HUMAN ACCOMPLISHMENT AND THE BRITISH INDUSTRIAL REVOLUTION: THE ROLE OF GREAT SCIENTISTS AND EDUCATION IN BRITISH GROWTH SINCE 1270

(Alesina and Alesina, Alberto, and Paola Giuliano. Forthcoming. “Family Ties”. In Handbook of Economic Growth, Philippe Aghion and Durlauf, Steven N. North Holland.)

We perform our analysis using the combined six waves of the World Value Survey (WVS), a collection of surveys administered to a representative sample of people in more than 80 countries from 1981 to 2010. We find that on average familistic values are associated with lower political participation and political action. They are also related to a lower level of trust, more emphasis on job security, less desire for innovation and more traditional attitudes toward working women. On the positive side, family relationships improve well-being as measured by self-reported indicators of happiness and subjective health.

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Abstract. This paper constructs annual data on primary, secondary and tertiary education, significant innovations and great scientists in the period 1270-2011 for Britain and shows how human capital lead to one of the greatest human accomplishments in human history; the British Industrial Revolution. Institutions, culture and other variables are used as instruments and to trace the origin of innovations and great scientists and educational attainment and to deal with endogeneity. The regressions show education and a highly innovative environment were influential in shaping the British Industrial Revolution.

Keywords: Economic growth, science, education, institutions, culture
JEL classification: O30; O40

1. Introduction

Although the British Industrial Revolution is one of the most significant events in human economic history little is known about the role played by human capital in freeing the British economy from its Malthusian straightjacket. In fact human capital has been deemphasized as being important for the British growth experience by some economic historians. Allen (2003, p. 405), for example, notes that “recent research has downplayed the importance of technological progress and

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literacy in explaining the British industrial revolution”. In his presidential address to the Economic History Association in 1980, Easterlin (1981) advocates education and science as the pillars of economic development and remarks that “at some point, we may look back and ask what produced this world – how we got where we are. Such inquiry will show, I believe, that the proximate roots of the epoch of modern economic growth lie in the growth of science and diffusion of modern education” (p 418).

Several studies of the Great Divergence and endogenous growth models have stressed human capital accumulation as a potentially important source of the Great Divergence and the British Industrial Revolution (see, e.g., Weber, 1905; Easterlin, 1981; Becker et al., 1990; Khan and Sokolof, 2008; Goodfriend and McDermott, 1998; Galor and Moav, 2002, 2004; Lucas, 2002; Cervellati and Sunde, 2005, 2011; Clark, 2005, 2007; Boucekkine et al., 2007; Baten and Zanden, 2008; Galor 2011). Human capital also plays a critical role for innovation-driven growth in the endogenous key growth models formulated by Lucas (1988) and Romer (1990) and in models of the transition from agriculture to industry (Hansen and Prescott, 2002; Lucas, 2002; Tamura, 2002). In Hansen and Prescott’s (2002) model, as the stock of knowledge grows, it eventually becomes profitable for manufacturers to start producing and the economy starts behaving like a standard Solow growth model.

This paper seeks to uncover the role played by human capital in British economic growth over the period from 1270 to 2011. Human capital is measured as educational attainment at the primary, secondary and tertiary levels, as well as knowledge capital created by great scientists. The data have been compiled over the past five years through extensive search in libraries and university web pages, examination of about 500 Parliamentary Papers, and numerous email correspondences with the 23 individual universities that were in existence in the UK before 1920 and merged with official statistics that are available after 1920. Most of the data are only available from annual university calendars that list of names of students enrolled in that particular year, matriculated or graduated and the aggregate number could not simply be added up since students have often been awarded more than one degree; e.g. M.B. and B.S, honorary degrees and ad eundem degrees.

This research contributes to the literature by investigating which factors shaped productivity growth in Britain in the period 1270-2011, including educational attainment at the primary, secondary and tertiary levels, fixed capital, international knowledge spillovers, the land-population ratio, and domestic knowledge created by great scientists. Instruments are used for schooling at all levels and for significant innovations and great scientists in order to gain insights into which factors shaped the formation of educational attainment and to deal with endogeneity of the regressors.

This paper is probably the first attempts to formally test for the role played by education and knowledge created by great scientists for British growth using annual data over the past millennium.
and, at the time, testing the influence of institutions and culture on the stock of knowledge created by great scientists. Furthermore, the paper is also among the very few papers on growth and human capital that have used external instruments for knowledge and education and, as such, is one of the first papers that tries to identify the factors underlying growth in human capital. Culture, the quality of institutions, real value of land rents, temperature, and real food prices, among other instruments, are used for identification of domestic knowledge and gross enrolment rates that, in conjunction with life tables, are used to construct educational attainment.

The paper is closely related to the research of Madsen et al. (2010) and Baten and Zanden (2008). Using patent statistics Madsen et al. (2010) show that the predictions of the Schumpeterian second-generation endogenous growth model are consistent with the British growth experience in the period 1620-2006. Baten and Zanden (2008) show that book production over the period 1450-1913 was influential for growth in Europe and interpret the results as evidence that human capital was influential for pre-industrial growth in Europe.

The paper is structured as follows. The empirical framework is presented in the next section and Section 3 discusses identification. Data issues are addressed in Section 4 and Empirical estimates are presented in Section 5. Section 6 presents model simulations and Section 7 concludes.

2. Empirical framework

Consider the following homogenous Cobb-Douglas production function:

\[ Y_t = A_t K_t^\alpha (1-\beta_t) T_t^{\beta_t} L_t^{(1-\alpha)(1-\beta_t)}, \quad (1) \]

where \( Y_t \) is real output, \( A_t \) is the knowledge stock, \( K_t \) is the capital stock, \( T_t \) is land, \( L_t \) is labor, \( \alpha(1-\beta_t) \) is the share of income going to capital and \( \beta_t \) is the share of income going to land under the maintained assumption of perfect competition. The production function exhibits constant returns to scale in \( K_t, T_t \) and \( L_t \) and increasing returns to scale in \( A_t, K_t, T_t \) and \( L_t \) together.

Eq. (1) can be written as per worker output so that:

\[ \left( \frac{Y}{L} \right)_t = A_t^{\frac{1}{1-\alpha(1-\beta_t)}} \left( \frac{K}{L} \right)_t^{\frac{\alpha(1-\beta_t)}{1-\alpha(1-\beta_t)}} \left( \frac{T}{L} \right)_t^{\frac{\beta_t}{1-\alpha(1-\beta_t)}}, \quad (2) \]

where labor productivity is cast in terms of the \( K-Y \) ratio to filter out technology-induced capital deepening (Klenow and Rodriguez-Clare, 1997) which gives some identification advantages as discussed in the next section. The reason why productivity growth triggers capital deepening is that technological progress increases expected earnings per unit of capital and causes Tobin’s \( q \) to exceed its steady-state value through the equity market. This initiates a capital deepening process that terminates when Tobin’s \( q \) reaches its steady-state equilibrium, which may not be one in the
presence of taxes, technological progress and population growth (see, for derivations, Madsen and Davis, 2006). The $K/Y$ ratio is assumed to be constant along the balanced growth path because factors that influence this ratio such as changes in the time preference and taxes have only temporary growth effects.

Taking logs of Eq. (2) yields

$$\ln \left( \frac{Y}{L} \right)_t = \frac{1}{1-\alpha(1-\beta_t)} \ln A_t + \frac{\alpha(1-\beta_t)}{1-\alpha(1-\beta_t)} \ln \left( \frac{K}{Y} \right)_t + \psi_t \ln \left( \frac{T}{L} \right)_t,$$

where $\psi_t = \beta_t/[1 - \alpha(1 - \beta_t)]$. Allowing $A$ to be a function of broadly defined human capital yields the following stochastic counterpart of Eq. (3):

$$\ln y_t = \alpha_0 + \alpha_1 EA_t + \alpha_2 \ln S^d_t + \alpha_3 Op_t \ln S^f_t + \alpha_4 \ln k_t + \alpha_5 \ln \tau_t + \varepsilon_t$$

where $y = Y/L$, $k = K/Y$ and $\tau = T/L$, $EA$ is educational attainment (average years of schooling of individuals of working age), $Op$ is openness (imports plus exports divided by nominal income), $S^d$ is domestic stock of knowledge created by great scientists, $S^f$ is the foreign stock of knowledge created by foreign great scientists and transmitted internationally through imports, and $\varepsilon$ is a stochastic error term. Here, $\psi$ is allowed to vary over time due to time variations in the share of agriculture, $\beta$, where $\beta$ is estimated as the share of agriculture in total production. Capital’s income share, $\alpha$, is fixed at 0.3 following the standard in the literature. The construction of the variables is discussed in Section 4 and data sources are listed in a separate 35 page Data Appendix.

