Human Capital Formation during the First Industrial Revolution: Evidence from the Use of Steam Engines[§]

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Abstract

We examine the effect of technological change on human capital formation during England's Industrial Revolution. Using the number of steam engines installed by 1800 to capture technological change and occupational statistics to measure working skills (using HISCLASS), our county-level regression analysis shows a negative correlation between the use of steam engines and the share of unskilled workers. We use exogenous variation in carboniferous rock strata (containing coal to fuel the engines) to show that the effect was causal. Technological change had, however, no significant effect on basic educational training including literacy and school enrollment rates.

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1. Introduction

Was technological progress during the Industrial Revolution skill-demanding or skill-saving? Recent contributions in economic growh theory have argued for a positive effect of technical change on human capital formation during the transition towards 'modern economic growth' (e.g. Galor 2011). This notion has recently received empirical support from 19th-centry France (Franck and Galor 2016). Interestingly, the French evidence contrasts with the traditional narrative about the effects of early industrialisation in England, where earlier work have argued that skill-displacement was the main outcome of technological change. In particular, the classical years of England's Industrial Revolution were characterized by stagnant rates of male literacy (e.g. Schofield 1973; Nicholas and Nicholas 1992; Mitch 1999); a decline in the average years of secondary schooling (de Pleijt 2015); a growth in the share of unskilled workers (de Pleijt and Weisdorf 2017); and the absence of any increase of the skill premium (e.g. Clark 2005; Van Zanden 2009; Allen 2009). Combined with a long list of chronicles about machine-breaking riots, allegedly triggered by the workers' fears that industrialisation would render their skills redundant (Nuvolari 2002), the English case, at least *prima facie*, seems to provide support to the Goldin and Katz (1998) hypothesis that the shift from workshop to factory production reduced the need for skilled workers. But the effect of new technology on human capital formation during England's early Industrial Revolution has not been tested formally.

This study breaks new ground along three lines. First, previous work attempting to quantify the evolution of human capital in England during the Industrial Revolution has mainly focused on literacy and numeracy rates. However, though meticulously documented (Nicholas and Nicholas 1992; Mitch 1999; Baten et al. 2014), literacy and numeracy skills measure only very basic competencies. For example, the literacy rate assigns the same level of ability to a literate factory worker and a literate industrial engineer, with no distinction

being made between the large variations in aptitude required for these two very different occupations. Moreover, the fact that any literacy and numeracy skills obtained were not necessarily used productively, such as a factory worker's ability to read and write, makes the potential discrepancy between the *acquisition* of skills and the *application* of skills in productive activities a relevant matter and one which is difficult to address using basic competencies, such as literacy or numeracy, to measure human capital attainments.

In this study, thanks to early 19th-century occupational statistics provided by the *Cambridge Group for the History of Population and Social Structure* and documented in Shaw-Taylor et al (2012), we are able to classify over 2.6 million English male workers according to the skill-content of their work. This categorisation of occupational titles by skill, which is done by employing a standardised work-classification system (HISCO-HISCLASS), allows us to quantify the shares of unskilled, lower-skilled, medium-skilled, and highly-skilled workers by county and to explore the correlation between those shares and country-specific technological change. The occupational data also enable us to identify the so-called 'density in the upper tail of professional knowledge' and to examine whether or not the diffusion of new technology during the Industrial Revolution created a growing class of highly-skilled mechanical workers, as proposed in recent studies (e.g. Mokyr 2005; Mokyr and Voth 2009; Meisenzahl and Mokyr 2012; Squicciarini and Voigtländer 2015; Feldman and van der Beek 2016). In addition to working skills derived from occupations, we also make use of the more conventional indicators of human capital, including literacy rates and school enrolment rates.

Second, we employ a methodological approch proposed in Franck and Galor (2016) for historical France, taking it across the channel to England, the cradle of the Industrial Revolution and the frontrunner in modern economic growth. Franck and Galor used regional variation in the diffusion of steam technology to show that more steam engines were

associated with higher rates of literacy, more apprentices, more teachers, and more schools. Similar to Franck and Galor, we exploit county-level variation in the use of steam engines to investigate the effect of technological change on the process of human capital formation in the English case. Our steam dataset is an updated version, previously used in Nuvolari et al (2011), of that originally constructed by Kanefsky and Robey (1980). Containing detailed information about all known steam engines built and installed in England, from when the first steam engine prototype was patented by Thomas Savery, in 1698, up until 1800, this dataset represents the best quantitative appraisal of the early diffusion of steam power during England's Industrial Revolution (Nuvolari et al 2011).

Last but not least and in order to establish whether or not any observed effects were causal, we use exogenous county-level variation in the prevalence of carboniferous rock strata (Asch 2005) as an instrument for the number of steam engines. Because steam engines were run on coal, which is found in the carboniferous rock strata, we are able to exploit the fact that the share of a county's carboniferous rock strata is highly correlated with the number of steam engines installed by 1800, but that the prevalence of carboniferous rock is independent of our pre-steam indicators of human capital formation.

Our empirical analysis shows that steam technology was positively associated with working skills. More steam engines were linked to lower shares of unskilled workers and higher shares of lower- and medium-skilled workers. We also establish that more engines were connected with higher shares of highly-skilled mechanical workers, including engineers, various wrights, machine makers and instrument makers, representing the 'density in the upper tail of professional knowledge'. However, our analysis documents that the use of steam technology was either negatively associated with elementary education or had no significant effect hereon. That is, more steam engines were linked to fewer primary schools per person and lower school enrolment rates. Also, although more steam engines were not significantly

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associated with literacy rates, we observe that counties with comparatively many steam engines had comparatively higher gender inequality in literacy.

Using the prevalence of carboniferous rock strata as an instrument for the number of steam engines, we document that a one standard-deviation increase in the number of steam engines led to a 0.78 standard-deviation decrease in the share of unskilled workers. An equally large effect of the implementation of early steam technology concerned the demand for highly-skilled mechanical workmen, where we find that a one standard-deviation increase in the number of steam engines caused a 0.91 standard-deviation increase in the share of highly-skilled mechanical workers. We do not find any significant causal effects of steam engines on elementary schooling, except for a positive effect of steam on gender inequality in literacy. In particular, a one standard-deviation increase in the use of steam engines caused a 0.79 standard-deviation increase in gender inequality. Our findings are robust to accounting for a wide range of confounding factors, including county-level geographical characteristics and pre-industrial development performances, as well as the use of alternative mechanical powers, including cotton-, wool-, and water-mills.

The ambiguous effect of the Industrial Revolution on the demand for skills supports the pre-existing narrative that England's early industrialisation either harmed or had a neutral effect on elementary education (e.g. Nicholas and Nicholas 1992; Mitch 1999; de Pleijt 2015). At the same time, the observed effects show that early industry positively influenced the formation of formal working skills, particularly industry-specific ones, as pointed out in previous studies (e.g., Mokyr 2005; Mokyr and Voth 2009; Van Der Beek 2012; Feldman and van der Beek 2016). The observed results are in line with one of the key tenets of *Unified Growth Theory*, according to which technological progress during the Industrial Revolution prompted the creation of working skills (Galor and Weil 2000; Galor 2011). The ambiguous

nature of the findings also chime with theoretical work by O'Rourke et al (2013), arguing that early technological progress could be skill-saving and skill-demanding at the same time.

The remainder of our paper is organised as follows. Section 2 presents the steam engine data and the various indicators of human capital, as well as the confounding variables. Section 3 explains the identification strategy and presents the results of our baseline OLS and IV regressions. Section 4 demonstrates that the results are robust to introducing a wide range of confounding factors. Section 5 summarises the main findings.

2. Data

We use cross-county variation in the number of steam engines built and installed by 1800 as a proxy for industrial technological progress.[1] The data used is an updated version of the steam dataset originally constructed and published by Kanefsky and Robey (1980). The first steam engine included in the dataset is the famous so-called *atmospheric engine*, which was patented by Thomas Savery in 1698 and put to use in 1702 (Nuvolari et al 2011). During the second half of the eighteenth century, steam engines were increasingly employed, especially in the more innovative and dynamic branches of the English economy. By 1800 a total of 2,207 steam engines had been built and installed in England.

The intensity in the use of steam power varied considerably across the English counties, as shown in Figure 1. Not surprisingly, steam engines were very common in England's industrial centres, including Lancashire and West Yorkshire, each of which had over 250 engines installed by 1800. On the other hand, counties that were dominated by agriculture during the classical years of the industrial revolution, such as Dorset and Sussex, had no steam engines installed at all. Our basic assumption is that the intensity in steam power adoption at county level can be taken as a synthetic indicator of technical change,

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[1] A map illustrating the location of the counties can be found in Appendix 1.

including the complex mix of technological and organisational innovations related with the unfolding of the process of industrialisation. Steam engines were initially used to help drain water from the mines. But from the 1740s onwards steam technology was increasingly used in the two key "modernizing" sectors in Crafts-Harley's interpretation of the industrial revolution, i.e. the production of textiles and metals (Crafts and Harley, 2002). [2] By 1800, steam technology had also been adopted in the mechanization of other dynamic branches of manufacturing, including brewing and paper-making (Von Tunzelmann, 1978 and Von Tunzelmann, 1986).

Figure 1. The distribution of steam engines built and installed by 1800
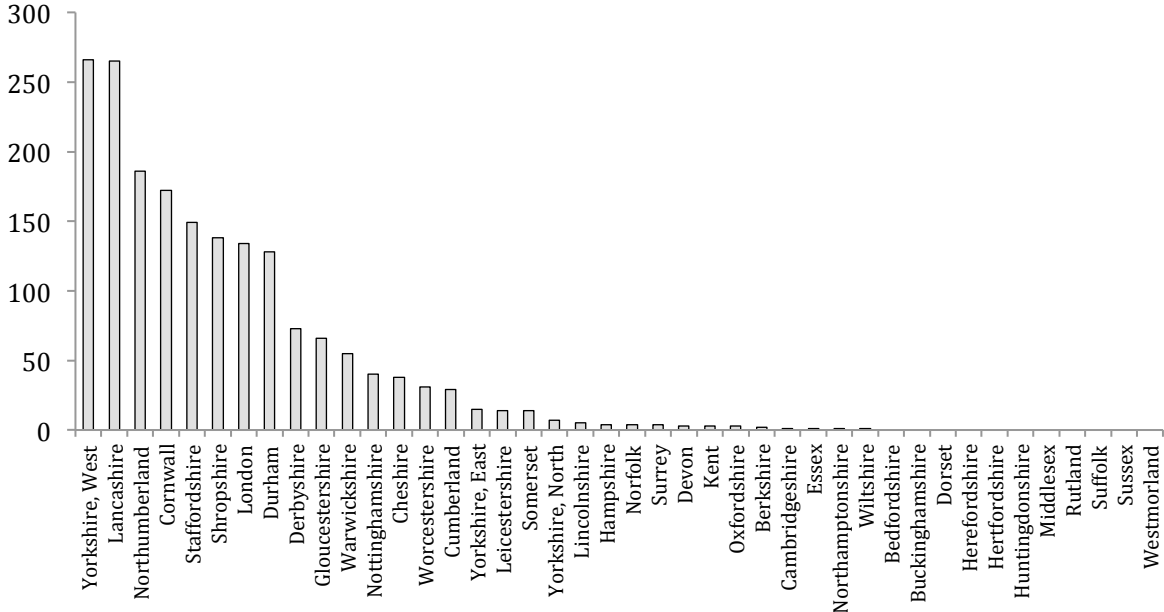
Source: Nuvolari et al (2011).

