literacy and primary schools, because they were not admitted to secondary and tertiary institutions. Figure 4 illustrates the stock of average years of males, where it differentiates between primary education, h_t^1, and higher education, h_t^2 to h_t^5.

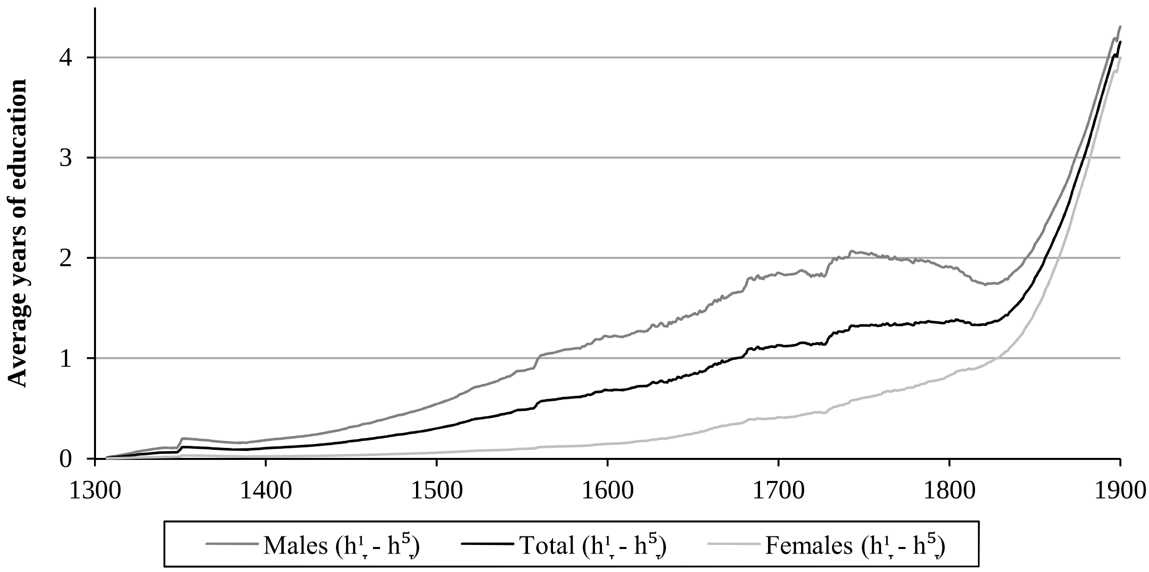

Figure 3. The stock of human capital per capita, 1300-1900.
Notes and sources: See main text.

[34] Regarding the years between 1300 and 1477, the life expectancy estimates of Russel (1948), Hatcher (1986) and Jonker (2003) are used. Harvey (1995) provides observations for the years between 1440 and 1595. Her life expectancy estimates are derived from evidence on English monasteries, and are indicative of high mortality rates between 1470 and 1530. Regarding the representativeness of the data, Harvey (pp. 142) concludes that high mortality was 'a case of roughly equal vulnerability to disease, shared between those inside the cloister and those outside'. However, the mortality of monks was enhanced by their exposure to infectious diseases: the vast majority of the people living outside the cloister enjoyed more favorable conditions (see discussion in Hatcher et al 2006). I am grateful to Jim Oeppen for pointing this out. For the above mentioned reason, the years between 1477 and 1540 are interpolated.

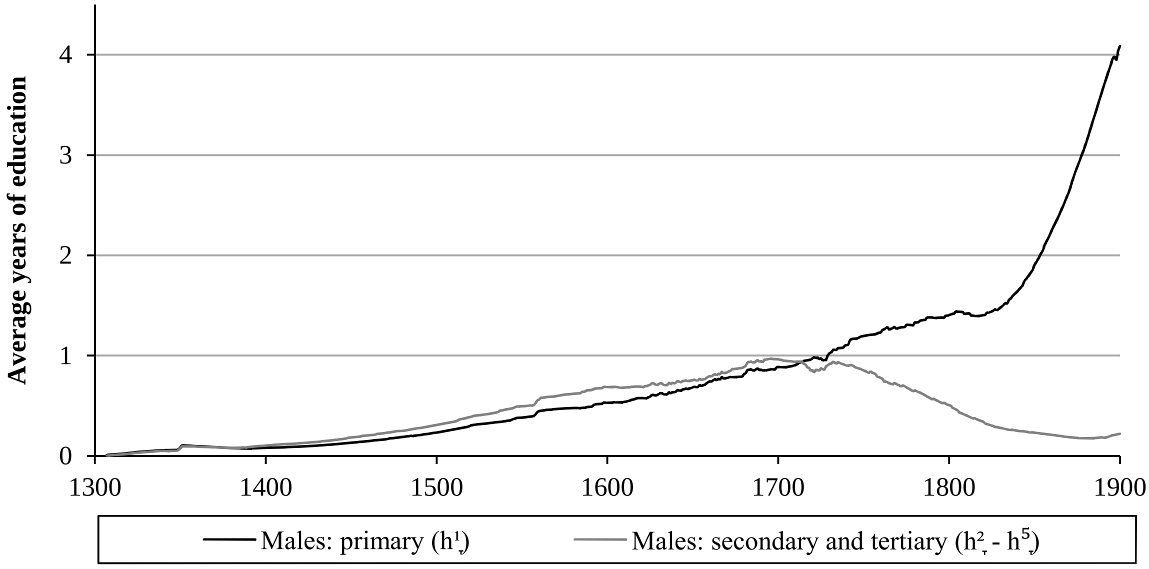

Figure 4. The stock of human capital per capita, 1300-1900: Primary and secondary attainment levels of males.
Notes and sources: See main text.