Explaining productivity by human capital and the stock of domestic and foreign knowledge is now standard in the empirical literature on endogenous growth following the pioneering work of Coe and Helpman (1995) (see, for example Engelbrecht, 1997; Keller, 2004; Cohen and Soto, 2007; Madsen, 2010; Venturini, 2012). International knowledge spillovers through the channel of imports is included in the models following the predictions of the endogenous models described in Grossman and Helpman (1991) and tested by Coe and Helpman (1995), Engelbrecht (1997), and Madsen (2007), among others (see, for a survey, Keller, 2004). In these models, foreign knowledge spillovers are transmitted internationally through the channel of imports, as imports of intermediate products with embodied knowledge enhance the productivity of domestic producers.

The $K/Y$ ratio is often omitted from long-run regressions under the assumption that the economy is in its steady state. Here it is included as a potential contributor to the British Industrial Revolution following the predictions of the model of Galor and Moav (2004) in which capital deepening was initiated by high returns to capital relative to the cost of capital, and the model of Voigtlander and Voth (2006) in which capital deepening was crucial for industrialization because of positive externalities from capital and embodied technological progress.
The approach here deviates from the empirical endogenous growth literature by basing the knowledge stock on the knowledge created by great scientists as opposed to patents or R&D because these data are not available before 1623 (patents) and 1960 (R&D). Patents have been used in the British historical studies of Oxley and Greasley (1998), Greasley and Oxley (2007), and Madsen et al. (2010). Annual data on great innovations are available back to 1270 and have the distinct advantage over patents in that it captures major scientific breakthroughs and tests the extent to which ideas created by great scientists initiate a host of minor innovations by practical people and engineers as forcefully argued in the writings of Jacob (1997). Based on an endogenous growth model, Garner (2008) shows that growth in scientific knowledge is a precondition for sustained growth in the very long run. Furthermore, new ideas created by great scientists precede patents in the innovation chain and, as such, give a deeper understanding of the impetus for innovations. Regressing the log of stock of patent knowledge from Madsen et al. (2010) on the log of the stock of significant innovations based on the chronology of Ochoa and Corey (1997) over the period 1625-2009 using dynamic OLS (DOLS) and robust standard errors yields a coefficient of the stock of great innovations of 3.22 ($t = 12.6$) and $R^2 = 0.83$, suggesting a strong positive relationship between the two variables.

The land-population ratio, $\tau$, is a main channel through which population growth influences output. Population growth gives rise to the population growth drag introduced by land as a semi-fixed factor of production; an effect that may be positive when $\psi$ is declining, as shown below. Since the land under cultivation has not varied much over time most of the identifying variation in $\tau$ comes from population growth and its interaction with $\psi$. Furthermore, the influence of population growth on output growth through this channel has diminished over time as the agricultural share in total output has diminished.

While education together with R&D is the driving force of growth in a modern growth regime in most endogenous growth models, it is less obvious why education would have played a role for growth over the past millennium. At the most basic level literacy skills are required for written communication, reading technical manuals and to broaden the understanding of economic and technical relationships. At higher levels of education the students are equipped with skills that are vital for innovation and improved organizational efficiency. Mokyr has long argued that macro inventions resulted in micro inventions that were carried out by educated and highly skilled craftsmen.

Collecting data for practical inventors among mechanics and engineers born over the period from 1660 to 1830, Meisenzahl and Mokyr (2012) show that among the inventors born before 1800, 25 percent of those whose background is known had a university degree and 37 percent had higher schooling or university degrees. Since the fraction of the population of working age with a tertiary
degree was, on average, 0.03 percent in the period 1600-1800, the fraction of inventors with a
tertiary education does not reflect the educational attainment of the working population but that
educated people were drawn into innovative activities. While self-selection was probably somewhat
at play, it is doubtful that, without education these entrepreneurs would have chosen the career path
they did. Another intriguing finding of Meisenzahl and Mokyr (2012) is that these skilled workmen
often published their work and engaged in debates over contemporary technological and social
questions, leading to positive technology externalities that initiated further inventions. Thus, it can
be argued that education was not only a way to increase the organizational efficiency of the society;
it also boosted innovations and transformed scientific breakthroughs into practical inventions.

3. Identification

Great innovations and educational attainment are instrumented to deal with endogeneity and to get a
better understanding of the more fundamental forces that are driving these variables. The $K-Y$ ratio
and the $T-L$ ratios are not instrumented, because it is incredibly difficult to find good instruments
that are available on an annual basis over the last millennium and, more importantly, because the
endogeneity of these variables will not affect the parameter estimates of the instrumented focus
variables. Furthermore, the $K-Y$ ratio is not likely to be influenced much by feedback effects from
per capita income because technological progress affects capital and income equally and, therefore,
leaves the $K-Y$ ratio independent of technological advances. Educational attainment and the stock of
knowledge created by great scientists are instrumented as follows.

3.1 Educational attainment

The computations of educational attainment are based on instrumented values of gross enrolment
rates (GERs) for primary, secondary and tertiary education individually, where GERs are the
fraction of an age cohort enrolled in schools or universities. Thus, it is not the educational
attainment per se that is instrumented; instead, the GERs are regressed on their instruments and the
predicted values from these regressions are used to generate educational attainment (the conversion
formulae are shown in the next section). The reasoning behind this identification strategy is that
external forces influence schooling at the time at which children and young adults decide to enroll
in the educational system; once the students finish their studies and join the labor force their level of
educational attainment is more or less set. For example, schooling of the oldest working age cohort
was decided up to 58 years earlier, and the identification strategy should reflect that. Despite the
time-gap between per capita income and the time at which the educated population did their
education, endogeneity cannot be ruled out. Bils and Klenow (2000), for example, show that
schooling is endogenous in growth regressions because the expected returns to education are
positive functions of expected productivity growth. Furthermore, if education is a normal good, productivity advances will enhance the demand for education.

GERs at each educational level are instrumented through the following first-round regression:

\[
GER_t^x = \beta_0 + \beta_1 Urb_t + \beta_2 Temp_t + \beta_3 \ln\left(\frac{P^f_t}{P_t}\right) + \beta_4 Lexp_t + \beta_5 (Rent_t/P_t) + \varepsilon_{1,t}
\]

where \(Urb\) is urbanization, \(Temp\) is temperature anomaly, \(P^f\) is food prices, \(P\) is consumer prices, \(Lexp\) is life expectancy, \(Rent\) is land rent, \(GER^x\) is gross enrolment rates at the primary (\(x = p\)), secondary (\(x = s\)), and tertiary (\(x = t\)) levels. Life expectancy is at birth is used for \(GER^p\) and \(GER^s\), while life expectancy at age 25 is used for \(GER^t\), reflecting the differences in age of graduation (data for life expectancy at ages between birth and 25 are not available very far back in time).

Real food prices are potentially good instruments for GERs because they are predominantly exogenously determined by weather conditions and by plant and animal disease and, consequently, impact on schooling affordability, particularly for the non-landed and the working classes. Temperature anomaly serves as a potentially good instrument in that persistent low temperatures may create hunger, starvation and a reduction in income. A small reduction in temperature is often associated with a reduction in the duration of light during the year and, consequently, with a reduction in the growing periods of crops and pastures and land cannot be cultivated at high altitudes. Malanima (2006), for example, finds climate to have been influential for living standards in Europe over the past millennium.

Contemporaneous per capita income is also likely to be affected by temperature and real food prices; however, this does not invalidate the exclusion restrictions for these two variables because of the long time-lag between school enrolment and joining the labor market and the fact that there is very little persistence in temperature anomalies or food prices. In other words, an income shock induced by temperature or food prices may affect income and the schooling decision; however, income is unaffected by the income shock at the time at which the graduates enter the labor market since the shock is serially uncorrelated.