Turning to our outcome variables, human capital is measured in three different ways: (i) in terms of rates of elementary schooling among the workforce; (ii) as the share of skilled and unskilled workers; and (iii) finally as the density in the upper-tail of professional

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[2] The share of steam engines used in manufacturing and other sectors by 1800 was much larger than that used in mining, Kanefsky and Robey (1980, p.181).

knowledge, i.e. the share of highly-skilled mechanical workers deemed important for the Industrial Revolution. These three different sets of human capital variables are derived from three main sources: the Church of England baptismal registers of 1813-1820 (Shaw-Taylor et al 2006); an education census conducted in 1850 (Education Census 1851); and, finally, Stephens (1987).

Figure 2. Schools and day-school pupils per 1,000 population

(a) Schools per 1,000 persons, 1801 (b) Share of day-school pupils, 1818
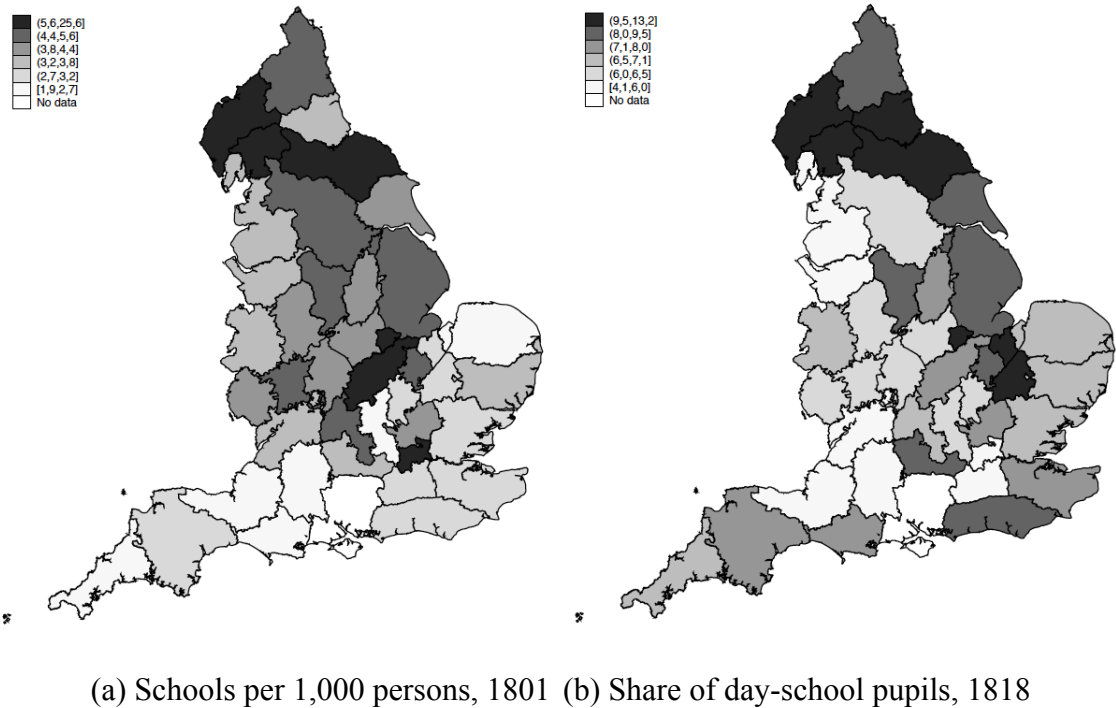
Sources: Educational Census of 1851. Population levels from Wrigley (2007).

Our first set of variables captures human capital formation associated with primary schooling. For this, two datasets of schooling are used: the number of day- and private schools existing in 1801 and the share of the population enrolled in day schooling in 1818. Both datasets are built from the Education Census (1851). Figure 2 (a) shows the number of schools per 1,000 persons, and Figure 2 (b) shows the number of day-school pupils per 1,000 persons. The correlation between the availability of primary schools per person and the share

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of pupils in the population is positive and highly significant.[3] The number of primary schools per person varied greatly across the English counties. For example, Westmorland, the northern neighbour of the industrial county of Lancashire, had five times more schools per person and three times more pupils compared to Lancashire. Conversely, Westmorland had no steam engines at all compared to Lancashire's 265 engines.

Since school enrolment rates and the number of schools per person do not necessarily capture the elementary school performance of the individuals involved, we also use the earliest available male and female literacy rates by county reported in Stephens (1987). These literacy rates are based on signatures on marriage certificates in 1841. Because marriage usually took place between the ages of 25 and 35 in this period (Schofield 1968), those who signed their certificate were expectedly born between 1806 and 1816. The male and female literacy rates by county are shown in Figure 3, which also illustrates gender inequality in literacy, i.e. the county-specific male literacy rate minus the female literacy rate.

Literacy in general was fairly widespread in Northern England, with three out of four men and two out of three women being able to sign their marriage contracts. Although literacy rates were lower in Southern England on average, the rates were still reasonably high: 60-70 per cent of all males and 50-60 per cent of all females had literacy skills. Central England, however, had comparatively low rates of literacy, especially the industrialised, western parts and particularly among women, with one out of three women being able to read and write. The poor literacy attainment among women in England's industrial centre is mirrored by the high rates of inequality in literacy between men and women. Indeed, the male literacy rates in Lancashire and West Yorkshire were 20-30 percentage points higher than those of females. In contrast, the counties surrounding London had less than 10 percentage-point gender differences and even sometimes higher literacy rates among women than men.

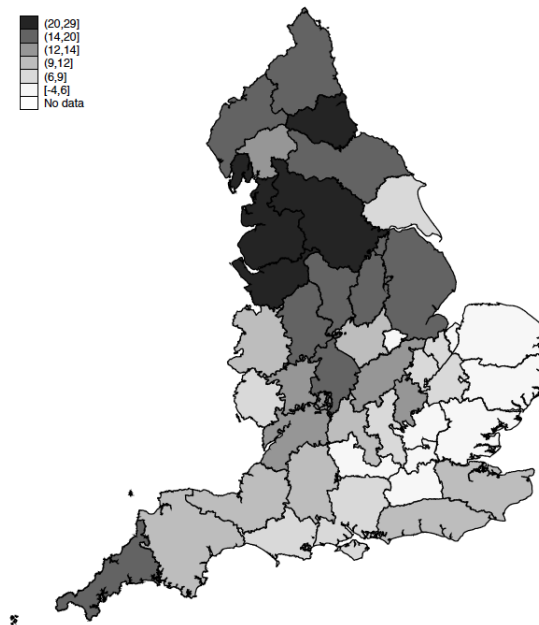[3] The correlation between the log of the number of primary schools in 1801 and the share of day-school pupils in 1818 is 0.59.

Figure 3. Literacy rates of individuals born c. 1806-1816
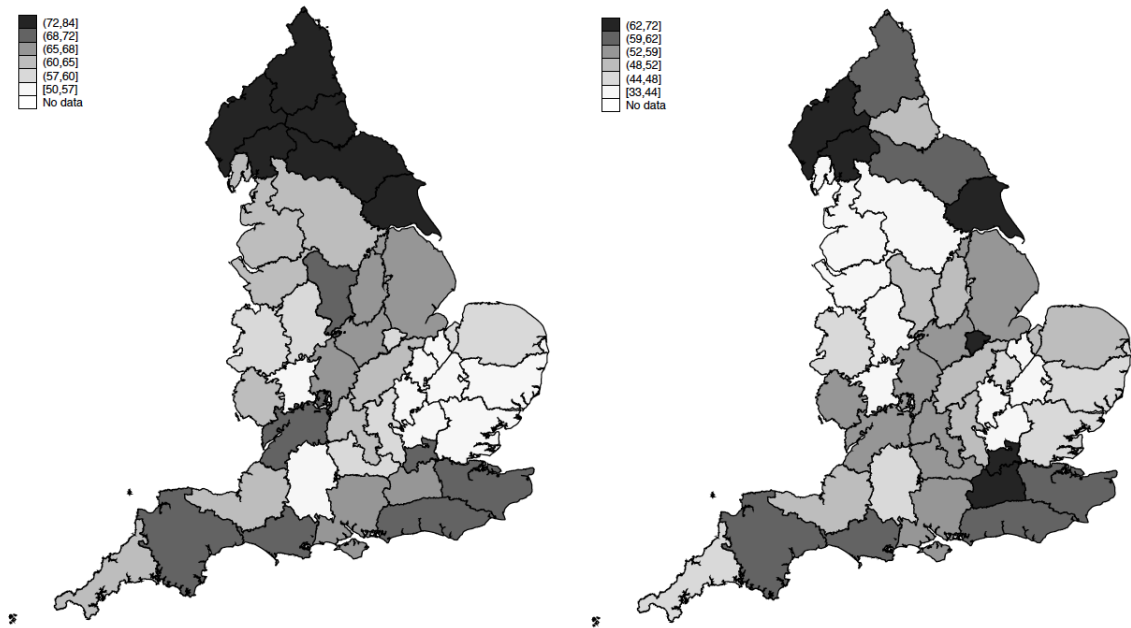
(a) Male literacy rates

(b) Female literacy rates

(c) Gender inequality in literacy

Note: Gender inequality is computed as the male literacy rate minus the female literacy rate. *Source*: Stephens (1987).