Figure 3 illustrates that the stock of human capital accumulated long before the Industrial Revolution began to take hold. Between ca. 1560 and 1740, the stock of average years of education of males had almost doubled. On the eve of the Industrial Revolution, however, there was a decline in the level of educational attainment. A closer look to Figure 4 reveals that the decline in the average year of schooling of males can be attributed to a staggering decrease in the stock of secondary and tertiary education: between ca. 1720 and 1880 it had fallen by 80%. There was some improvement in primary attainment levels over the course of the 18th century as indicated by an increase in the stock of roughly 50%, but this was not fast enough to counterbalance the fall in attainment levels of secondary and tertiary education. Stone’s (1964, pp. 69) observation that “English higher education did not get back to the level of the 1630s until after the first World War; did not surpass it after the second” seems therefore rather acceptable.

Strikingly, as Figure 3 shows, the stock of human capital of females in the period before 1740 were about one-fifth of the level of males. In contrast to the stagnation in educational attainment levels of males, the stock of human capital of females accelerated during the Industrial Revolution: it had more than doubled between ca. 1740 and 1830. The slow growth in the overall human capital stock as set out in Figure 3 can therefore be completely attributed to increases in the educational attainment level of females.

The estimates on the educational attainment levels of males correspond with the findings of previous research focussing on male literacy rates (Nicholas and Nicholas 1992, Mitch 1993, Clark 2005). It is furthermore consistent when the evidence of Humphries (2010, pp. 314). Humphries derives average years of schooling of boys from autobiographical evidence, and documents a similar dip in schooling during the first Industrial Revolution. However, as the results in Figure 4 revealed, the fall in human capital levels of males can be mainly attributed to the strong decline in secondary and tertiary schooling. The evidence presented in this section therefore suggests that the demand for formal education had fallen remarkably. It seems that human capital for the masses was of limited use in the transition towards modern economic growth.

Interestingly, research has found a close correlation between working-skills and literacy rates. Houston (1982) and Nicholas and Nicholas (1992) demonstrate that medium- and high-skilled professional groups had much higher literacy rates than unskilled ones, and De Pleijt and Weisdorf (2015) empirically show that skilled workers were more likely to be literate than unskilled workers. Since the stock of primary schooling is largely based on the evidence from literacy rates, the findings presented in this section may therefore also support the view of Sanderson (1995) that during the Industrial Revolution a whole range of new occupations opened up that required less formal and informal skills than the old ones. Likewise, the decline in the stock of human capital of males may be indicative of a process of 'deskilling'- i.e. that the transition from artisan workshops to factory production reduced the need for skilled workers (Goldin and Katz 1998, Nicholas and Nicholas 1992). Finally, although more indirect, it may also help to explain the increase in demand for and supply of unskilled child labour used in production (Kirby 2005, Humphries 2010).

Finally, the results in Figure 3 highlight the acceleration in human capital over the course of the 19th century. The stock of education of males doubles, whereas the stock of females even quadruples. This finding gives rise to the notion of Mokyr (2013) that high levels of human capital were more important in later stages of the Industrial Revolution. Most of the important macro-inventions were implemented during the second Industrial Revolution, which required more formally educated workers (see also Goldin and Katz 1998).

3. The contribution of human capital to early modern growth

This section carries out a time series approach to find out if the growth in human capital formation contributed to pre-industrial economic growth. The latest attempts to estimate British output and productivity reveal an upward trend in per capita GDP that began long before the Industrial Revolution. Between 1650 and 1850, per capita income levels had increased by about 30% (Broadberry et al 2015: see Figure A1 in Appendix II). Hence, if a positive per capita GDP to human capital relationship is found for the years preceding the Industrial Revolution, then this could add support to recent studies stressing the role of human capital in facilitating pre-industrial growth (Baten and van Zanden 2008, Dittmar 2011). However, as discussed in the previous section, there was a movement away from formal schooling that started in the first half of the 18th century, whilst there was additional growth in per capita GDP. The finding of a significant negative per capita GDP to educational attainment relationship during the age of cotton and steam could provide statistical evidence to the view of Mitch (1992) that the contribution of human capital to economic growth was moderate. He has argued that the stock of human capital was well in excess of what was called for by the jobs performed: only 2% of the females and 5% of the males were employed in occupations for which literacy was required.