Urbanization, which is measured as the fraction of the population living in cities of more than 5,000 inhabitants, is used as an instrument for GERs because it enables economies of scale and because production becomes more complex with urbanization (Murtin and Viarengo, 2011). Increasing returns and increasing production complexity increases the demand for skills and, therefore, the returns to human capital. Similarly, Boucekkine et al. (2007) argue that literacy rates increased in Britain in the period 1540-1860 predominantly because of increasing population density that ensured better access to schooling. The shortcoming of urbanization as an instrument is
that it is partly a reflection of economic development; however, as shown below, it is only a significant determinant for primary GERs and, therefore, endogeneity is not likely to be a major problem.

Life expectancy is an important determinant of the optimal years of schooling. In the schooling model of Bils and Klenow (2000) a one year increase in life expectancy is associated with an additional year of schooling in a frictionless economy, because excess returns from schooling is recouped over a longer time-span. This instrument has the additional advantage that there is large agreement in the literature that life expectancy is independent of per capita income (Cutler et al., 2006). Furthermore, Acemoglu and Robinson (2008) show that income is not directly affected by life expectancy at birth suggesting that the exclusion restriction that productivity is affected, with a considerable delay, by life expectancy through the channel of education, is valid. Finally, using an overlapping generation model Hashimoto and Tabata (2005) show that there is no clear relationship between economic development and mortality; instead, the mortality path depends on initial endowments.

Real land rent measures the expected returns from being a land owner as opposed to pursuing a career in manufacturing or services (see, for example, Peretto and Valante, 2011). In periods of high land rents the expected returns to education is low because little education is required for a career in the agricultural sector as compared to other sectors in the economy. Conversely, in periods of low land rent the pupils will have an incentive to pursue an education because the expected returns from a career within manufacturing or services are high relative to joining the landed class. The land rent is likely to affect only secondary and tertiary education since the landless and the working classes were unlikely to enter the landed and the capitalist classes, noting that secondary and tertiary education before the post-WWII period was elitist.

A related channel through which relative prices of land rent influence education is through the struggle between the landed class and capitalists as proposed by Galor et al. (2009). In their model the landed class had an interest in depriving the landless class of education to prevent them from migrating to the urban sector because it would lower the marginal productivity of land. Since human capital and capital were complements during industrialization, the capitalist elite saw an interest in having an educated labor force. The implications of their model is that the higher is the land rent relative to the price of other products, the lower is the potential influence of the landed class in the political decision process.

Finally, the exclusion restriction that land rent influences productivity through education is likely to be met since land rent is more a measure of the distribution of income than the level of income within an agrarian economy.
3.2 Great Scientists and significant innovations

The stock of great scientists or significant innovations is instrumented using cultural and institutional variables as follows:

\[ \ln S_t^d = \gamma_0 + \gamma_1 \ln Inst_t + \gamma_2 \ln Cul_t + \varepsilon_{2,t} \]  

where \( Inst \) is the quality of institutions and \( Cul \) is culture. \( Inst \) and \( Cul \) are used as instruments to deal with endogeneity and to give insight into the forces that drove the increase in great scientists or great innovations and why Britain produced great scientists well ahead of other countries. The exclusion restriction here is that institutions and culture influence productivity through the creation of great scientists and new ideas. This is a reasonable assumption since R&D is the main channel of productivity advances in endogenous growth models.

Although culture and institutions are not strictly exogenous they are less endogenous than the knowledge created by great scientists in that these variables come before great scientists in the causal chain and instruments will always be a link in a causal chain – one will never be able to identify the first link in a causal chain. Take the example of legal origin, which is probably the most popular instrument used in economic growth regressions for different variables (which, by implication, renders the exclusion restrictions invalid since there can only be one exclusion restriction). Clearly, this is not a strictly exogenous instrument since the legal institutions were formed by other factors in the causal chain. The same applies to culture and the quality of institutions.

Institutions are often an outcome of the struggle between various groups with different interests (Acemoglu et al., 2005, Acemoglu and Robinson, 2012). Similarly, Blaydes and Chaney (2013) argue that the development of European institutions emerged in response to the feudal revolution. European monarchs lacked the resources to fight wars following the fall of the Roman Empire. The feudal relationships that evolved served as the foundation for military resources for the monarchs, and warriors provided by the feudal elite would be used to constrain the executive. For culture very little empirical modeling has taken place to determine their forces, probably because it is mostly used by sociologists and hardly by economists. Lesthaeghe and Surkyn (1988), for example, argue that the dynamics of culture are determined by the cultural elitist class – often by the intellectuals who do not have large commercial interests.

The quality of institutions is often considered to be fundamental for economic development and growth (see, for an overview, Acemoglu et al., 2005; Acemoglu and Robinson, 2012). Britain is the perfect testing ground for the institutional hypothesis since Britain is often highlighted as a sterling example of how institutional progression, culminating with the Glorious Revolution in
1688, not only paved the way for the British Industrial Revolution but also spread across the world through British settlements. The improvement of the quality of institutions has long been put forward as one of the leading forces behind the British Industrial Revolution. Acemoglu et al. (2002, 2005) and Acemoglu and Robinson (2012) argue that Britain provided the legal foundations that enabled entrepreneurs to pioneer the industrial revolution, making contracts binding and lead to a system that allowed the formation of joint-stock companies and free market capitalism. The protection of property rights enhanced entrepreneurs and great scientists’ incentives to innovate and make scientific breakthroughs as they received the reward from their effort.

Culture is a key determinant of the values, preferences and beliefs of individuals and societies and is advocated to have been an important factor behind the Industrial Revolution by Weber (1905), Landes (1998), and Doepke and Zilibotti (2008). Landes (1998) concludes that, “if we learn anything from the history of economic development it is that culture makes all the difference ... what counts is work, thrift, honesty, patience, tenacity” (pp. 516, 523). For Mokyr (2005) the Industrial Enlightenment is a milestone in the improvement of organizational efficiency in human history as people became more tolerant to new ways of solving problems. People’s attitudes towards knowledge are critical to the progress of human civilization and a positive attitude towards knowledge is shaped by secularism. The key here is that the British Enlightenment was associated with increasing religious and political tolerance, human rights and freedom and natural law and justice and potentially outrageous and eccentric innovators; ideas were tolerated without violent responses (Mokyr, 2005).

4. Measurement and Data Issues

The per capita income data of Broadberry et al. (2011), spliced to Maddison’s (2003) data after 1820 are displayed in Figure 1. Income fluctuated around a relatively constant level before the early 1600s and Britain, subsequently entered a post-Malthusian growth regime that lasted to around 1830, and entered a modern growth regime from around 1830. Thus, British industrialization was represented by a gradual increase in income that started already in the early 1600s. A noticeable feature of the graph is the high volatility of per capita income up to the 19th century. The 1920 depression and the Great Depression are dwarfed in comparison to downturns before the 19th century.

A possible growth scenario, as advocated by Mokyr (2005), is that technological progress was random and unsystematic before the 17th century and the positive growth effects of technological progress were restrained by the population growth drag. As more systematic R&D was undertaken, technological progress became more persistent and, consequently, promoted higher growth (see, for a theoretical exposition, Peretto, 2012). The efficiency gains before entering the
The fixed capital stock is measured as the sum of working animals (oxen and horses) in the period 1270-1760 and spliced with economy-wide stock of capital based in the perpetual inventory method in the period 1760-2011. Non-working animals are not included in the pre-1760 data because they are not capital inputs in the production process and other investment items are omitted due to the unavailability of the data.