Our second set of indicators of human capital formation concerns working skills derived from occupational titles. For this, we use a well-known and standardised historical classification system, the HISCLASS scheme, to extract information about the working skills required in order to perform the job described by an occupational title, as explained in Maas and van Leeuwen (2011). The coding of occupational titles in the HISCLASS scheme is based on a worker's general educational development and concerns three features regarding the intellectual competencies necessary to fulfil the tasks of the worker's job: the worker's reasoning abilities; his or her ability to follow instructions; and his or her acquisition of the necessary language and mathematical skills needed to conduct the work. It also assesses the worker's specific vocational training, which covers the time-investment needed in three main areas: the time required by the worker to learn the techniques necessary for carrying out the job; the time needed to acquire the relevant information to conduct the work; and the time needed to develop the competencies required for an average performance in a job-specific working situation. Based on these considerations, the HISCLASS scheme organises several thousand distinct historical occupational titles into four groups: highly-skilled, medium-skilled, lower-skilled, and unskilled workers. For example, a labourer is classified as an unskilled worker in HISCLASS; a weaver is lower-skilled; a carpenter is medium-skilled; and a lawyer is highly-skilled.

The occupational titles used for the analysis have been collected from Anglican parish registers by the *Cambridge Group for the History of Population and Social Structure* and are described in Shaw-Taylor et al (2006). The system of baptismal registration, introduced by the English parliament in 1813, required the occupation of the father of the baptised child to be recorded by the Anglican Church. This enabled the Cambridge Group to build an early occupational census covering the whole of England in the period between 1813 and 1820 including 10,528 parishes. The data report the individual occupational titles of over 2.6

million adult males. Out of these we were able to classify some 1,700 distinct titles into one of the four skill-categories described above, covering 99 per cent of the sampled adult males.[4]

Figure 4 (a)-(d) shows the distribution of the working skill, by county, for each of the four skill-categories. The overall patterns of the geographical distribution of working skills were rather clear. Unskilled work (panel a) was more prevalent in South-East England and was also concentrated to the north-west of London. For example, the agricultural county of Hertfordshire, situated north of London, had 60 per cent of its workforce coded as unskilled. By contrast, the industrial county of Cheshire had half as many coded as such, i.e. some 30 per cent. Lower- and medium-skilled work displayed a geographical pattern rather opposite to that concerning unskilled work. Lower-skilled work (panel b) was mostly concentrated in the west of England, particularly in the industrial centres and to the far north. The same is true of medium-skilled work (panel c), which is also found in the industrial counties, with a very high prevalence in Yorkshire West Riding. Unlike lower- and medium-skilled work, however, highly-skilled work (panel d) was rather uncommon in England's industrial centre and was mostly a Southern England phenomenon, concentrated in Devon and south of London.

Two more indicators of human capital formation are introduced in order to try to measure the industry-specific training of workers. The first measure concerns the share of highly-skilled mechanical workmen. This is based on work by Mokyr and collaborators, who have emphasised the importance of 'the density in the upper tail of professional knowledge' vis-à-vis the average level of human capital present in the workforce (Mokyr 2005; Mokyr and Voth 2009; Feldman and Van Der Beek 2016). To follow Meisenzahl and Mokyr (2012), it was not the average level of human capital that was important in the process of industrialisation, but rather the upper tail of the human capital distribution, i.e. technological change and the adoption of machinery affected the demand for high-quality workmen such as

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[4] 'Gentleman', 'Esquire', 'Pauper', 'Widower' and 'Slave' were excluded from the original data set. These titles, which make up some one per cent of the sampled population, do not refer to an actual profession and hence cannot be coded using the HISCLASS scheme.

engineers, mechanics, wrights, instrument makers, and chemists. These highly-educated workers supported innovation and helped bring about the Industrial Revolution.

Figure 4. Working skills from occupations, 1813-20

(a) Share of unskilled workers

(b) Share of low-skilled workers

(c) Share of medium-skilled workers

(d) Share of high-skilled workers
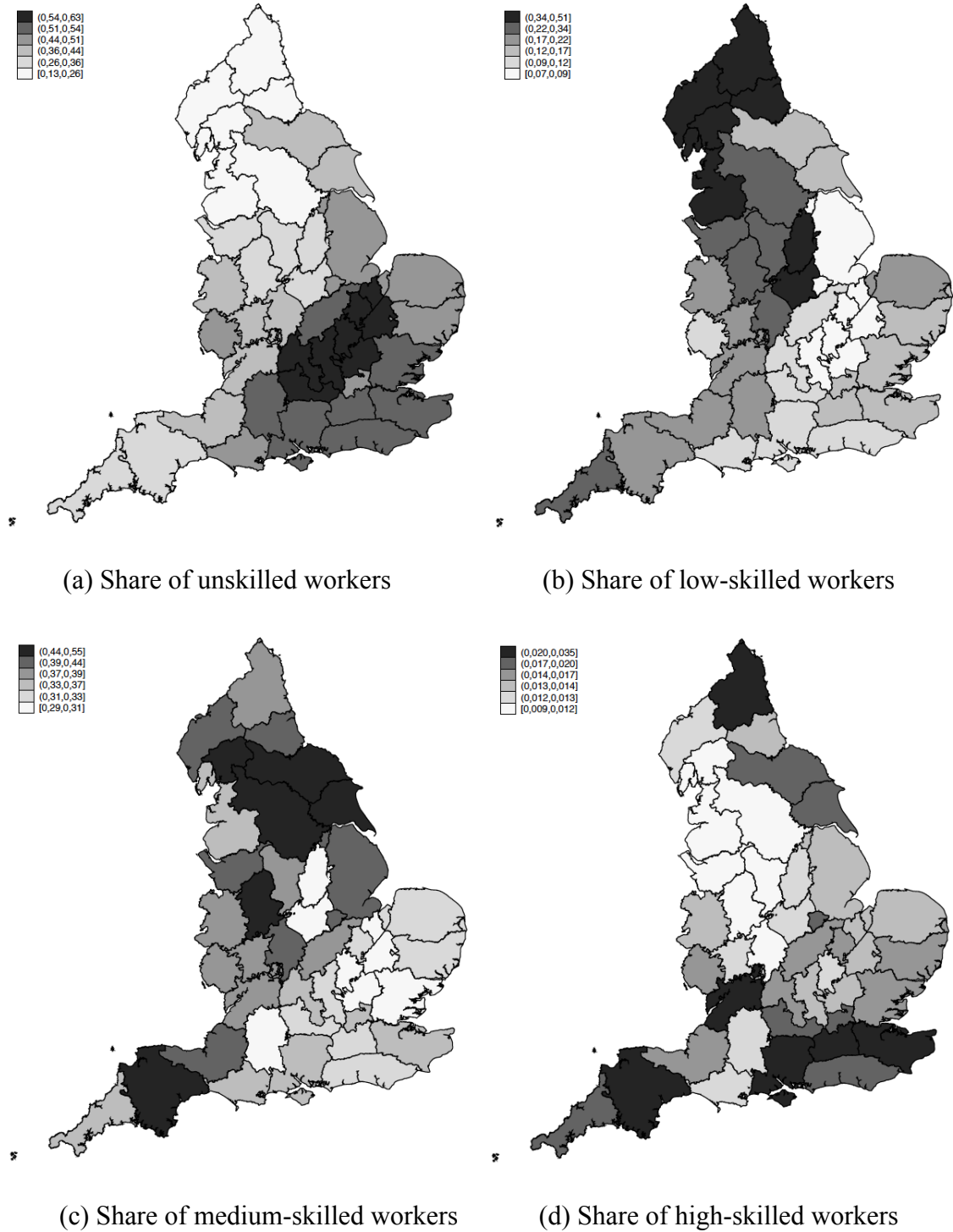
Note: Working skills are derived using the HISCLASS scheme (see text). *Source*: Shaw-Taylor et al (2006).

Figure 5. Share of industry-specific occupational skills, 1813-1820

(a) Share of highly-skilled mechanical workers   (b) Share of skilled workers in industry
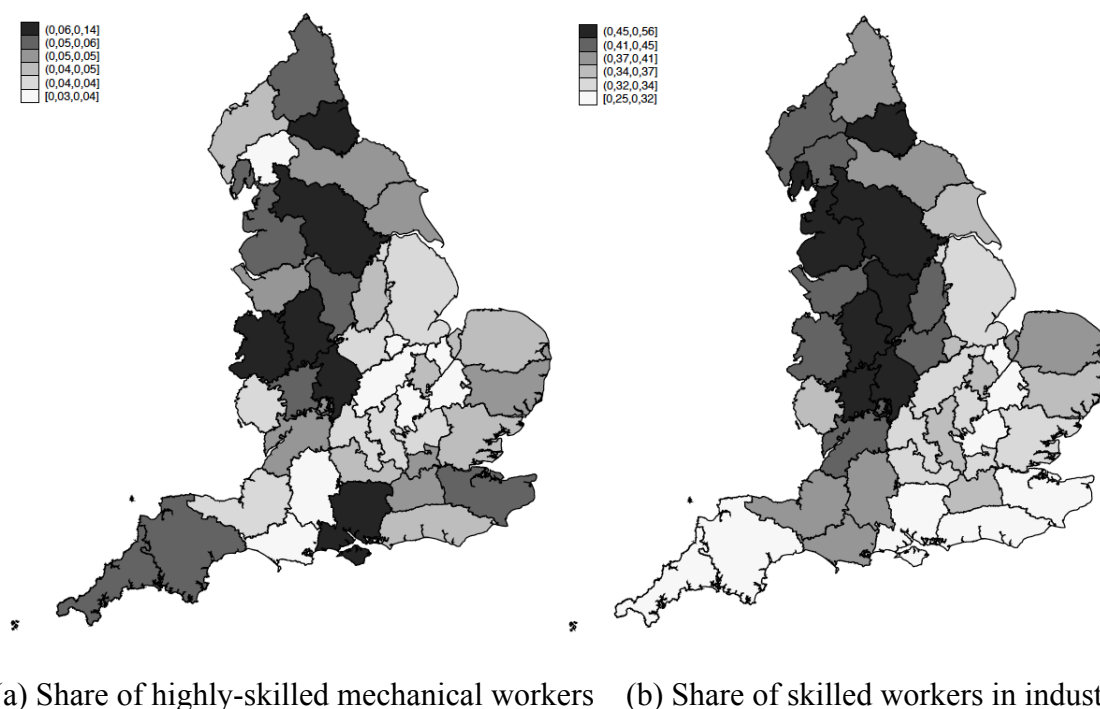
Note: A full list of the highly-skilled mechanical occupations can be found in Appendix 2. Working skills from the secondary sector are derived using the HISCO/HISCLASS scheme (see text) *Source*: Shaw-Taylor et al (2006).

Feldman and Van Der Beek (2016) have defined a specific set of mechanical professions that would enable this. Based on the occupational titles found in the baptismal data mentioned above, we have computed the shares, by county, of all the professions mentioned in their article (see the full list of occupational titles in Appendix 2). Figure 5a illustrates the shares, showing that highly-skilled non-routine mechanical workmen were typically (though not exclusively) concentrated in England's early industrial counties, including Lancashire, West Yorkshire, and Shropshire. Consistent with the theory of Mokyr and others, counties that were more agricultural, such as Kent, Surrey, and Sussex, had lower shares of those workmen.