The focus of the empirical analysis is on the period after 1600 due to the quality of the underlying datasets: The annual population estimates are available only for the period after 1540; observations on literacy and elementary schooling for the medieval period are based on the diocese of York and might therefore not be representative for England as a whole (it is likely to underestimate the growth in primary schooling as discussed Section 2.1); and, finally, whereas there is very detailed information on the growth of secondary schooling between 1300 and 1530, information on matriculations to Oxford and Cambridge is relatively scant. From 1600 onwards, the estimates of the stock of human capital are independent of these datasets.

It should be stressed here that the statistical models presented in this section are underspecified, and the obtained estimates of the stock of human capital and per capita GDP relationship might therefore not be robust. A fully specified model would include other important determinants of per capita GDP, such as international trade (Allen 2003), the quality of institutions (North and Weingast 1989, Acemoglu et al 2005), physical capital, and the like.[35] The focus on a simple two-variable model reduces the possibility to identify cointegration and affect the consistency of the estimators of the adjustment coefficient matrix. However, cointegration as a property is robust to the omission of relevant variables, which makes it possible to draw conclusions upon the estimated cointegrating relationships (Pashoutidou 2003).

Research has also indicated a relationship among human capital formation and skill premiums – i.e. the wage rate paid to unskilled workers relative to skilled ones (Clark 2005, Van Zanden 2009, Allen 2009). The idea is that if there was a rise in the reward to skills, this should be reflected by an increase in the demand for human capital. Ideally it would have been interesting to relate the stock of human capital to real wages (as well as to skill premiums in the broader sense), but the wage series of skilled building labourers is stationary (see Figure A1 in Appendix II). This finding indicates that there was no long-run relationship between real wages and human capital formation.[36]

The two variables used in the time series analysis are therefore the natural logarithm to the level of per capita GDP (*gdp*) and the natural logarithm of stock of human capital (*h*).[37] In order to model the long-run relationship among *gdp* and *h*, the following model is estimated:

$$\Delta Y_t = \alpha\beta' Y_{t-1} + \Gamma\Delta Y_{t-1} + \gamma + \alpha\beta_0' t + \varepsilon_t , \qquad (4)$$

where $Y_t = (gdp_t, h_t)'$ and t is the trend. The model assumes that the $p = 2$ variables in Y_t are related through r equilibrium relationships with deviation from equilibrium $u_t = ß'Z_t$, and α

[35] Unfortunately it is not possible to include these variables in the statistical model, as there are no annual estimates available.
[36] The real wage of building workers is not the ideal group of labourers for testing the effects from increases in formal education upon the skill premium. It would perhaps be better to relate it to the wage earnings of those professions for which formal education was required.
[37] The analysis makes use of the per capita GDP series of Broadberry et al (2015): See Figure A1 in Appendix II.

characterizes the equilibrium correction. *ß* and α are *pxr* matrices and the rank of $\prod = \alpha ß'$ is $r \leq p$. Γ is the autoregressive parameter which models the short-run dynamics. It is furthermore assumed that $\varepsilon_t \sim iidN_p\ (0, \Omega)$. The analysis uses a lag-length of 2 in the model. Using information criteria, it is found that $k = 2$ lags is sufficient to characterize the systematic variation in the model.[38]

The model assumes constant parameters, but the results presented in Section 2.3 are indicative of the human capital and per capita GDP relationship changing over time: there was a decrease in the stock of human capital of males after ca. 1740, which was mainly the result of the sharp decline in secondary and tertiary education that set in after about 1700 (see Figures 3 and 4). The Quandt-Andrews unknown breakpoint test is performed to identify the structural breaks in the per capita GDP and human capital relationship (Quandt 1960, Andrews 1993). The results report on two breakpoints: 1696 and 1743. The sample is therefore divided into three sub-periods: 1600-1696, 1696-1743 and 1743-1900.

The next step is to determine *r*, i.e. the number of equilibrium relationships. It is expected $r = 1$ if there is a causal relationship, because there are only two variables. A necessary condition for cointegration is that each of the variables should be integrated of the same order (more than zero) (Engle and Granger 1987). Figure A1 in Appendix II gives the levels and differences of *gdp* and the human capital stocks. The growth rates of *gdp* (first differences) are clearly stationary I(0), implying that the levels of per capita GDP seems to be a I(1) non-stationary process in all sub-periods. The growth rates of *h* follow a I(0) stationary process, although it appears to be a I(1) process in the period after 1811. The results from the Augmented Dickey-Fuller tests verify the conclusions (upon request from the author). It was therefore necessary to split sub-period 1743-1900 into two: 1743-1811 and 1811-1900. There can never be cointegration in sub-period 1811-1900, since the variables are not integrated of the same order.

Given that the integration of both per capita GDP and the stock of human capital variables is of the same order for sub-periods 1600-1696, 1696-1743 and 1743-1811, Johansen cointegration tests are conducted to examine the possibility of a long-term relationship (Johansen 1995). The maximum eigenvalue test gives similar results (with an exception of male education in the sub-period 1743-1811: see discussion below), but these test results are not reported on.