The $K/Y$ ratio, which is displayed in Figure 2, is constant in the extremely long run as predicted by standard growth models. The $K/Y$ ratio shows a positive growth trend in the approximate periods 1270-1450 and 1750-2011 and a negative growth trend in the period 1450-1750. These movements reflect changes in the time preference (propensity to save) and complex interaction between capital deepening and tax rates (see, for an analytical framework, Madsen and Davis, 2006). Assuming that movements in the $K/Y$ ratio predominantly mirror changes in the time-preference, the data suggest low returns to capital in the periods surrounding 1450 and in the post-1960s, where the low returns in the 15th century may, perhaps, have been induced by increasing risk aversion following the Black Death. Furthermore, the reduced life expectancy at birth caused by the Black Death may have lowered thriftiness and induced myopic behavior. The temporary reduction in the $K/Y$ ratio between 1863 and 1931 may reflect increasing age-dependency caused by high population growth.

Annual data for institutional quality is constructed over the period 1200-1800 and the construction of the index is detailed in the separate Data Appendix. The quality of institutions is the accumulated value of scoring counts, where the value 2 is given for major positive events such as
constitutional improvements of parliamentarianism or the democratization that further limits the power of the executive; 1 is given for normal positive events such as the establishment of a legislative sector or parliament; 0.5 is given for minor positive events such as the decentralization of a political regime that prevents the government or the church from arbitrary property confiscation; and -0.5 is given for minor negative events. The accumulated score is kept at a constant level after 1800 up to 2011 following Polity IV in which Britain gets the maximum score for constraints on executives during the entire period 1800-2011.

The institutional quality score is displayed in Figure 3. The index is likely to be a good indicator of the quality of institutions as it fits extremely well with the index on constraints on executives of Acemoglu et al. (2002) which has, independently, been constructed for the periods, 1200, 1300, 1400, 1500, 1600, 1700, 1750, and 1800. The development in property rights institutions in Britain over the past millennium is predominantly the history of conflicts between the royalty and other classes. It can be divided into three phases. The first phase is the period before the establishment of the parliament in England in 1264, during which the king controlled the state. The second phase brought about a series of parliamentary reforms dominated by conflicts among the loyalists, aristocracy, and bourgeois (Langer, 1972, p. 289). Two milestones in British history permanently contributed to a great leap forward, namely the Civil War of 1642-1649, when Parliamentary forces defeated Charles I, and the Glorious Revolution in the period 1688-1689, where parliament asserted its role as the legitimate seat of power. These events introduced major checks on royal power and mark the beginning of the third phase of British parliamentary history that has lasted until the present day.

In the absence of any value survey data available long back in history, culture is measured by the number of churches per capita. Underlying this construct is the assumption that culture is closely related to religiosity, which in turn is proportional to the number of churches per capita. The latter assumption is not difficult to defend since religiosity is found to be highly correlated with the
frequency at which people go to church (Lesthaeghe, 1983; Cukur et al., 2004). Several studies have found that religiosity is positively associated with value systems that have high preferences for preservation of social order, protection of the individual against uncertainty, moral and relational values and low preferences for personal competency and egoistic values such as pleasure, freedom, openness-to-change and being independent (Schwartz and Huismans, 1995; Cukur et al., 2004; Heine, 2007). Religiosity impacts on the scientific and innovative culture through the individualist-collectivist distinction that is used by sociologists to distinguish cultures (Cukur et al., 2004; Heine, 2007).

Individualism, at one end of the scale, emphasizes personal freedom, self-fulfillment, self-chosen goals, and achievement and forms a culture that is open to change. Consequently, a secular society will try to control its own fate and not appeal to supernatural powers, while non-secular societies believe that they cannot do much to influence their own fate (Schwartz and Huismans, 1995; Schwartz, 1999). Secular cultures encourage individuals to express and develop their special talents and to challenge conventional wisdom and to shape the environment for the benefit of the society and endorse ambition, success, and competitiveness. Collectivism, at the other end of the scale, is an authoritative system, such as a society that is ruled by religious authorities, and emphasizes group interests, conservation (conformity, security and preservation of tradition) and discourages behavior that makes the individual stand out (Schwartz and Huismans, 1995; Schwartz, 1999; Heine, 2007). Since new ideas are judged on the social status of the originator in authoritative religious systems, while judged on merits in non-authoritative secular societies, we would expect the creation of knowledge and new ideas to be higher in secular as opposed to non-secular societies.

The degree of religiosity, displayed in Figure 4, increases up to 1438 and, subsequently, declines markedly over the next two centuries. This time profile fits well into the taxonomy made by religion historians. Under the influence of the plague in 1348 people turned to God for salvation or, simply, they believed that the plague was a result of God punishing them for their sins (Byrne, 2006). Priests and preachers agreed that God was the ultimate source of the plague and that disease was the expression of God’s wrath provoked by humanity’s sinfulness (Byrne, 2006). This resulted in increasing religiosity. The sharp increase in churches per capita in the years 1348-50 is partly a reflection of a massive decline in the population that, automatically, pushed the ratio up because churches were unlikely to be demolished due to a potential declining attendance. To cater for this possibility dummy variables are included in the period of sharp population decline in the first-round regressions below.

The decline in religiosity after 1438 is often associated with the Renaissance, a cultural movement that originated in Italy in the 14th century and triggered secularization as it spread across the European continent (Pirenne 1963, pp. 377-378). The intellectual transformation that resulted in
the Renaissance is viewed as a bridge between the middle ages and the modern era and contained ideas critical of the Papal supremacy and the secular state gained strength during this period (Pirenne, 1963). The Reformation, starting in the early 16th century, accelerated the secularism process that was already set in motion by the Renaissance.

However, the movement against the Roman Catholic Church had actually already started in the late 14th century under the influence of John Wycliffe (1320-1384) and gained momentum through the Lollards; a religious movement, that from the late 14th century and throughout, particularly the early 15th century campaigned against the dogmas of the Roman Catholic Church (Roberts, 2006). The church with the support of the crown struck back and Lollards were persecuted and the movement was driven underground. Thus, it was not until 1534, following the Pope’s refusal to consent his divorce in 1534, Henry VIII established Protestantism as state religion (Ferm, 1957). The 16th century was a turning point in British history of culture and secularism dominated by free and independent thinking gradually took over as a social movement. It is probably no chance-occurrence that Shakespeare (1564-1611), who is considered to be the greatest writer ever, lived during the greatest cultural enlightenment experienced in modern British history.

Importantly, Calvinists, who dominated the Reformation in Britain, believed that God had predestined all people to heaven or hell and that nothing, including prayer, could change God’s decision (Byrne, 2006, p. 87). Since God was everywhere, and not especially present in the church, these buildings tended to lose there sacredness (Byrne, 2006, p. 89). Furthermore, Calvinism relied upon reason, encouraged education and trusted science, since it considered that knowledge leads to God (Pirenne, 1963). “Calvinists rejected Papal obedience, refused to admit the intermediary of the clergy between God and man, rejected ceremonies of worship, the orders of the Church and the monastic orders” (Pirenne, 1963, p. 527). Since individualism is one of the core values of the Protestantism while Catholicism emphasizes collectivism, the Reformation was a milestone in the transition from collectivism to individualism in the British society.

Educational attainment is estimated from school enrolment rates and age distributions of different school cohorts that take into account age dependent mortality rates. The data on primary and secondary school enrolment rates are compiled from various sources as detailed in the separate Data Appendix. Enrolment data are available from 1812 at the primary level and from 1903 at the secondary level. Prior to these dates enrolment is computed as the accumulated number of non-Latin (primary) and Latin (secondary) schools, respectively, multiplied by a fixed number of pupils per school over the period from 1160 to 1811. The number of pupils per school is set to 50 because the pupil capacity of schools, when listed, was scattered around 50 and this number was relatively constant over time.
Data on tertiary education before 1920 and after 1996 are collected from numerous sources and we were able to compile data back to or close to the foundation years for almost all universities. The post-1996 data are estimated as the sum of enrolment rates for the 65 universities that were granted the Royal Charter prior to 1992. Aggregated official enrolment data in the post-1996 period are not used because the explosion in tertiary student enrolments in institutions that were not granted the Royal Charter, such as open universities, gives a misleading picture of the growth in tertiary education enrolment rates in this period. The pre-1920 data are available for all universities in the UK during almost all years from their foundation dates. The data were interpolated to bridge gaps in the data and transformed to enrolment data in the instances in which only data on graduates and matriculation are available.