Lastly, in order to capture skill formation in the industrial sector only, we have also restrict the labour force to those workers that according to the HISCO system are classified as

belonging to the secondary (i.e. industrial) sector. Their shares, by county, are illustrated in Figure 5b and appear to concentrate in England's industrial centres.

Our regression analysis below accounts for the confounding geographic and institutional characteristics of each county, as well as their pre-industrial developments. All of these characteristics may have contributed to industrialisation, as well as to the formation of human capital. In particular, pre-industrial developments, such as the early growth of cities or the prevalence of pre-industrial schools, may have helped encourage industrialisation and education independently. Our first set of control variables capture the geographical characteristics of the English counties. Specifically, regional differences in geography linked to land quality and agricultural output may have affected the process of industrialisation helping the adoption of steam engines. Land quality and output may also have affected landownership and landowners' attitudes regarding educational institutions and hence the human capital formation of workers (Galor and Vollrath 2009). Our analysis accounts for this by controlling for land quality, measured by land rents (Clark 2002), as well as climatic characteristics, captured by average rainfall and temperatures.[5] Figure 6 (a)-(c) shows the county-level variation in rainfall, temperature, and land rents. Rainfall was high in the west of England and temperatures were high in the south, whereas the quality of land shows no distinct geographical pattern. Our analysis also controls for the latitude of each county, measured in the location of the counties' administrative centres. A list of the administrative centres is found in Appendix 3.

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[5] From: http://www.metoffice.gov.uk/.

Figure 6. Geographical control variables
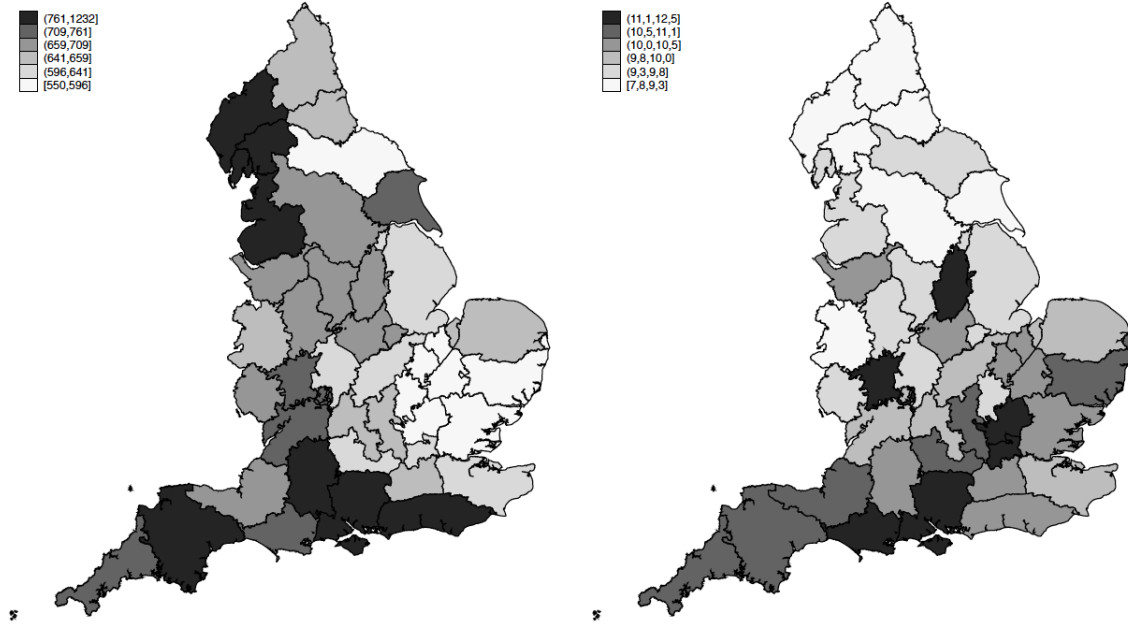
(a) Average rainfall

(b) Average temperature

(c) Average land quality

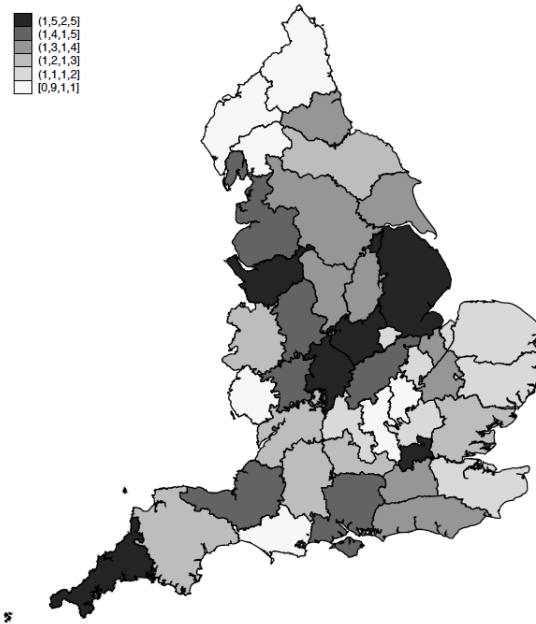*Note*: The average land quality is proxied by average land rents. *Sources*: Rainfall and temperature: http://www.metoffice.gov.uk/. Soil quality measured by land rents: Clark (2002).

We also control for effects that might emerge as a result of the geographical location of a county vis-à-vis the possibilities for foreign influences. Trade or various forms of cultural impacts, stemming from contacts with non-nationals, may have stimulated the development of industry or the formation of human capital. Our analysis controls for this by using dummy variables accounting for counties that were bordering other countries (i.e. Wales or Scotland) or had access to the sea (Maritime). Our study also controls for political institutions and their influences on industry and human capital formation. For example, the English Parliament, located in London, may have exercised a stronger influence on nearby counties than on countries situated further away. The analysis accounts for such effects using dummy variables for the counties surrounding London (i.e. Essex, Hertfordshire, Kent, Middlesex, and Surrey) and for the aerial distance (in km) from London to the administrative centre of each county.

Finally, our study controls for the potential confounding effects stemming from regional variation in developments achieved during the pre-industrial period. Counties that had many primary and secondary schools (see Figures 7a and 7b) may have had higher levels of pre-industrial human capital than others. Similarly, counties that were more urbanised before the Industrial Revolution (see Figure 7c) may have been more likely to industrialise or to successfully attract human capital. We therefore control for these pre-industrial developments by accounting for the county-specific numbers of primary schools, taken from the Schools Inquiry Commission (1868a), and secondary schools, taken from Schools Inquiry Commission (1868b). We also control for the urbanisation ratio in 1700, which is defined as the population in cities with more than 5,000 inhabitants divided by the total population. These numbers were provided in Bosker et al (2012).

Figure 7. Pre-industrial developments
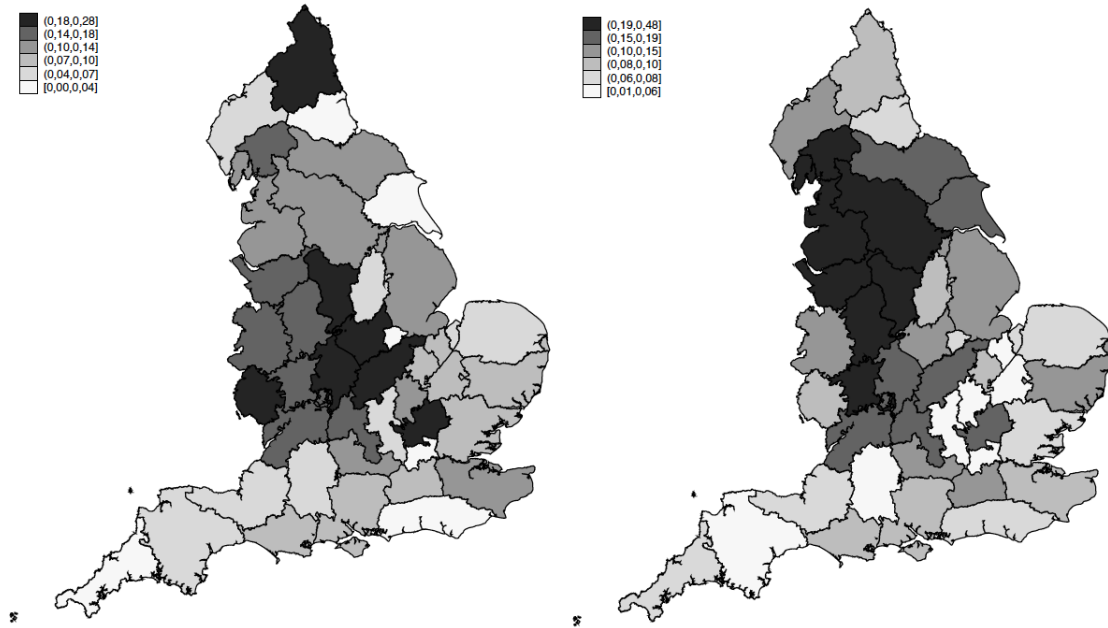
(a) Primary schools per 1,000 person, 1700   (b) Secondary schools per 1,000 person, 1700
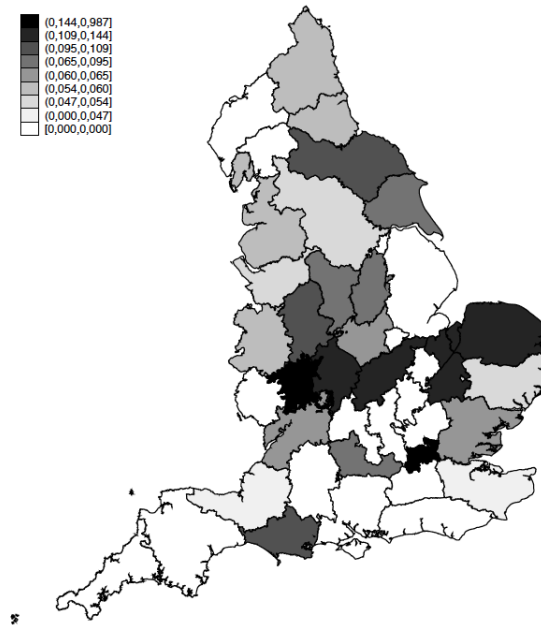
(c) Urbanisation ratio, 1700

Note: The urbanisation ratio is the population in cities with more than 5,000 inhabitants divided by the total population. *Sources*: Primary schools from Schools Inquiry Commission (1868a) and secondary schools from Schools Inquiry Commission (1868b). Urbanisation rates from Bosker et al (2012).