For sub-period 1600-1696 there is evidence of one cointegrating vector for the overall human capital stock, educational attainment levels of males, and the series capturing formal secondary and tertiary schooling. For sub-period 1743-1811 there seems evidence for one cointegrating vector for the overall stock, as well as for the stock capturing educational attainment of males. No support is found for a cointegrating vector for the stock of human capital of females and of primary attainment levels of males, neither is there any evidence for a cointegrating relationship in sub-period 1696-1743. Since the models are not fully specified, the failure to find a significant cointegrating relationship does not imply none existed.

[38] This applies to all sub-periods in the analysis.

Tables 2 and 3 report on the restricted cointegrating vectors and the adjustment coefficients for sub-periods 1600-1696 and 1743-1811. The model given in (4) assumes that the residuals are iid and normally distributed. The robustness of the obtained results is therefore evaluated by using the Jarque-Bera normality residual test (N) and the Lagrange Multiplier autocorrelation test (LM). There is no indication of autocorrelation. The most serious misspecification occurs in the case of non-normality of the residuals in the cointegrating relationship of the stock of human capital of males and per capita GDP in sub-period 1743-1811 (Equation 5 in Table 3).

	Adjustment parameters		Cointegrating vector	Test results
1)	Overall: h_t^1 - h_t^5			
	Δgdp_t	-$\underline{0.42}$		
	Δh_t	0.01	(y – $\underline{7.90}h$ + $\underline{0.02}t$ – 3.02)	J: 27.93
				N: $\chi^2(4)$ = 5.302 (0.2577)
				LM: $\chi^2(4)$ = 1.08 (0.8976)
2)	Males: h_t^1 - h_t^5			
	Δgdp_t	-$\underline{0.39}$		
	Δh_t	0.01 1)	(y – $\underline{7.37}h$ + $\underline{0.02}t$ – 1.27)	J: 28.62
				N: $\chi^2(4)$ = 5.525 (0.2376)
				LM: $\chi^2(4)$ = 1.24 (0.8719)
3)	Males: h_t^2 - h_t^5			
	Δgdp_t	-$\underline{0.49}$		
	Δh_t	0.01	(y – $\underline{6.20}h$ + $\underline{0.01}t$ – 3.85)	J: 31.82
				N: $\chi^2(4)$ = 5.543 (0.2360)
				LM: $\chi^2(4)$ = 0.55 (0.9688)

Table 2. Results for sub-period 1600-1696

Notes: Underlined typeface indicates that the parameter is significant at the 1% level. J: Johansen cointegration test for r = 1; N: Jarque-Bera normality test; LM: Lagrange Multiplier autocorrelation test. P-value in parentheses. 1) Coefficient is significant at the 10% level.

	Adjustment parameters		Cointegrating vector	Test results
4)	Overall: h_t^1 - h_t^5			
	Δgdp_t	-$\underline{0.35}$		
	Δh_t	-0.02 1)	(y + $\underline{8.83}h$ - $\underline{0.01}t$ – 14.90)	J: 28.00
				N: $\chi^2(4)$ = 8.225 (0.0837)
				LM: $\chi^2(4)$ = 2.10 (0.7169)
5)	Males: h_t^1 - h_t^5			
	Δgdp_t	-$\underline{0.59}$		
	Δh_t	-0.00	(y + $\underline{3.80}h$ + 0.00t – 11.72)	J: 24.05 2)
				N: $\chi^2(4)$ = 20.037 (0.0005 3)
				LM: $\chi^2(4)$ = 2.71 (0.6069)

Table 3. Results for sub-period 1743-1811

Notes: Underlined typeface indicates that the parameter is significant at the 1% level. J: Johansen cointegration test for r = 1; N: Jarque-Bera normality test; LM: Lagrange Multiplier autocorrelation test. P-value in parentheses. 1) Parameter is significant at the 10% level. 2) Cointegration is found at the 10% level. Unlike the Johansen cointegration test, Maximum Eigenvalue test does suggest cointegration at 5% level. 3) The residuals are non-normal.

The results for sub-period 1600-1696 as reported in Table 2 are indicative of a positive educational attainment to per capita GDP relationship. For sub-period 1743-1811 (Table 3), there seems to be a negative relationship. Regarding the short-run dynamics, the adjustment coefficients of per capita GDP are significant at the 1% level, whereas those of the stock of human capital are not significantly different from zero. This result therefore indicates that per capita GDP responded more quickly than did human capital between 1600 and 1811.

Overall the regression results presented in this section suggest a changing relationship among human capital and per capita GDP over the course of England's early industrialisation. Formal education was positively related to the phases of growth that occurred over the course of the 17th century. During the Industrial Revolution itself, the association among the years of schooling measure and per capita GDP became clearly negative. The finding of a negative relationship, as well as the result that economic growth adjusted more quickly than did human capital, implies that a decrease in educational attainment would have caused faster per capita GDP growth. This conclusion therefore rather supports the view of McCloskey (2010) that investment in human capital can be massively misallocated and even have a negative impact on economic performance. It also supports the controversial notion of Mitch (1992) that England was grossly overeducated during the age of cotton and steam.