Following Madsen (2014) the following formulas are used to construct educational attainment at the primary, secondary and tertiary levels for age cohort \(i\) in the labor force completing grade \(j\):

\[
EA^P_t = \frac{\sum_{i=0}^{49} \left[ \text{pop}_{15+i} \sum_{j=4}^{9} GER^P_{t-i-j} \right]}{\sum_{i=0}^{49} \text{pop}_{15+i}},
\]

\[
EA^S_t = \frac{\sum_{i=0}^{46} \left[ \text{pop}_{15+i} \sum_{j=1}^{4} GER^S_{t-i-j} \right]}{\sum_{i=0}^{45} \text{pop}_{15+i}},
\]

\[
EA^T_t = \frac{\sum_{i=0}^{41} \left[ \text{pop}_{19+i} \sum_{j=0}^{4} GER^T_{t-i-j} \right]}{\sum_{i=0}^{40} \text{pop}_{15+i}},
\]

where \(\text{pop}_{15+i}\) is the size of the population aged \(15+i\), and, as stated above, \(GER^P\), \(GER^S\) and \(GER^T\) are gross enrolment rates at the primary, secondary and tertiary levels. GER’s are estimated as student enrolment in a given year divided by the population of the ages at which they are enrolled at a certain level. The term \(\text{pop}_{15+i} \sum_{j=4}^{9} GER^P_{t-i-j}\) in the numerator of Eq. (7), for example, is the total primary educational attainment among the \(15+i\) age cohort at time \(t\) and \(\sum_{j=4}^{9} GER^P_{t-i-j}\) is primary school educational attainment. For 64 year olds in 1570, for example, the primary educational attainment is the sum of GERs over the period 1512-1518. The school ages were 6-11 for primary schooling, 12-14 for secondary schooling up to around 1902 (Gordon and Lawton, 2003). The school reforms in the end of the 19th century and the beginning of the 20th century changed the years of schooling at the primary, secondary and the tertiary levels from the 6-4-5 model to the 7-5-5 model. This is incorporated into the estimates of the educational attainment with breaking point in 1902 as detailed in the separate Data Appendix.
The log of educational attainment, which is displayed in Figure 5, increased steadily up to the onset of the First Industrial Revolution around 1760. By international standards the literacy rates were high in Britain around 1760 and created a workforce that was able to operate the machines, read and create manuals and to understand and implement the ideas created by scientists and engineers in the production process (Easterlin, 1981; Boucekkine et al., 2007). However, although new schools were built, the number of schools failed to pace with the rapid increase in population in the period 1750-1820 and educational attainment at the primary and secondary levels, consequently, suffered. Furthermore, industrialization increased opportunities for child labor which halted access to education for many children (Sanderson, 1991). The declining educational attainment is also consistent with the finding by Nicholas and Nicholas (1992) of deskilling of the English workforce during the early phase of British industrialization up to 1840 as industry substituted unskilled female and child laborers for skilled workers and relied on power-driven machinery that could be operated by unskilled labor. The marked increase in educational attainment in the period 1845-1900 reflects an increasing demand for educated labor during the Second Industrial Revolution (Galor and Moav, 2004, Galor, 2011) that also lead to the establishment of several universities in the second half of the 19th century.

The ratio between land under cultivation and the total population is displayed in Figure 6. Most of the variations in the land-population ratio comes from variations in population growth; however, not all. Land under cultivation decreased by 30 per cent in the period 1300-1443 and, therefore, mitigated the growth-drag effects of population at the outbreak of the Plague during which the land-population ratio almost doubled (1348-1350). The land under cultivation subsequently doubled over the period 1450-1850 and, again, mitigated some of the effects of the increasing population on the land-population ratio. Regressing the log of land on the log of population in the period 1270-2011 yields a coefficient of population of 0.26, indicating some
response in land under cultivation to population pressure; even in Britain in which the population
density exceeded that of most other countries in the world.

Domestic knowledge is measured as accumulated number of great scientists in Britain compiled
from Gascoigne (1984) and by accumulated significant innovations (Ochoa and Corey, 1997). The
score of one is given for each entry (scientist or innovation). For great scientists the data are
classified on time and country using the 15918 biographies of great scientists listed in Gascoigne
(1984). The knowledge stock is displayed in Figure 7. The trend growth rate is fairly steady over
most of the period except for the marked advance in the period 1270-1330 and, particularly, during
the 17th century. Remarkably, the increase in the 17th century is not reflected in a corresponding
increase in the number of university graduates, suggesting that it not the sheer number of university
students and then, perhaps, the number of professors that are crucial for scientific discoveries.

Instead it suggests that it was the institutional and the cultural environment that was crucial for
the growth in knowledge, as shown in the next section. The surge in knowledge stock in the 17th
century coincides with an equally strong improvement in the quality of institutions and
secularization, indicating that they may have been the driving forces behind the Scientific
Revolution during the 17th century. Research was supported by inclusive institutions and there was
a decisive change in the focus from an Aristotelian natural philosophy to chemistry and biological
sciences such as botany, anatomy, and medicine during the 16th and 17th centuries (Debus, 1978).
Debus (1978) argues that the preparedness to question previously held truths and the search for new
answers resulted in an epoch of major scientific advancements. Similarly, Bernal (1937) argues that
religion, superstition, and fear were replaced by reason and knowledge during the Renaissance. The
advances in science were marked by the foundation of the Royal Society in 1660.
Knowledge spillovers through imports in the period 1270 to 1870 are measured as a weighted average of the stock of knowledge created by great scientists before 1870 and as a weighted average of patent knowledge stock after 1870. The following weighting schemes are used:

\[
S^\text{im}_{UK,t} = \sum_{k=1}^{16} \frac{M_{UK,k}^t}{M_{UK,t}} S^d_{kt},
\]

1270-1869

\[
S^\text{im}_{UK,t} = \sum_{j=1}^{18} \left( \frac{M_{UK,j}^t}{Y_j^t} \right) S^d_{jt},
\]

1870-2011

where \(M_k\) is imports of goods from country \(k\) to Britain, \(M_{UK}\) is total imports of goods to Britain, \(M_{UK,j}\) is UK imports of high technological products from country \(j\), \(Y_j\) is the nominal GDP of country \(j\), \(S^d_{kt}\) and \(S^d_{jt}\) are the patent stock in countries \(k\) and \(j\). The 18 countries in the \(j\)-group consist of the core OECD members and are listed in Madsen (2007), while the 16 countries in the \(k\)-group are listed in the separate Data Appendix. Bilateral imports are used as weights in the pre-1870 estimates because of the unavailability of nominal GDP and bilateral exchange rates over the period 1270-1870. Accumulated significant innovations, as classified by Ochoa and Corey (1997), are used to construct the knowledge stock of each individual trade partner.

Imports of foreign knowledge were fairly flat up to around 1790, increased slightly from 1790 to 1860 and increased steeply thereafter (Figure 8). The marginal increase in international technology transmission through the channel of imports up until 1860 reflects a slow increase in scientific knowledge outside Britain and the fact that Britain imported heavily from countries with little growth in scientific knowledge such as India and the West Indies from the late medieval period. It was not until the middle of the 19th century that Britain expanded its imports from countries with strong growth in scientists such as the US and Western Europe.

5. Regression results

5.1 First-round regressions

The first-round regressions are displayed in Table 1. Insignificant variables are deleted following the general-to-specific model reduction procedure, and the DOLS estimator with two leads and lags is used to ensure that the coefficients are unbiased and the test statistics follow the tabulated values, provided that the variables are cointegrated. The null hypothesis of no cointegration is rejected at the 1 percent level in all cases, suggesting that the instruments adequately explain the paths of GERs and knowledge stock and that the parameter estimates are super consistent, that is, the parameter estimates are robust to problems such as omitted variables, simultaneity and endogeneity. Furthermore, the coefficients of the variables in the restricted models in Table 1 are highly significant, reinforcing the cointegration tests that the selected variables are influential.
regressors. Note that the OLS estimator is used to create the instruments to the structural estimates; the DOLS estimates are used only in the exposition in Table 1.