3. Empirical analysis

What was the effect of early industrialisation on human capital formation in England? To find out, we explore the empirical relationship between the county-level distribution of steam engines and the indicators of human capital described above, while controlling for confounding factors. Of course, an observed relationship between industrialisation and human capital formation is not necessarily causal. The process of industrialisation and that of human capital formation may have taken place independently, governed by common forces of economic development. In order to deal with this potential issue of endogeneity, we use exogenous variation in the distribution of carboniferous rock strata as an instrument for the number of steam engines installed by 1800. Coal is often found in rock strata from the Carboniferous age (360 to 300 million years ago). During this era, large forests covered the areas that later on formed the earth's coal layers. Coalfields therefore habitually emerged near to rock strata from the Carboniferous epoch. Crafts and Malutu (2006) have shown that coal abundance mattered for the location of steam-intensive industries, and Fernihough and O'Rourke (2014) that it linked to industry. For instance, due to its absence of coal, the county of Dorset was unable to compete with counties such as Lancashire and as a result remained largely rural up until the present (Cullingford 1980). Below we will use the fact that the share of a county's carboniferous rock strata is highly correlated with the number of steam engines built and installed by 1800, but that the concentration of rock is independent of the indicators of pre-industrial development.

Figure 8. Steam engine and carboniferous rock strata

(a) Number of steam engines in 1800	(b) Share of carboniferous rock strata
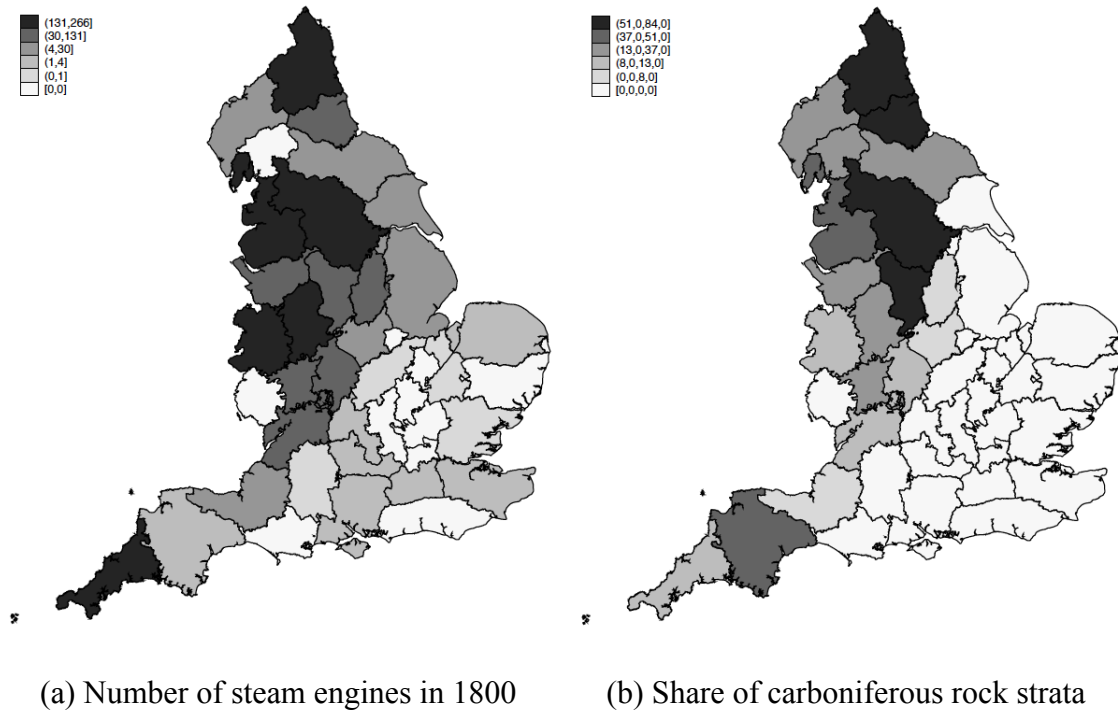
Sources: Steam engines by county: Nuvolari et al (2011). The share of rock strata by county were computed based on Asch (2005).[6]

Figure 8 (a) illustrates the county-specific distribution of steam engines and Figure 8 (b) gives the share of the counties covered by carboniferous rock. Table 1 shows the statistical relationship of the two variables, confirming that it was positive and strongly significant, also after controlling for the confounding effects of geography, institutions, and pre-industrial developments described above. Specifically, using standardized coefficients, we observe that a one standard-deviation increase in the share of carboniferous rock strata is associated with a 0.59 standard-deviation increase in the log of the number of steam engines (via the coefficient in Column (7)).[7]

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[6] We are thankful to Alan Fernihough for preparing the data for us.

[7] Because some counties had zero engines (see Figure 1), the number of engines were log transformed using the formula: ln(x+1). The regression results presented in this section do not change when controlling for small sample size.

Table 1. Steam engine and carboniferous rock strata

	OLS (1)	OLS (2)	OLS (3)	OLS (4)	OLS (5)	OLS (6)	OLS (7)
			Log number of steam engines installed by 1800				
Share Carboniferous	6.658***	6.473***	5.841***	5.835***	5.850***	6.176***	6.251***
	(6.48)	(4.06)	(3.58)	(3.48)	(3.55)	(3.88)	(3.91)
							[0.562]
Rainfall		-0.290	-0.919	-0.911	-1.011	-0.928	-0.867
		(-0.15)	(-0.58)	(-0.56)	(-0.57)	(-0.60)	(-0.48)
Temperature		0.145	1.983	1.977	2.002	1.308	1.223
		(0.04)	(0.50)	(0.49)	(0.50)	(0.32)	(0.30)
Latitude		7.931	4.060	4.024	3.456	4.537	5.630
		(0.44)	(0.22)	(0.22)	(0.18)	(0.25)	(0.28)
Land rents		3.781**	4.898***	4.904***	4.886***	5.800***	5.902***
		(2.51)	(3.36)	(3.37)	(3.28)	(3.06)	(3.28)
Maritime border			-0.213	-0.206	-0.196	-0.177	-0.240
			(-0.52)	(-0.46)	(-0.44)	(-0.43)	(-0.52)
International border			1.189	1.180	1.193	1.288	1.360
			(1.53)	(1.44)	(1.49)	(1.52)	(1.31)
London and surroundings			1.231	1.230	1.218	0.856	0.831
			(1.29)	(1.28)	(1.30)	(1.26)	(1.15)
Distance to London			0.692	0.692	0.686	0.377	0.343
			(1.32)	(1.30)	(1.32)	(0.92)	(0.80)
Primary schools, 1700				0.143			-0.967
				(0.04)			(-0.23)
Secondary schools, 1700					0.476		-0.611
					(0.11)		(-0.11)
Urbanisation ratio, 1700						-1.907	-2.184
						(-0.75)	(-0.84)
Constant	1.423***	-29.52	-18.08	-17.99	-15.15	-16.91	-21.11
	(5.33)	(-0.38)	(-0.23)	(-0.22)	(-0.17)	(-0.21)	(-0.24)
r2	0.387	0.559	0.639	0.639	0.639	0.650	0.651
N	42	42	42	42	42	42	42

Notes: All variables are in logarithm, using ln(x+1), except rates and dummies. Primary and secondary schools in 1700 are per 1,000 persons. The counties surrounding (i.e. bordering) London are Berkshire, Buckinghamshire, Essex, Hertfordshire, Kent, and Surrey. *T*-statistics are reported in round brackets; standardized coefficient in square brackets. Standard errors are robust to control for heteroskedasticity. *** indicates significance at the 1% level; ** at the 5% level; and * at the 10% level. *Sources*: see text.

With the exception of land rents, which were positively linked to the use of steam engines, none of the confounding variables, including those capturing pre-industrial development, are significantly associated with the adoption of steam. Moreover, consistent

with this relationship, the three counties with the most steam engines, i.e. West Yorkshire, Lancashire, and Northumberland, had some of the highest share of carboniferous rock, ranging between 50 and 80 per cent of the county's surface area. There were 15 counties that had more than 20 steam engines, and only one of these had no carboniferous rock. For each of the remaining 14 counties, at least one third of the area had carboniferous rock strata. By contrast, 10 out of those 11 counties that had no steam engines also had no carboniferous rock at all (see also Figure 1).

Table 2. Carboniferous rock strata and pre-industrial developments

	OLS (1) Primary schools, 1700	OLS (2) Secondary schools, 1700	TOBIT (3) Urbanisation ratio, 1700
Share carboniferous	0.0399	-0.0188	0.176
	(0.67)	(-0.30)	(1.22)
Rainfall	-0.0569	0.193**	-0.00468
	(-0.89)	(2.44)	(-0.05)
Temperature	0.0387	-0.0410	-0.354
	(0.22)	(-0.23)	(-1.20)
Latitude	0.256	1.271*	0.250
	(0.36)	(2.00)	(0.22)
Land rents	-0.0452	0.0253	0.473***
	(-0.76)	(0.37)	(3.20)
Maritime border	-0.0475**	-0.0363**	0.0186
	(-2.44)	(-2.05)	(0.58)
International border	0.0655**	-0.00874	0.0519
	(2.49)	(-0.28)	(1.07)
London and surroundings	0.0123	0.0276	-0.197**
	(0.38)	(0.81)	(-2.31)
Distance to London	0.00348	0.0130	-0.165***
	(0.17)	(0.59)	(-3.30)
Constant	-0.631	-6.158**	0.612
	(-0.19)	(-2.10)	(0.12)
Sigma			0.105***
			(8.01)
r2	0.310	0.484	
N	42	42	42

Notes: All variables are in logarithm, using ln(x+1), except rates and dummies. Primary and secondary schools in 1700 are per 1,000 persons. *T*-statistics are reported in round brackets. Standard errors are robust to control for heteroskedasticity..*** indicates significance at the 1% level; ** at the 5% level; and * at the 10% level. *Sources*: see text.

The validity of using the distribution of carboniferous rock as an instrument for the distribution of steam engines is increased by the fact that rock strata is not significantly correlated with pre-industrial developments. Table 2 shows that there is no statistically significant association between the share of carboniferous rock and the number of primary schools per 1,000 person in 1700 (Column 1); the number of secondary schools per 1,000 person in 1700 (Column 2); or the urbanisation ratio in 1700 (Column 3). Table 2 also shows why it is vital to control for geography and institutions, which in many cases link to pre-industrial development.

Our 2SLS analysis is a cross-sectional estimate of the relationship between the number of steam engines installed in each county by 1800 and our proxies for human capital:

$$H_{it} = \alpha + \beta E_i + \boldsymbol{X'}_i \ \gamma + \varepsilon_{it}, \tag{1}$$

where H_{it} is the level of human capital of county i in year t; E_i is the log of the number of steam engines of county i in 1800; $\boldsymbol{X'}_i$ is a vector of geographical, institutional and pre-industrial economic characteristics of county i; and ε_{it} is the error term of county i in year t.