4. Conclusion and discussion

Economic historians have long debated whether human capital formation contributed to the Industrial Revolution. Almost all studies however take as their starting point 1750 and focus on the trends in (male) literacy (Nicholas and Nicholas 1992, Mitch 1993). The finding of a pause in the rise of male literacy rates between 1750 and 1850 led to the conclusion that human capital was irrelevant to England's early industrialisation. The contribution of this paper was to re-evaluate this conclusion by quantifying the stock of human capital of the population between 1300 and 1900. In contrast to previous studies on the topic, the stock not only take into account the evidence from literacy rates but also the growth in secondary and tertiary schooling.

It is shown that the stock of human capital can be quantified rather well, in particular for the early modern period. The data on the stock of years of schooling suggest that the growth in human capital before the Industrial Revolution must have been far greater than previously assumed from evidence on literacy: secondary education comprised up to half of the stock of educational attainment of males. After ca. 1700, however, a profound decline in the average years of schooling began to take hold as indicated by stagnation in primary educational attainment levels and a vast decline in the years of secondary and tertiary schooling.

The results from the time series analysis indicated that human capital contributed to economic growth before ca. 1750. This finding adds further evidence to the work of Baten and Van Zanden (2008) stressing the importance of human capital formation for pre-industrial growth. During the Industrial Revolution itself there seems to have been a negative relation between average years of education and per capita GDP growth. This finding supports the predominant view that human capital was not key to England's industrialisation (Mitch 1993, Mokyr 1990, Clark 2005). Relative to this view several contributions have been made. Incorporating the evidence from secondary and tertiary schooling informs us that the movement away from formal schooling was much larger than the trends in (male) literacy alone would suggest. Consequently, the fall in the demand for educated workers during the classic years of the Industrial Revolution must have been more pronounced than previously assumed by scholars (e.g. Mitch 1992). On top of this, the results following the regression analysis suggested that a decline in average years of education would have caused higher levels of per capita GDP. It is likely then that this paper is therefore the first to empirically demonstrate that England's relatively high level of human capital on the eve of the Industrial Revolution may have actually hampered its economic take-off.

The conclusion that formal education for the masses was unimportant for per capita GDP growth during the Industrial Revolution has implications for future research on the topic. It should be stressed here that the stock of human capital focussed on the average level of formal education present in the population. It does not include the acquisition of those elements which did not involve formal schooling but which could have nevertheless been important for the productivity of workers such as on the job learning and apprenticeships (see Humphries 2003, Wallis 2008, Mokyr 2009). In analysing the role of human capital during the Industrial Revolution, future research should therefore shift focus to measures capturing more informal skills. Economic historians have made some headway in this regard: Kelly et al (2014) show that on the eve of the Industrial Revolution, English labourers were taller, heavier, savvier and more productive than elsewhere on the continent; Jacob (2013, pp. 157) documents a significant increase in scientific training believed to be important in facilitating the Industrial Revolution; and Mitch (2004) argues that as many as one out of four boys went through some kind of apprenticeship in 1700.

Following the empirical findings of recent studies, an additional distinction should also be made between the 'density in the upper tail of professional knowledge' (cf. Mokyr 2005 and Mokyr and Voth 2009) and more widespread education. De Pleijt and Weisdorf (2015) quantify the occupations of more than 30,000 English male workers according to the skill-content of their work. These results demonstrate an increase in the share of unskilled workers alongside a constant share of 'high-quality workmen' such as machine erectors and engineers deemed necessary by Meisenzahl and Mokyr (2012) in bringing about the Industrial Revolution. Similarly Squicciarini and Voigtländer (2014) show that the French Industrial Revolution was not spurred by a broad distribution of skills, but rather by a small highly knowledgeable elite. Hence, if we believe that human capital contributes to technological progress, then it is likely that the Industrial Revolution depended on a concentrated core of skilled workers rather than on the average level of human capital in a broader sense. In that way, as recently suggested by Squicciarini and Voigtländer (2014), too much attention is given to average human capital levels when we talk about economic growth, whereas not enough research has been performed to figure out when and how countries achieved a critical mass of educated workers.

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APPENDIX I: DATA CONSTRUCTION

Literacy rates, 1550-1900:

The study of Cressy (1980) provides evidence on literacy for the years 1500, 1550, 1560, 1580, 1600, 1610, 1640, 1660, 1680, 1710 and 1750. The growth of literacy between 1500 and 1750 was an unstable and noncumulative process. Cressy (1981) distinguishes between eight different phases in the development of literacy in this period. Dates in the interval are interpolated and take the variations in the development of literacy into account. The literacy estimates corresponds well with the estimates provided by Stone (1969, pp. 101). The estimates of Schofield (1981) are used for sub-period 1754-1840. Lord Hardwicke's Marriage Act (1754) prescribed that grooms and bridges should sign their names in the marriage register, which means that after ca. 1750 there exists abundant evidence about literacy rates (of both sexes). The estimates of Schofield are derived from a random sample of 274 English parish registers to estimate the annual percentage of males and females able to sign their marriage contracts. Stephens (1987) gives the percentage of illiterate brides and grooms between 1839 and 1885. The largest part of his statistics concern yearly observations, sometimes with intervals of 5 years. Cressy's (1980) estimates are again used to derive the literacy rates for sub-period 1885-1915.