The regression results are intriguing in that the determinants of secondary and tertiary GERs are the same and, at the same time, mostly different from the determinants of primary GERs. That the same variables determine \( GER^s \) and \( GER^t \) is intuitive from the perceptive that Latin schools, the precursor of high schools before the 20\textsuperscript{th} century, were primarily meant as a preparation for tertiary education (Wiesner-Hanks, 2006). Life expectancy is a much more significant determinant of \( GER^s \) and \( GER^t \), than for \( GER^p \), which makes sense in that the excess returns from schooling are recouped over a longer time-span and, therefore, are less sensitive to expected life. Urbanization is a significant determinant for primary schooling as the schools were predominantly concentrated in urban areas (Eyre and Spottiswore, 1868). Location of schools is probably less relevant at the secondary and tertiary levels since students are more likely to have lived away from their parents compared to pupils in primary schools.

Real food prices are significant determinants of GERs at the primary but not at the secondary and tertiary levels, which one would expect since working class children were probably over represented at the primary level but rarely entered the secondary or tertiary levels. Given that real food prices are more influential for the distribution than the level of income, it is not surprising that education at higher levels is unaffected by real food prices. Conversely, temperature anomaly is a significant determinant of \( GER^s \) and \( GER^t \), but not of \( GER^p \), which is likely to reflect that temperature anomalies affect the level of income of all income classes, while high food prices affect the distribution of income in favor of the landed class. Real land rent is negative and highly significant for secondary and tertiary schooling, which is consistent with the thesis that higher land rent discourages secondary and tertiary education because the returns from entering the commercial sector are low.

### Table 1. First round regressions

<table>
<thead>
<tr>
<th>Dep var</th>
<th>( GER^p )</th>
<th>( GER^s )</th>
<th>( GER^t )</th>
<th>( S^s(Sci) )</th>
<th>( S^r(Sci) )</th>
<th>( S^r(S&amp;T) )</th>
<th>( S^r(S&amp;T) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Urb_t )</td>
<td>126.3(6.03)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( Temp_t )</td>
<td></td>
<td>2.60(4.24)</td>
<td>0.84(4.81)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( Ln(P/P)_t )</td>
<td>-14.2(5.30)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( Lexp_t )</td>
<td>0.94(3.30)</td>
<td>2.15(29.5)</td>
<td>0.55(8.44)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( (Rent/P)_t )</td>
<td>-6.01(15.7)</td>
<td>-1.17(7.28)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( Ln(Cul)_t )</td>
<td></td>
<td>-1.11(20.0)</td>
<td>-0.80(15.4)</td>
<td>-0.81(37.6)</td>
<td>-0.77(37.4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( Ln(Inst)_t )</td>
<td></td>
<td></td>
<td>5.54(42.9)</td>
<td>5.56(44.8)</td>
<td>2.48(38.8)</td>
<td>2.47(39.6)</td>
<td></td>
</tr>
<tr>
<td>( Pest_t )</td>
<td></td>
<td></td>
<td></td>
<td>-2.20(40.4)</td>
<td>-0.56(24.2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( Pest_Time )</td>
<td></td>
<td></td>
<td></td>
<td>0.01(24.0)</td>
<td>0.01(20.1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \chi^2(k) )</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>( DF )</td>
<td>-2.48</td>
<td>-3.89</td>
<td>-2.74</td>
<td>-3.08</td>
<td>-5.56</td>
<td>-4.77</td>
<td>-5.73</td>
</tr>
</tbody>
</table>
Notes. The figures in parentheses are absolute $t$-statistics. Constant terms are included in the regressions but not shown. $Urb =$ urbanization rate, $Temp =$ temperature anomaly, $F =$ food prices, $P =$ consumer prices, $Lexp =$ life expectancy at birth, $Cul =$ culture (per capita churches), $Inst =$ institutions, $Pest =$ a dummy taking the value of 1 in the period 1348-1448 and zero elsewhere, $Time =$ time trend. $S^c(Sci) =$ accumulated stock of great scientists (Gascoigne 1984). $S^c(S&T) =$ accumulated great innovations (Ochoa and Corey, 1997). The regressions are based on DOLS where two leads and lags of the regressors in first differences are included in the regressions. $\chi^2(k) =$ $p$-value for chi-squared test for excluded restrictions, where $k$ is the number of restrictions. $DF =$ Dickey-Fuller test for cointegration where the change in the residual is regressed on the lagged residual with no constant term and no time trend. The critical values of the Dickey-Fuller tests are -2.58 and -2.23 at the 1 and 2.5 percent levels.

Turning to the first-round regression for great scientists, the coefficients of $Cul$ and $Exec$ are statistically highly significant and have the signs predicted by theory (column 4 Table 1). Quantitatively, they are both also important, as shown in the simulations in the next section. Pest-dummies are included in the science regression in the last column in Table 1 to cater for the possibility that, despite increasing religiosity, the decline in the population was so massive during the period 1348-1448 that some of the existing churches may have been quite empty during services. The pest dummy, $pest$, takes the value of one in the period 1348-1448 and zero elsewhere. The $Pest*Time$ dummy caters for increasing attendance during services as the population recovers to its pre-plague level. The coefficients of the pest dummies are highly significant and have the expected signs, suggesting that the increasing religiosity during the period 1348-1448 was less marked than indicated by Figure 4. In any event, the increasing religiosity during the first hundred years following the outbreak of the Plague was a large deterrent to the development of scientific knowledge in the late Middle Ages.

5.2 Estimates of the structural model

The results of regressing Eq. (4) are presented in Table 2. All coefficients are significant in the OLS regression in the first column and most of the parameter estimates are similar to those of the IV regressions in the other columns in the table. The results are also insensitive to inclusion of Pest dummies in the first-round regression for domestic knowledge (column 5). The distinguishing feature of the regressions in columns 2-4 is that the domestic stock of knowledge is based on the chronology of Ochoa and Corey (1997) (innovations) in column 2, Asimov (1982) (innovations) in column 3 and Gascoigne (1984) (great scientists) in column 4.

Clark’s (2010) income data are used in the regression in the last column. While the data of Broadberry et al. (2011) are constructed using the output approach, Clark’s (2010) data are based on the income approach. Clark’s income data show almost the same time-profile as Broadberry et al.’s (2011) data except that it starts at a higher level in 1270 and the population decline following the outbreak of the Black Death in 1348 appears to have produced an increase in Clark’s income data up to 1430 and the subsequent surge in population resulted in a decline in income up to the end of the 17th century. The coefficients of all the regressors in the regressions in column 6 are highly
significant. The main difference between the results in columns 2 and 6 is that the coefficients of the K-Y ratio and the land-population ratio are higher in the regression based on Clark’s data.

Domestic stock of knowledge, $S^d$, is highly significant and positive in all regressions, indicating that the creation of domestic knowledge was pivotal for technological advances and, consequently, productivity growth. Since the domestic knowledge stock advanced substantially faster in Britain than elsewhere in the world in the period 1600-1900, the British scientific revolution was influential for the unique British growth experience, particularly during the growth spurt in the 17th century. The results are consistent with the discussion of Jacob (1997) and Mokyr (2005). Mokyr (2005) gives several examples of how theories developed by great minds were subsequently used by practical people to develop new technologies and to find new ways of doing things. Newton’s contribution to the understanding of the laws of thermodynamics was, for example, vital for the invention and development of the steam engine (Mokyr, 2005).

Educational attainment is also highly significant and positive in all regressions. Economically, educational attainment is also highly influential for growth, as shown in the simulations in the next section. The decline in educational attainment in the approximate period 1750-1825 explains, to a large extent, the poor growth performance during the First Industrial Revolution; a low growth rate that has, for long time, been considered a mystery among economic historians (see, for example, Clark, 2010). Furthermore, the marked increase in educational attainment during the second half of the 19th century was a significant contributor to the high growth in Britain during the Second Industrial Revolution.

Table 2. Structural regression results (Eq. (4)).