In the first stage, the log of the number of steam engines is instrumented by the share of the county's carboniferous area:

$$E_i = \emptyset_1 CS_i \ + \boldsymbol{X'}_i \ \emptyset_2 + \mu_i, \tag{2}$$

where CS_i is the share of the county i's area covered by carboniferous rock; $\boldsymbol{X'}_i$ is the vector of control variables included in equation (1); and μ_i is the error term. The standard errors are robust to control for the possibility of heteroskedasticity.

3.1 Working skills

We now turn to the regression results. We begin by looking at the effect of steam technology on working skills. Table 3 shows a strong relationship between new technology and workers' average skill-achievements. In the unconditional analysis, reported in Column (1), steam engines and the share of unskilled workers were negatively and significantly associated at the one per cent level. The negative relationship is illustrated in Figure 9.

Figure 9. The shares of unskilled workers and the numbers of steam engines
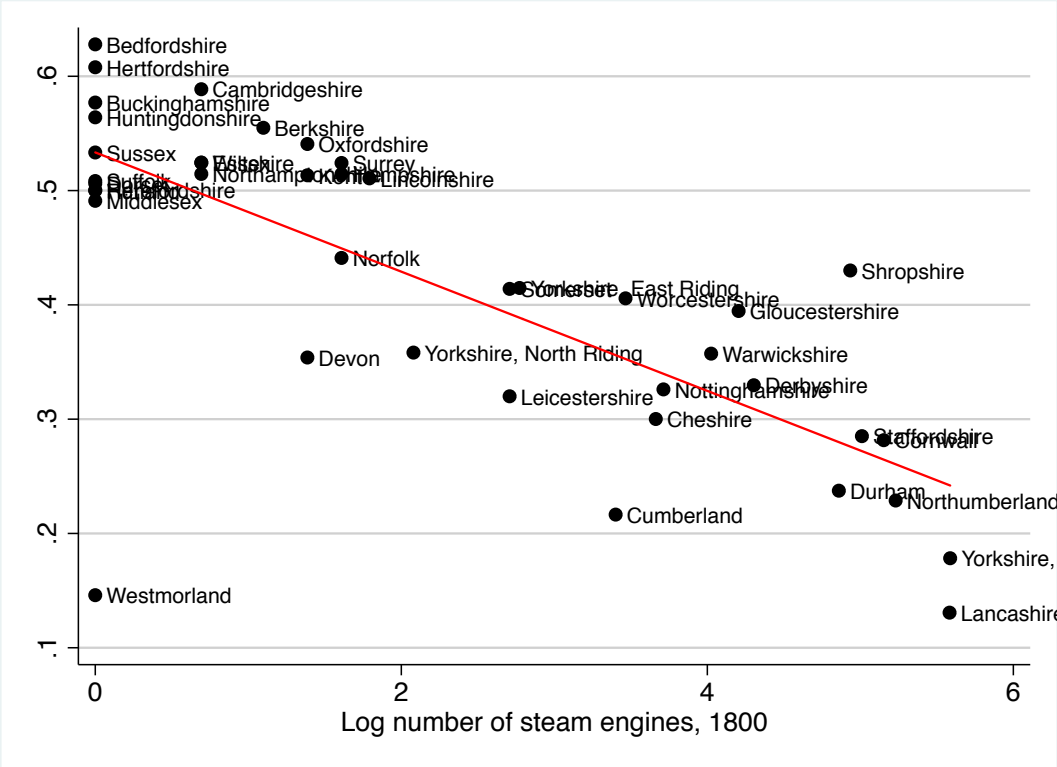
Note: Some counties had zero engines. The formula used to log transform the number of steam engines was ln(x+1). *Sources*: see text.

Table 3. The effect of industrialisation on the share of unskilled workers

	OLS	OLS	OLS	OLS	IV	IV
	(1)	(2)	(3)	(4)	(5)	(6)
	Share of unskilled workers, 1813-1820					
Log of steam engines	-0.0540***	-0.0375***	-0.0391***	-0.0401***	-0.0621***	-0.0563***
	(-6.97)	(-4.96)	(-5.68)	(-6.00)	(-4.16)	(-5.16)
						[-0.775]
Controls:						
Geography	No	Yes	Yes	Yes	Yes	Yes
Institutions	No	No	Yes	Yes	Yes	Yes
Pre-industrial	No	No	No	Yes	No	Yes
Constant	0.535***	10.57***	10.65***	8.355***	7.574**	6.004**
	(21.01)	(4.27)	(4.22)	(3.03)	(2.29)	(1.97)
r2	0.588	0.837	0.842	0.881	0.788	0.854
N	42	42	42	42	42	42
F-statistic					12.79	15.31

Notes: All variables are in logarithm, using ln(x+1), except rates and dummies. *T*-statistics are reported in round brackets; standardized coefficient is reported in square brackets; *F*-statistics report on the strength of the instrument. Standard errors are robust to control for heteroskedasticity. *** indicates significance at the 1% level; ** at the 5% level; and * at the 10% level. *Sources*: see text.

The coding of occupations into a total of four skill categories allows us to investigate the deeper relationship between steam engines and working skills. Tables 4 and 5 show the results of regressing the steam engines and their instrument on the shares of lower- and medium-skilled workers, respectively. Column (6) of Tables 4 and 5 reports, in terms of standardized coefficients, that a one standard-deviation change in the number of steam engines increased the shares of lower- and medium-skilled workers by 0.62 and 0.63 standard-deviations, respectively, establishing that industrialisation led to the formation of both lower- and medium-level work-related human capital. Although the estimated effect of steam on the share of higher-skilled workers was generally positive, Table 6 shows it was not significantly influenced by steam technology.

Table 4. The effect of industrialisation on the share of lower-skilled workers

	OLS	OLS	OLS	OLS	IV	IV
	(1)	(2)	(3)	(4)	(5)	(6)
	Share of low-skilled workers, 1813-1820					
Log of steam engines	0.0383***	0.0268***	0.0285***	0.0284***	0.0384***	0.0346***
	(5.65)	(4.30)	(4.87)	(4.69)	(3.61)	(3.72)
						[0.622]
Controls:						
Geography	No	Yes	Yes	Yes	Yes	Yes
Institutions	No	No	Yes	Yes	Yes	Yes
Pre-industrial	No	No	No	Yes	No	Yes
Constant	0.110***	-10.79***	-11.03***	-11.70***	-9.711***	-10.79***
	(6.34)	(-4.26)	(-4.33)	(-4.00)	(-4.12)	(-3.94)
r2	0.501	0.771	0.779	0.792	0.763	0.786
N	42	42	42	42	42	42
F-statistic					12.79	15.31

Notes: All variables are in logarithm, using $\ln(x+1)$, except rates and dummies. *T*-statistics are reported in round brackets. Standardized coefficient is reported in square brackets. *F*-statistics report on the strength of the instrument. Standard errors are robust to control for heteroskedasticity. *** indicates significance at the 1% level; ** at the 5% level; and * at the 10% level. *Sources*: see text.

Table 5. The effect of industrialisation on the share of medium-skilled workers

	OLS	OLS	OLS	OLS	IV	IV
	(1)	(2)	(3)	(4)	(5)	(6)
	Share of medium-skilled workers, 1813-1820					
Log of steam engines	0.0157***	0.0103*	0.0102*	0.0113*	0.0228**	0.0210**
	(3.21)	(1.82)	(1.70)	(1.73)	(1.96)	(2.25)
						[0.631]
Controls:						
Geography	No	Yes	Yes	Yes	Yes	Yes
Institutions	No	No	Yes	Yes	Yes	Yes
Pre-industrial	No	No	No	Yes	No	Yes
Constant	0.339***	0.827	0.925	3.976	2.616	5.386*
	(26.97)	(0.34)	(0.36)	(1.65)	(0.81)	(1.86)
r2	0.238	0.449	0.453	0.582	0.375	0.536
N	42	42	42	42	42	42
F-statistic					12.79	15.31

Notes: All variables are in logarithm, using $\ln(x+1)$, except rates and dummies. *T*-statistics are reported in round brackets. Standardized coefficient is reported in square brackets. *F*-statistics report on the strength of the instrument. Standard errors are robust to control for heteroskedasticity. *** indicates significance at the 1% level; ** at the 5% level; and * at the 10% level. *Sources*: see text.

Table 6. The effect of industrialisation on the share of highly-skilled workers

	OLS (1)	OLS (2)	OLS (3)	OLS (4)	IV (5)	IV (6)
	Share of highly-skilled workers, 1813-1820					
Log of steam engines	-0.000081	0.000429	0.000372	0.000383	0.00084	0.000544
	(-1.17)	(0.78)	(0.88)	(1.05)	(0.63)	(0.93)
Controls:						
Geography	No	Yes	Yes	Yes	Yes	Yes
Institutions	No	No	Yes	Yes	Yes	Yes
Pre-industrial	No	No	No	Yes	No	Yes
Constant	0.0160***	0.396***	0.453***	0.374***	0.515***	0.397***
	(17.20)	(1.85)	(2.40)	(2.07)	(2.38)	(2.17)
r2	0.001	0.319	0.528	0.602	0.515	0.6
N	42	42	42	42	42	42
F-statistic					12.79	15.31

Notes: All variables are in logarithm, using ln(x+1), except rates and dummies. *T*-statistics are reported in round brackets. *F*-statistics report on the strength of the instrument. Standard errors are robust to control for heteroskedasticity. *** indicates significance at the 1% level; ** at the 5% level; and * at the 10% level. *Sources*: see text.

One reason for the lack of a significant effect between steam technology and the share of highly-skilled workers could be that many highly-skilled jobs, e.g. accountants, doctors, and lawyers, were not directly related to the Industrial Revolution, but rather to the expansion of the tertiary sector. In order to focus on those occupations that could be expected to be closely related to the process of early industrialisation, we run two additional analyses. The first regresses the shares of skilled workers on steam engines, but it considers only those occupations that belonged to the secondary (i.e. industrial) sector, including occupational titles such as 'cooper', 'weaver', 'spinner', 'dyer' etc. Table 7 reports the results, finding that the coefficient on the log of the number of steam engines is statistically significant at the 1% level in all regressions. Column (6) shows, when reported in terms of standardized coefficients, that a one standard-deviation increase in the number of steam engines led to a 0.62 standard-deviation increase in the share of skilled workers in the secondary sector.