Literacy rates, 1300-1550:

The reading-literacy rates of Hoeppner Moran (1985) are projected backwards in time by taking the growth in primary schools into account (see discussion in Section 2.1). Multiplying the reading-literacy rates by 0.75 (level of schooling which is based on ratio of reading- to signature-literacy) gives the results of Table 1 in Section 2.1.

Year	1300	1350	1400	1450	1500	**1530**	1548
Elementary schools	12	20	20	36	70	104	124
Male literacy	2.6	4.3	4.3	7.8	15.2	**22.5**	26.9
Female literacy	0.9	1.5	1.5	2.6	5.1	**7.5**	9.0

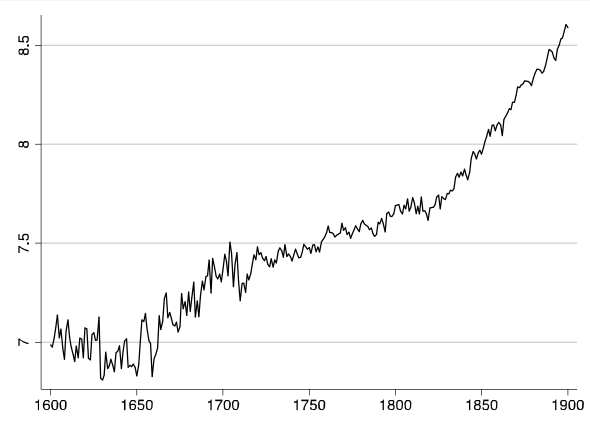
Table A1. Reading literacy rates, 1300-1548

Notes and sources: See Section 2.1. Percentages are rounded up to the nearest digit. Bolt typeface indicates the year from which is projected backwards in time.

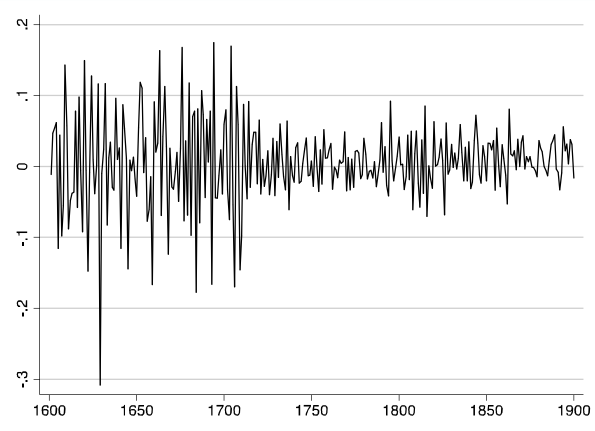
Adjustments made to the number of secondary schools, 1500-1720

The SIC (1868a) only reported on those schools that were *endowed*, which is very likely to underestimate the number of secondary schools as it does not take into account private fee-paying institutions (see Vincent 1969). Since it only reports on those schools that were still in existence by the 1860s, it is furthermore likely to underestimate the number of school establishments when moving backwards in time. The data on the number of secondary schools is therefore adjusted upwards. For sub-period 1530 - 1600, the ratio of endowed to non-endowed schools of Orme (2006) is used. As discussed in Section 2.2, many of the secondary schools that Orme recorded became endowed between 1480 and 1530 (the ratio decreased from 35/156 to 116/234). It is therefore assumed that the ratio of non-endowed to endowed schools decreased at a similar rate between 1530 and 1600 as it did for the period 1480 to 1530. For sub-periods 1600-1660 and 1660-1720, the ratio of grammar schools to private schools of Vincent (1969) is applied. The number of private tutors is not included as the student numbers are not known.