<table>
<thead>
<tr>
<th>Estimator</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>OLS</td>
<td>IV</td>
<td>IV</td>
<td>IV</td>
<td>IV</td>
<td>IV</td>
</tr>
<tr>
<td>Data</td>
<td>O&amp;C</td>
<td>O&amp;C</td>
<td>Asimov</td>
<td>Gers</td>
<td>O&amp;C</td>
<td>O&amp;C/Clark</td>
</tr>
<tr>
<td>( EA_t )</td>
<td>0.08 (12.1)</td>
<td>0.09 (13.0)</td>
<td>0.09 (12.9)</td>
<td>0.10 (13.9)</td>
<td>0.05 (4.45)</td>
<td>0.05 (7.66)</td>
</tr>
<tr>
<td>( lnS^d_t )</td>
<td>0.39 (20.8)</td>
<td>0.39 (20.6)</td>
<td>0.33 (20.4)</td>
<td>0.17 (17.7)</td>
<td>0.43 (25.6)</td>
<td>0.28 (14.9)</td>
</tr>
<tr>
<td>( Op_t lnS^f_t )</td>
<td>0.08 (5.77)</td>
<td>0.10 (7.28)</td>
<td>0.10 (6.99)</td>
<td>0.13 (9.88)</td>
<td>0.12 (12.3)</td>
<td>0.05 (4.49)</td>
</tr>
<tr>
<td>( lnk_t )</td>
<td>0.15 (5.17)</td>
<td>0.04 (1.60)</td>
<td>0.02 (0.70)</td>
<td>0.08 (2.38)</td>
<td>0.00 (0.14)</td>
<td>0.34 (13.3)</td>
</tr>
<tr>
<td>( pt ln \tau_t )</td>
<td>0.67 (12.9)</td>
<td>1.20 (21.8)</td>
<td>1.27 (23.3)</td>
<td>0.90 (12.5)</td>
<td>1.03 (9.19)</td>
<td>1.31 (18.3)</td>
</tr>
<tr>
<td>Pest Dum.</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

Notes. See notes to Table 1. The t-statistics are based on robust standard errors. Instruments are used for educational attainment and domestic knowledge stock, except in the regression in column 1. The dependent variable is the log of per capita income based on Broadberry et al. (2011) except in column 6 in which the per capita income data are based on Clark (2010). Domestic stock of knowledge (\( S^d \) measure) is based on O&C = Ochoa and Corey (1997) (innovations), Asimov = Asimov (1982) (innovations), and Gers = Gascoigne (1984) (great scientists). Estimation period: 1270-2011.
Foreign knowledge is a significant determinant of per capita income, indicating that foreign knowledge contributed to growth in Britain from the late 19th century, when the foreign knowledge finally started to grow (see Figure 8). Thus, the Industrial Revolution was homemade in the sense that the economic advances were driven by domestic forces, while imports of knowledge stock first started to contribute to growth well into the Second Industrial Revolution. The result that the British Industrial Revolution was homemade is reinforced by the finding that the coefficient of foreign stock of knowledge is well below that of domestic knowledge stock; especially when it is taken into account that $\ln S_f$ is multiplied by openness, which automatically pushes its coefficient up by the inverse average of openness.

The coefficients of per capita land area adjusted for the agricultural share is consistently significant and positive in all the regressions in Table 2. Thus, population growth has been a drag on the economy; particularly before the 17th century when the share of agriculture in total economic activity started declining. However, the population term can have positive growth effects even if the $T-L$ ratio is decreasing because the structural adjustment of the economy during industrialization reduced the population drag – simply because the average number of workers per acre is reduced and agriculture moves up its declining marginal productivity of labor schedule. This is shown more formally in the next section.

The $K-Y$ ratio is statistically significant at conventional significance levels in half of the regressions in Table 2. The decline in the $K-Y$ ratio over the period 1500-1750, may therefore, have contributed to the stagnation during the same period. Conversely, the increasing $K-Y$ ratio from 1760 contributed positively to the income advances during the British Industrial Revolution, which is consistent with the predictions of the models of Galor and Moav (2004) and Voigtlander and Voth (2006). Finally, comparing the results in columns 2 and 6, it is important to note that the parameter estimates of the focus variables, $S_d$ and $EA$, are not sensitive to whether Broadberry et al. or Clark’s data are used; reinforcing the finding in the other regressions that the knowledge generated by great scientists and educational attainment have been significant determinants of growth over the past millennium and, particularly, during the British Industrial Revolution.

6. Simulations

Thus far the focus has predominantly been on statistical significance of the variables included in the model. To get a better picture of the contribution of each of regressor in Eq. (4) to economic growth Table 3 decomposes the sources of growth by simulating the key regressions in Table 2 (columns 2-4) using the actual movements of the data. The simulation results are presented in Table 3. The following three eras in British growth history are considered: the preindustrial growth regime, 1270-1600, industrialization, 1600-1900, and the modern growth regime, 1900-2011.
Considering the preindustrial period 1271-1600 the growth, on face value, looks like a race between the population growth drag and technological progress. As shown below, the race was really between improved institutions and de-secularization that strongly pulled the growth in domestic knowledge in two different directions. The annual per capita income growth rate was minus 0.08 percent during this period. The growth rate would have been slightly positive if geometric instead of arithmetic growth rates were used noting that arithmetic growth rates are approximately reduced by half the standard deviation of the average growth rates relative to geometric growth rates. The population growth was low during this period due to the Plague and created a growth drag of only 0.09-0.10 percent. The only significant contributor to growth during this period was the domestic stock of knowledge.

Table 3. Decomposing sources of percentage growth in productivity and domestic knowledge stock.

<table>
<thead>
<tr>
<th></th>
<th>$EA_t$</th>
<th>$lnS^d_t$</th>
<th>$lnk_t$</th>
<th>$Op_t \cdot lnS^d_t$</th>
<th>$\psi_t ln\tau_t$</th>
<th>Actual $y_t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Innovations, O&amp;Co (Column 2 in Table 2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1271-1600</td>
<td>0.00</td>
<td>0.33</td>
<td>0.00</td>
<td>0.03</td>
<td>-0.09</td>
<td>-0.08</td>
</tr>
<tr>
<td>1601-1900</td>
<td>0.12</td>
<td>0.42</td>
<td>0.00</td>
<td>0.16</td>
<td>0.03</td>
<td>0.57</td>
</tr>
<tr>
<td>1901-2011</td>
<td>0.69</td>
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<td>0.14</td>
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<td>0.02</td>
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<tr>
<td>Culture</td>
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<td>1601-1900</td>
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Notes: the growth rates are arithmetic averages of annual growth rates.

The average annual growth rate was 0.57 percent during the crucial period of industrialization, 1601-1900. The main contributors to growth were domestic knowledge created by great scientists followed by education and imports of knowledge. Taking the average of the simulations in the three top panels in Table 3, domestic stock of knowledge contributed 0.40 percent to annual growth, while education contributed another 0.11 percent. Imports of knowledge furthered income growth by 0.15 per cent, on average. Remarkably, population growth was a positive contributor to growth, which may appear paradoxical given that the population size expanded eight-fold in the period 1600-2011 while domesticated land responded only moderately to the population pressure. As
shown analytically below, this result is an outcome of the interaction between population growth and the share of agriculture in overall economic activity.

Education takes over as the most important contributor to growth in the modern growth regime (0.62%), 1901-2011, followed by foreign stock of knowledge (0.24%), and domestic stock of knowledge (0.16%), where the figures in parentheses are averages of the first three panels in Table 3. The number of great scientists and significant innovations has not grown much over the last century and has muted the contribution of science to growth. However, the number of great scientists and significant innovations are unlikely to have been representative for the growth in R&D that has taken over as an important engine of growth since the Second Industrial Revolution (Aghion and Howitt, 2009; Madsen, 2010). Innovations were not an outcome of systematic R&D effort by firms before the 20th century and significant innovations were taken into use by practical people such as tradespeople and engineers. R&D undertaken by firms has gained momentum during the 20th century and it is likely that educational attainment in the simulations has captured some of the effects of innovations on growth in the last century.

The importance of knowledge stock in shaping growth during the period 1270-1900 begs the question of the relative importance of institutions and culture in explaining growth during this period. The simulations in the last panel in Table 3 show the contribution of institutions and culture to growth. Institutions were a major contributor to growth in significant innovations before 1900. It contributed a whopping 1.5 percent to growth annually before 1600; however, the growth in knowledge was dragged down by a marked increase in collectivist thinking dominated by religious dogmas that impaired creative and original thinking. The growth in collectivism had a severe adverse effect on the growth in knowledge up to around 1500. The marked move from collectivism towards individualism during the 16th century reversed this trend and was a main impetus to the significant increase in knowledge during the 16th century.