Table 7. The effect of industrialisation on the share of skilled workers employed in industry

	OLS (1)	OLS (2)	OLS (3)	OLS (4)	IV (5)	IV (6)
			Share of skilled workers in industry, 1813-1820			
Log of steam engines	0.0240***	0.0211***	0.0213***	0.0215***	0.0259***	0.0249***
	(4.24)	(2.92)	(2.90)	(2.90)	(3.02)	(3.59)
						[0.623]
Controls:						
Geography	No	Yes	Yes	Yes	Yes	Yes
Institutions	No	No	Yes	Yes	Yes	Yes
Pre-industrial	No	No	No	Yes	No	Yes
Constant	0.333***	-3.647	-4.172	-2.027	-3.562	-1.539
	(32.25)	(-1.06)	(-1.29)	(-0.52)	(-1.25)	(-0.50)
r2	0.394	0.477	0.579	0.623	0.571	0.619
N	42	42	42	42	42	42
F-statistic					12.79	15.31

Notes: All variables are in logarithm, using ln(x+1), except rates and dummies. *T*-statistics are reported in round brackets. Standardized coefficient is reported in square brackets. *F*-statistics report on the strength of the instrument. Standard errors are robust to control for heteroskedasticity. *** indicates significance at the 1% level; ** at the 5% level; and * at the 10% level. *Sources*: see text.

The second analysis considers the suggestions made by Mokyr (2005), Mokyr and Voth (2009) and Meisenzahl and Mokyr (2012) that the Industrial Revolution in England prompted the formation of highly-skilled mechanical occupations. The results of regressing the share of those workers (listed in Appendix 2) on steam engines and their instrument are reported in Table 8. The analysis shows that there was a positive association between industry and the share of highly-skilled mechanical workers, and that this effect is strongly significant, also after controlling for the confounding effects of geography, institutions, and pre-industrial developments (Columns 1 to 6). The IV estimation shows that the effect is causal and, reported in terms of standardized beta coefficients, that a one standard-deviation increase in the log of the steam engines led to a 0.91 standard-deviation increase in the share of highly-skilled mechanical occupations.

Table 8. The effect of industrialisation
on the share of highly-skilled mechanical occupations

	OLS	OLS	OLS	OLS	IV	IV
	(1)	(2)	(3)	(4)	(5)	(6)
	Share of highly-skilled mechanical workers, 1813-1820					
Log of steam engines	0.00730***	0.00858***	0.00918***	0.00914***	0.0129***	0.0112***
	(4.48)	(4.20)	(4.40)	(4.46)	(3.30)	(3.36)
						[0.909]
Controls:						
Geography	No	Yes	Yes	Yes	Yes	Yes
Institutions	No	No	Yes	Yes	Yes	Yes
Pre-industrial	No	No	No	Yes	No	Yes
Constant	0.0370***	1.29	1.196	1.583	1.698*	1.877**
	(17.73)	(1.57)	(1.50)	(1.57)	(1.83)	(2.08)
r2	0.383	0.500	0.524	0.582	0.473	0.567
N	42	42	42	42	42	42
F-statistic					12.79	15.31

Notes: All variables are in logarithm, using ln(x+1), except rates and dummies. *T*-statistics are reported in round brackets. Standardized coefficient is reported in square brackets. *F*-statistics report on the strength of the instrument. Standard errors are robust to control for heteroskedasticity. The occupation are found in Appendix 2. *** indicates significance at the 1% level; ** at the 5% level; and * at the 10% level. *Sources*: see text.

3.2 Elementary education

Having established the positive and significant effect of steam engines on work-specific human capital formation, we now turn our attention to their effect on elementary schooling. Table 9 reports the result of regressing the number of steam engines installed by 1800 on the number of primary schools per 1,000 inhabitants existing in 1801. Although the point estimates are significant and negative in the OLS regression after controlling for geography (Column 2), institutions (Column 3), and pre-industrial developments (Column 4), the IV estimation renders the point estimates statistically and economically insignificant. This result is largely mirrored in the effect of industrialisation on school enrolment rates: Table 10, which shows the results of regressing steam engines on the share of pupils in 1818, establishes a negative and significant relationship between the two, but the IV estimation shows that the causal effect is not significant.

Table 9. The effect of industrialisation on the number of primary schools per 1,000 persons

	OLS	OLS	OLS	OLS	IV	IV
	(1)	(2)	(3)	(4)	(5)	(6)
	Log number of primary schools per 1,000 person, 1801					
Log number of steam engines	-0.0286	-0.133**	-0.131**	-0.123***	-0.0223	-0.0525
	(-0.82)	(-2.41)	(-2.43)	(-2.85)	(-0.52)	(-1.29)
Controls:						
Geographical	No	Yes	Yes	Yes	Yes	Yes
Institutional	No	No	Yes	Yes	Yes	Yes
Pre-industrial	No	No	No	Yes	No	Yes
Constant	1.676***	-49.53***	-47.64***	-22.88*	-33.09***	-12.62
	(12.83)	(-3.46)	(-3.42)	(-1.77)	(-2.84)	(-1.14)
r2	0.0154	0.431	0.53	0.714	0.417	0.667
N	42	42	42	42	42	42
F-statistic					12.79	15.31

Notes: All variables are in logarithm, using ln(x+1), except rates and dummies. *T*-statistics are reported in round brackets. *F*-statistics report on the strength of the instrument. Standard errors are robust to control for heteroskedasticity. *** indicates significance at the 1% level; ** at the 5% level; and * at the 10% level. *Sources*: see text.

Table 10. The effect of industrialisation
on the number of day-school pupils per 1,000 persons

	OLS	OLS	OLS	OLS	IV	IV
	(1)	(2)	(3)	(4)	(5)	(6)
	The number of day-school pupils per 1,000 person, 1818					
Log number of steam engines	-0.171	-0.360**	-0.409**	-0.395**	-0.261	-0.145
	(-1.06)	(-2.30)	(-2.41)	(-2.30)	(-1.18)	(-0.53)
Controls:						
Geographical	No	Yes	Yes	Yes	Yes	Yes
Institutional	No	No	Yes	Yes	Yes	Yes
Pre-industrial	No	No	No	Yes	No	Yes
Constant	7.911***	-113.5	-131.1*	-110.5	-112.1	-77.6
	(15.83)	(-1.62)	(-1.78)	(-1.35)	(-1.55)	(-0.95)
r2	0.0321	0.446	0.517	0.555	0.505	0.524
N	40	40	40	40	40	40
F-statistic					10.68	12.62

Notes: All variables are in logarithm, using ln(x+1), except rates and dummies. *T*-statistics are reported in round brackets. *F*-statistics report on the strength of the instrument. Standard errors are robust to control for heteroskedasticity. No data exist for Hampshire. London and Middlesex are joint. *** indicates significance at the 1% level; ** at the 5% level; and * at the 10% level. *Sources*: see text.

Table 11. The effect of industrialisation on male literacy

	OLS	OLS	OLS	OLS	IV	IV
	(1)	(2)	(3)	(4)	(5)	(6)
	Male literacy rate of individuals born c. 1806-1816					
Log number of steam engines	1.245*	0.0937	-0.0368	0.18	1.454	0.928
	(1.77)	(0.14)	(-0.05)	(0.25)	(1.15)	(0.88)
Controls:						
Geographical	No	Yes	Yes	Yes	Yes	Yes
Institutional	No	No	Yes	Yes	Yes	Yes
Pre-industrial	No	No	No	Yes	No	Yes
Constant	62.28***	-337.0	-285.5	-322.0	-93.2	-223.6
	(30.77)	(-0.88)	(-0.78)	(-0.77)	(-0.24)	(-0.53)
r2	0.0781	0.352	0.469	0.516	0.417	0.503
N	41	41	41	41	41	41
F-statistic					10.49	12.83

Notes: All variables are in logarithm, using ln(x+1), except rates and dummies. *T*-statistics are reported in round brackets. *F*-statistics report on the strength of the instrument. Standard errors are robust to control for heteroskedasticity. London and Middelsex are joint. *** indicates significance at the 1% level; ** at the 5% level; and * at the 10% level. *Sources*: see text.

Table 12. The effect of industrialisation on female literacy

	OLS	OLS	OLS	OLS	IV	IV
	(1)	(2)	(3)	(4)	(5)	(6)
	Female literacy rate of individuals born c. 1806-1816					
Log number of steam engines	-1.360*	-1.898**	-1.679	-1.293	-1.54	-1.889
	(-1.75)	(-2.30)	(-1.60)	(-1.34)	(-0.91)	(-1.27)
Controls:						
Geographical	No	Yes	Yes	Yes	Yes	Yes
Institutional	No	No	Yes	Yes	Yes	Yes
Pre-industrial	No	No	No	Yes	No	Yes
Constant	55.60***	143.5	228.7	222.3	246.7	143.8
	(26.51)	(0.34)	(0.52)	(0.47)	(0.55)	(0.30)
r2	0.0813	0.19	0.299	0.372	0.299	0.365
N	41	41	41	41	41	41
F-statistic					10.49	12.83

Notes: All variables are in logarithm, using ln(x+1), except rates and dummies. *T*-statistics are reported in round brackets. *F*-statistics report on the strength of the instrument. Standard errors are robust to control for heteroskedasticity. London and Middelsex are joint. *** indicates significance at the 1% level; ** at the 5% level; and * at the 10% level. *Sources*: see text.

Table 13. The effect of industrialisation on gender inequality in literacy

	OLS (1)	OLS (2)	OLS (3)	OLS (4)	IV (5)	IV (6)
	Gender inequality among individuals born c. 1806-1816					
Log number of steam engines	2.606***	1.562***	1.643***	1.473***	2.994***	2.817***
	(6.61)	(3.64)	(3.64)	(3.05)	(3.51)	(3.79)
						[0.794]
Controls:						
Geographical	No	Yes	Yes	Yes	Yes	Yes
Institutional	No	No	Yes	Yes	Yes	Yes
Pre-industrial	No	No	No	Yes	No	Yes
Constant	6.672***	-504.8***	-514.1***	-544.3***	-339.9*	-367.5**
	(6.13)	(-2.98)	(-3.09)	(-3.08)	(-1.93)	(-2.16)
r2	0.557	0.693	0.697	0.727	0.628	0.661
N	41	41	41	41	41	41
F-statistic					10.49	12.83

Note: Gender inequality is computed as the male literacy rate minus the female literacy rate. *Notes*: All variables are in logarithm, using ln(x+1), except rates and dummies. *T*-statistics are reported in round brackets. Standardized coefficient is reported in square brackets. *F*-statistics report on the strength of the instrument. Standard errors are robust to control for heteroskedasticity. London and Middelsex are joint. *** indicates significance at the 1% level; ** at the 5% level; and * at the 10% level. *Sources*: see text.