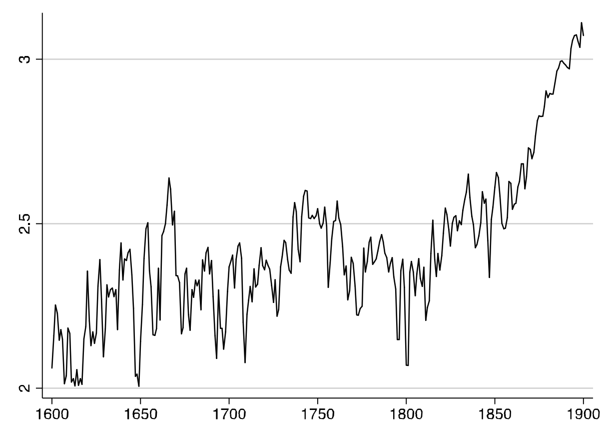
APPENDIX II: FIGURES TIME SERIES



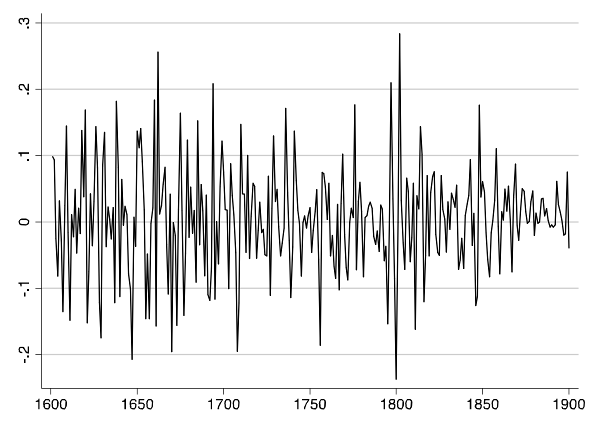
Log of per capita GDP



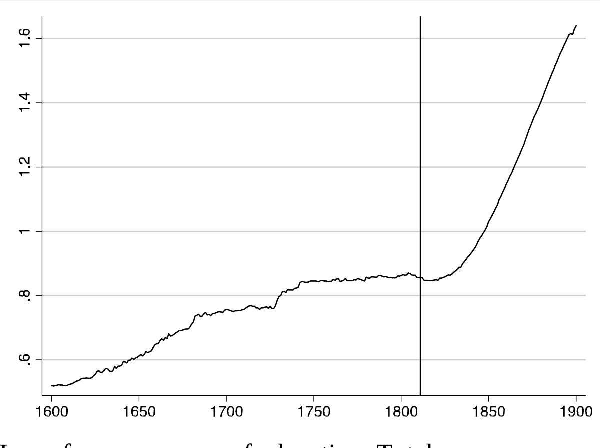
Growth of the log of per capita GDP



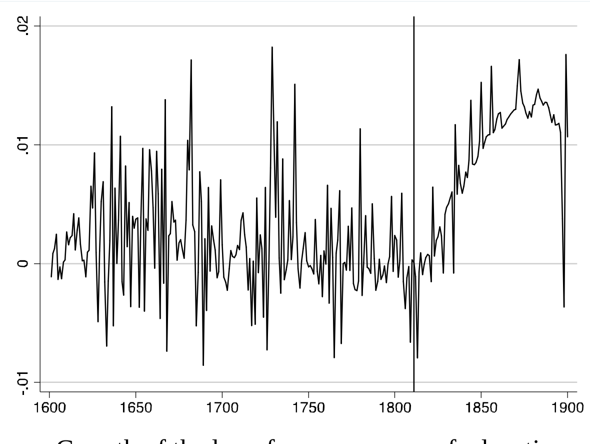
Log of the real wage



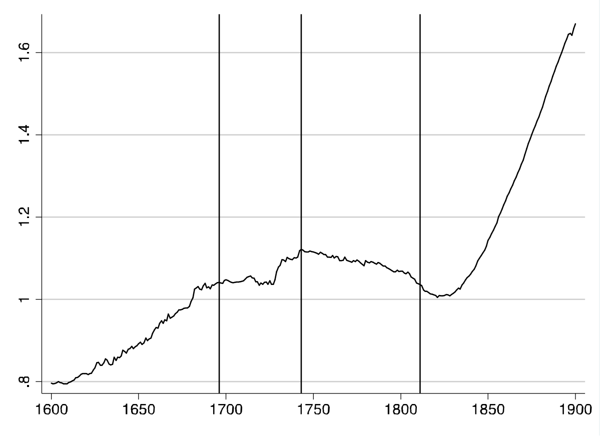
Growth of the log of the real wage



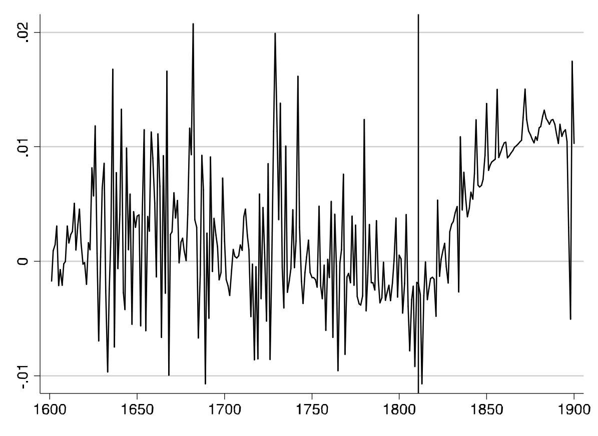
Log of average years of education: Total



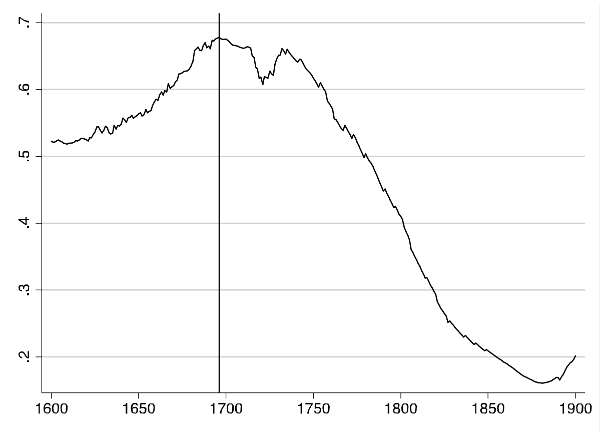
Growth of the log of average years of education: Total