Considering the key period of industrialization, 1601-1900, simulations of the model show that improved institutions explain approximately 55 percent of the increasing domestic knowledge created by great scientists, while the increasing secularism explains the remaining 45 percent. Improved institutions were particularly influential for the surge in knowledge during the 17th century, while secularism was a major contributor to the scientific advances during the First Industrial Revolution.

Thus improvements in institutions and increasing secularization during the 16th and the 17th centuries created the preconditions to what was later to become the First Industrial Revolution. Bernal (1937), for example, argues that “the Renaissance enabled a scientific revolution which let scholars look at the world in a different light. Religion, superstition, and fear were replaced by reason and knowledge” (p. 60). Similarly, the Civil War of 1642-1649 and the Glorious Revolution...
in 1688 were milestones in the long march towards inclusive institutions that furthered the incentives to innovate.

Finally, it remains to be explained why the $\psi_t \ln \tau_t$-term has been a positive contributor to growth in the period 1600-2011 during which the $T/L$ ratio has been reduced substantially by population growth. Population growth is usually considered to be a drag on economic growth due to diminishing returns introduced by land as a fixed factor of production. However, the population growth drag may be overshadowed by a decline in the $\psi_t$-term as the economy industrializes and this is the reason behind the apparently counterintuitive results of the population growth drag in reverse; an effect that has been neglected in the literature on the population growth drag. If the decline in $\psi$ is sufficiently strong, the population growth can actually have positive productivity growth effects. Thus, differentiating the production function with respect to $L$ to find the population growth drag does not give the right results because $\psi$ is not constant. Differentiating will only give the first order linear effects while a Taylor series approximation will give non-linear effects and will explicitly show the growth effects of $X$ and $\psi$ when they are coming from above and from below.

More formally, the partial effect of population on per capita income is given by:

$$\Theta = \left(\frac{T}{L}\right)^\psi = X^\psi = F(X, \psi).$$

(10)

Here $T/L$ is, on average, 0.60 and $\psi$ is, on average, 0.34 over the period 1270-2011. Using a second-order Taylor series approximation around the value $X = X_0 = 0.6$ and $\psi = 0.34$ yields:

$$F(X_t, \psi_t) \approx 0.6^{0.5} + (X_t - 0.6) \frac{\partial X_t^\psi}{\partial X_t} + (\psi_t - 0.34) \frac{\partial X_t^\psi}{\partial \psi_t}$$

$$+ 1/2 \left[(X_t - 0.6)^2 \frac{\partial^2 X_t^\psi}{\partial (X_t)^2} + (\psi_t - 0.34)^2 \frac{\partial^2 X_t^\psi}{\partial (\psi_t)^2}\right],$$

which yields:

$$F(X_t, \psi_t) \approx 0.6^{0.34} + (X_t - 0.6)\psi_t X_t^{\psi_t - 1} + (\psi_t - 0.34)X_t^{\psi_t} \ln X_t$$

$$+ 1/2 \left[(X_t - 0.6)^2 \psi_t (\psi_t - 1)X_t^{\psi_t - 2} + (\psi_t - 0.34)^2 X_t^{\psi_t} (\ln X_t)^2\right].$$

(11)

From this expression it can be seen that a decrease in $X = T/L$ induced by population growth can have positive as well as negative effects on income depending on the counterbalancing effects of the first and the second order terms and the size of $\psi$ and $X$. Since $\psi$ and $X$ were consistently above their average values of 0.34 and 0.6 before 1600, population growth was unambiguously negative for productivity during this period, noting that the last two terms in Eq. (11) are always overpowered by the second and third right-hand-side terms. After 1600, $X$ and $\psi$ are mostly below their averages.
The intuition behind this result in Eq. (11) is that a decrease in $\psi$ eases the land-constraint of the existing population employed in agriculture as the population moves out of the agricultural sector and eases the overall population drag. If the migration from agriculture is larger than the inflow to agriculture due to increasing population, the net growth effect of population is positive. In other words, the decreasing population in agriculture ensures that productivity in agriculture increases as we move up the downward sloping agricultural marginal productivity line. If overall effects from depopulation in agriculture overpowers the population growth drag induced by population growth, the $\psi_t \ln \tau_t$ term will contribute positively to growth as happened in the post-1600 period.

8. Concluding remarks

A tremendous amount of scholarly work has tried to shed light on approximate causes of the British Industrial Revolution and why Britain was the first country in the world that succeeded in transforming a regime with minuscule and patchy growth into a regime with persistent positive growth rates. However, due to the lack of data the quantitative side of the British industrialization has remained underdeveloped. This paper is the first step to illuminate the influence of human capital on income growth in Britain over the past millennium by testing the growth-effects of educational attainment at the primary, secondary and tertiary levels, knowledge created by great scientists, significant innovations, culture and the quality of institutions.

The regressions showed that education and knowledge created by great scientists were the ultimate drivers of growth in Britain throughout the pre-industrial as well as the industrial eras. More fundamentally, the amount of knowledge created by great scientists was found to be a result of culture and institutions, while enrolment rates, were outcomes of real land rent, food prices, temperature, life expectancy and urbanization. Saving-induced capital accumulation and population growth were found also to have affected growth in the pre as well as the industrial eras. A remarkable finding is that population has been a positive contributor to growth during the central industrialization period 1600-1900. This stems from the fact that the agricultural share in total income was declining along with the increasing population, which, due to a positive interaction effect between population and agricultural share, more than counterbalanced the negative growth effects due to diminishing returns introduced by land as a fixed factor of production.

Growth in the pre-industrial period, 1270-1600, was dominated by a tight race between the growth enhancing effects of education and knowledge created by great scientists, on the one hand, and the population growth drag, on the other hand. Although the net growth-effects of great scientists was relatively modest during this period its path hides two strong almost counterbalancing effects; improved institutions and de-secularization. There were large improvements in the quality
of institutions during the period 1270-1600 and these were important contributing factors to the increase in scientific knowledge; however, increasing conservatism and traditional beliefs created by increasing religiosity discouraged innovative behavior and independent thinking. The increasing religiosity during the Plague put a large strain on independent thinking and may even have prevented the industrialization from unfolding earlier than it did.

The industrialization period 1600-1900 was driven, predominantly, by a marked improvements in the quality of institutions and the enlightenment created the perfect environment for development of new knowledge. Remarkably, the number of students enrolled in universities first started to significantly increase at the second half of the 19th century, suggesting that it was not a massive increase in the resources to learning that produced the British Industrial Revolution; it was a very creative environment stimulated by good institutions and secular thinking. Britain entered the modern growth regime from around 1900 and increasing educational attainment followed by domestic knowledge formation and international knowledge spillovers as the major driving forces behind this transformation.

Was the British Industrial Revolution inevitable? The foundations of Oxford and Cambridge Universities in the 13th century raised the curtain up for what was to become the most successful industrial revolution in human history. However, Britain was not the only country in the world endowed with universities before 1600. Several universities were established throughout most of Continental Europe before 1600 and in other countries in the world. What distinguished Britain from other European countries during its industrialization was its culture and the quality of its institutions. The institutional quality improved substantially faster in Britain than other countries in the world in the period 1600-1800 (Acemoglu et al., 2002) and the force of the Reformation and the Renaissance were, according to Weber (1905) and Pirenne (1963), powerful factors behind Britain’s success. The most significant development in the 16th and the 17th centuries was not a specific discovery, but rather a process for discovery; the so-called scientific method (Brotton, 2006). The scientific culture created by the enlightenment subsequently ensured the results created by scientists were put into use in terms of innovations and engineering projects as advocated by Jacob (1997), Khan and Sokolof (2008), and Mokyr (2005).

Although random elements would have played a role for the British Industrial revolution Britain certainly had the prerequisites for an industrial revolution: a well-developed infrastructure, an affluent middle class that is able and willing to finance mass production of new technologies, a market-driven economy, a positive attitude towards change and independent thinking, an educated elite, strong work ethics, access to energy sources, and an inclusive political system.
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