The relationships between industrialisation and male and female literacy attainment are reported in Tables 11 and 12, respectively. Consistent with the IV analysis above regarding school enrolment rates and the number of schools per person, the IV regression results in Tables 11 and 12 show that more steam engines are not significantly associated with the ability to read and write as inferred from signature literacy. However, Table 13, which reports the results of regressing steam engines on gender inequality in literacy, establishes a large and positive significant effect of steam on how well males perform relative to females. The OLS and IV estimations both arrive at the same conclusion. After controlling for geography, institutions, and pre-industrial development, the IV regression documents that a one standard-deviation increase in the use of steam engines caused a 0.79 standard-deviation increase in gender inequality (Table 13, Column 6).

Overall the analyses of the effect of new industrial technology on literacy, as well as schools and school enrolment rates, leave the impression that England's Industrial Revolution had no influence on the formation of elementary education. These findings chime well with the earlier analysis of Humphries (2010) showing that industrialisation led to a decrease in average years of schooling. They also correspond with previous work that has documented a stagnant literacy rate of men during the classic period of the Industrial Revolution (e.g. Schofield, 1973; Nicholas and Nicholas 1992). In summary, therefore, early industry in England, as captured by the number of steam engines installed by 1800, had a positive effect on the formation of working skills, but a neutral effect on the formation of basic schooling skills, including literacy, and a negative effect on gender inequality in literacy.[8]

4 Robustness checks

This section explores the robustness of the baseline analyses conducted above. While the baseline analyses dealt mainly with confounding factors to be considered exogenous in the process of the Industrial Revolution, our robustness analyses below deal also with variables that might have been endogenous in this process. All tables mentioned in in the following are reported in Appendix 4.

4.1 Raw materials

The presence of raw materials, such as iron, could have influenced the location and therefore concentration of steam engines. Moreover, the wealth generated by those raw materials could have helped pay for the formation of human capital. However, Table A1 in Appendix 4 shows that our results are robust to controlling for the county-level distribution of blast furnaces, capturing the tendency to use iron in production across the English counties. Interestingly, the

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[8] These findings are robust to using the county-level number of steam engines *per person* rather than the absolute number of steam engines, except that the shares of carboniferous rock is not instrumenting the numbers of steam engines per person as well as they instrument the *absolute* numbers of steam engines.

analysis shows that more blast furnaces has the opposite effect on human capital formation compared to steam engines, i.e. they are associated with more unskilled and fewer lower skilled workers and with less gender inequality in literacy.

4.2 Population growth

Faster population growth may have been caused by higher rates of fertility, which came about at a cost to the formation of human capital, as suggested by the existing quality-quantity trade-off of children in this period, documented in Klemp and Weisdorf (2015). Table A2 shows, however, that the baseline results are robust to controlling for the growth of population by county between 1600 and 1700.[9] It is interesting to note that population growth had a negative effect on female literacy and thus increased gender inequality in literacy. At the same time, population growth is also negatively linked to the share of unskilled workers.

4.3 Market size

Population concentration may have given rise to large markets, which in turn may have increased the returns to investments in industrial technology and also more wealth and human capital. But Table A3 shows that the effect of steam technology on human capital is robust to controlling also for the county-level variation in the density of population in 1700, calculated by dividing the county-specific population size by the size of each county.[10] High population density is associated with fewer pupils per capita, lower rates of literacy and more inequality in literacy. More densely populated counties also have significantly more lower-skilled and fewer higher-skilled workers.

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[9] Population growth rates are computed using the population census data, which are reported at http://www.visionofbritain.org.uk/census/SRC_P/6/GB1841ABS_1.

[10] County size is measured in square miles and are taken from http://county-wise.org.uk/counties/.

4.4 Religion

The occupational data used to construct the shares of skills by county come from Anglican Church registers. The Anglican Church was the dominant religious institution in England at the time. However, since other religious groups – including Catholics, Orthodox Christians, and Jews – co-existed and could have had different views regarding the importance of human capital, the county-level shares of other religious groups may have influenced not only the formation of human capital but also the accumulation of wealth which helped industrialisation. In order to account for the degree to which the counties were dominated by Anglicans, we use the shares of Anglican Church seats to the total number of church seats in a county reported in Mann (1854). Table A4 shows that the baseline results are robust to accounting for these shares. Although counties with relatively more Anglican seats had significantly more schools, there were fewer females who were literate, and also gender inequality was higher than counties with fewer Anglicans. Moreover, more Anglicans meant significantly more lower-skilled and fewer higher-skilled workers.

4.5 Distance to nearest university

A nearby university may have stimulated the formation of human capital and could also have helped promote early industry through the spread of knowledge. Some of the sampled counties were near to the two English universities that existed at the time, i.e. the universities of Cambridge and Oxford; others were closer to the two prevalent Scottish universities, i.e. that of Glasgow and that of Edinburgh. Meanwhile, Table A5 shows that the baseline results are robust to accounting for the distance to the nearest university. Proximity to a nearby university, although this was negatively linked to the share of higher-skilled workers, was significantly associated with more schools and fewer unskilled workers.

4.6 Mills

Steam engines were not the only source of mechanical power present in England at the time. Cotton-, wool-, and watermills also played an important role, not just during the time of the Industrial Revolution, but also before this. Tables A6a and A6b show, however, that steam engines are still significantly influencing the formation of human capita also after controlling for the county-level use of mechanical power as measured by the numbers of cotton-, wool-, and watermills. In fact, the magnitude of the effects of steam engines on human capital are sometimes larger after we account for the presence of mills than they were in the baseline analysis.

In summary, the baseline results presented in Section 4 are robust to controlling for the key confounding factors, which could have been endogenous to the process of industrialisation and the formation of human capital.

5. Conclusion

Economic historians have traditionally regarded the process of technological change during England's Industrial Revolution as inherently deskilling. Indeed, new technologies, including steam engines, are said to have been introduced with the specific aim to substitute or 'dilute' workers skills, as argued in Berg (1980; 1994). This view has recently been challenged in a number of studies, notably in Franck and Galor (2016), which shows that the Industrial Revolution in France was skill-demanding, and in Meisenzahl and Mokyr (2012) and Feldman and van der Beek (2016), which argue that the introduction of new technologies during England's Industrial Revolution led to the creation and consolidation of new working skills. Those new working skills were not only needed for the production and instalment of new machines, but also in order to operate and maintain them. These arguments are consistent with the central mechanism in the Unified Growth Theory, which states that technological

progress encouraged more investments in human capital formation and hence growth in the average skills of the work force (Galor 2011).

Inspired by these studies, this paper has carried out a systematic quantitative assessment of the effect of industrialisation, captured by the number of steam engines installed in England by 1800, on the average working skills of workers. We obtained several measures of working skills by coding more than 2.6 million occupations recorded in the early 19th century, finding strong support for the notion that England's Industrial Revolution was skill-demanding and that the effects were causal. In turn, this lends credence to the basic mechanism proposed by Unified Growth Theory.

We also tested the impact of industrialisation on a number of measures of more basic human capital formation, finding that early industrialisation was negatively associated with elementary school attainments. We did not, however, find any causal effects, except a negative influence on gender inequality in literacy. The lacking effect of industrialisation on the attainment of literacy is consistent with previous observations by Nicholas and Nicholas (1992), observing a pause in the growth in English literacy rates during the Industrial Revolution. It also confirms Mokyr (2005)'s conclusion that basic education was not a key ingredient in England's early industrialisation.

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Appendix 1 (published online only)
Map and names of counties

1	Bedfordshire
2	Berkshire
3	Buckinghamshire
4	Cambridgeshire
5	Cheshire
6	Cornwall
7	Cumberland
8	Derbyshire
9	Devon
10	Dorset
11	Durham
12	Essex
13	Gloucestershire
14	Hampshire
15	Herefordshire
16	Hertfordshire
17	Huntingdonshire
18	Kent
19	Lancashire
20	Leicestershire
21	Lincolnshire
22	London
23	Middlesex
24	Norfolk
25	Northamptonshire
26	Northumberland
27	Nottinghamshire
28	Oxfordshire
29	Rutland
30	Shropshire
31	Somerset
32	Staffordshire
33	Suffolk
34	Surrey
35	Sussex
36	Warwickshire
37	Westmorland
38	Wiltshire
39	Worcestershire
40	Yorkshire, East Riding
41	Yorkshire, North Riding
42	Yorkshire, West Riding

To quantify the shares of highly-skilled mechanical workmen, we have used the classification provided in Table A1 of Appendix A in Feldman and van der Beek (2016, pp. 110-11). That is, we have included the trades classified by Feldman and van der Beek as 'non-routine' and 'mechanical'. These include: Coach maker; Engineers and wrights; Machine and instrument makers; Plumber Brazier; Goldsmith/Silversmith; Jeweler; Ship builder; Gun and Lock smiths.

As a robustness-check, we have also performed regression analysis including those trades classified as 'mechanical' (but not 'non-routine'). Trades included in this group of workers are: Cabinet Maker; Coach Maker; (House) Carpenter; Joiner; Engineers and wrights; Machine and instrument makers; Plumber; Brazier; Cutler; Goldsmith/Silversmith; Jeweler; Printing and engraving; Working with precious metals; Ship builder; Gun and Lock smiths; Other smiths and founders; Pewterrer; Smith; Carver; Cooper; Turner in wood. Our findings were robust to this broader definition of mechanical workmen (regression tables available upon request).

Appendix 3 (published online only)
List of administrative centres by county

Administrative centre	County	Administrative centre	County
Bedford	Bedfordshire	Brentford	Middlesex
Reading	Berkshire	Monmouth	Monmouthshire
Aylesbury	Buckinghamshire	Norwich	Norfolk
Cambridge	Cambridgeshire	Northampton	Northamptonshire
Chester	Cheshire	Alnwick	Northumberland
Truro	Cornwall	Nottingham	Nottinghamshire
Carlisle	Cumberland	Oxford	Oxfordshire
Derby	Derbyshire	Oakham	Rutland
Exeter	Devon	Shrewsbury	Shropshire
Dorchester	Dorset	Taunton	Somerset
Durham	Durham	Stafford	Staffordshire
Chelmsford	Essex	Ipswich	Suffolk
Gloucester	Gloucestershire	Guildford	Surrey
Winchester	Hampshire	Chichester	Sussex
Hereford	Herefordshire	Warwick	Warwickshire
Hertford	Hertfordshire	Appleby	Westmorland
Huntingdon	Huntingdonshire	Trowbridge	Wiltshire
Maidstone	Kent	Worcester	Worcestershire
Lancaster	Lancashire	Hull	Yorkshire, East Riding
Leicester	Leicestershire	Northallerton	Yorkshire, North Riding
Lincoln	Lincolnshire	Leeds	Yorkshire, West Riding