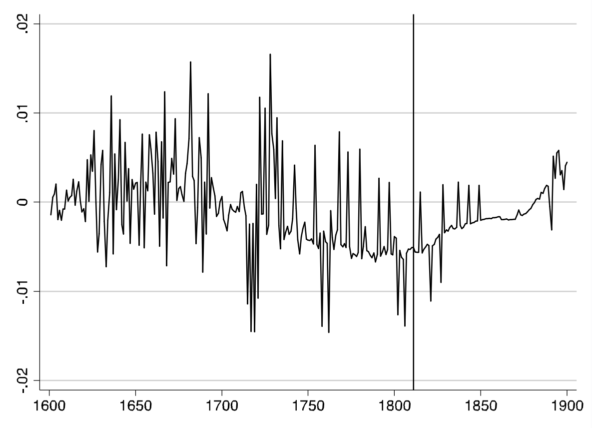
Log of average years of education: Males



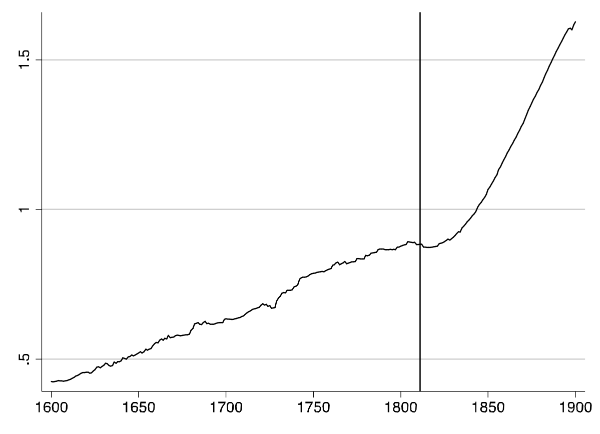
Growth of the log of average years of education: Males



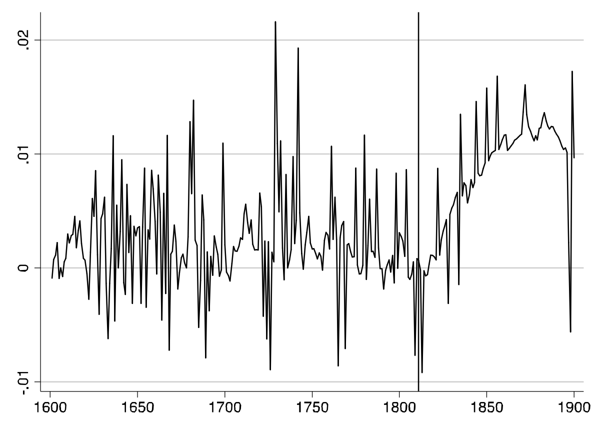
Log of average years of secondary and tertiary education: Males



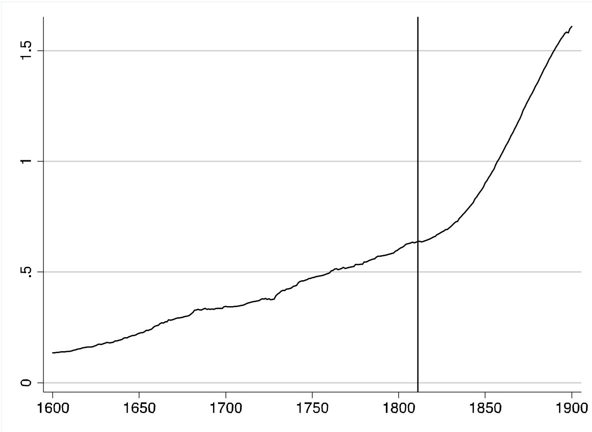
Growth of the log of average years of secondary and tertiary education: Males

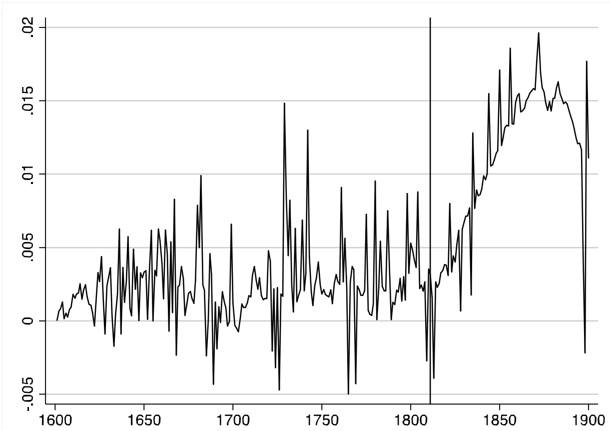


Log of average years of primary education: Males



Growth of the log of average years of primary education: Males





Log of average years of education: Females

Growth of the log of average years of education: Females

Figure A1. *The figures of the time series: levels in left panel, growth rates in right panel*
Notes and sources: Human capital stocks: see Section 2; per capita GDP: Broadberry et al 2015; real wages: Allen (2001). The vertical lines refer to the break points as identified by the Quandt-Andrews unknown break-point test (test results upon request from the author).