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Education and Catch-up in the Industrial Revolution[†]

By Sascha O. Becker, Erik Hornung, and Ludger Woessmann*

Research increasingly stresses the role of human capital in modern economic development. Existing historical evidence—mostly from British textile industries—however, rejects that formal education was important for the Industrial Revolution. Our new evidence from technological follower Prussia uses a unique school enrollment and factory employment database linking 334 counties from pre-industrial 1816 to two industrial phases in 1849 and 1882. Using pre-industrial education as instrument for later education and controlling extensively for pre-industrial development, we find that basic education is significantly associated with nontextile industrialization in both phases of the Industrial Revolution. Panel data models with county fixed effects confirm the results. (*JEL* I20, J24, N13, N33, N63)

> *But probably education is especially important to those functions requiring adaptation to change. Here it is necessary to learn to follow and to understand new technological developments.*
> — (Richard R. Nelson and Edmund S. Phelps 1966, 69)

Given the large existing differences in long-run growth rates, there is a renewed interest in understanding the factors underlying the process by which lagging economies catch up to technological leader nations (cf. Robert E. Lucas, Jr. 2009). Models of technological diffusion in the spirit of Nelson and Phelps (1966) suggest that education is the key ingredient to absorb new technologies and adapt to change (cf. Jess Benhabib and Mark M. Spiegel 2005; Jerome Vandenbussche, Philippe Aghion, and Costas Meghir 2006). An obvious application to test such models is the most fundamental technological shift in modern history, the Industrial Revolution. Most unified growth models stress the role of human capital for the transition to modern growth, at least during the second phase of industrialization (cf. Oded Galor 2005). Narrative accounts also sometimes argue that education was important for the transfer

* Becker: Department of Economics, University of Warwick, Coventry CV4 7AL, United Kingdom, and Ifo, CESifo, CEPR, and IZA (e-mail: s.o.becker@warwick.ac.uk); Hornung: Ifo Institute for Economic Research, Poschingerstr. 5, 81679 Munich, Germany (e-mail: hornung@ifo.de); Woessmann: University of Munich, Poschingerstr. 5, 81679 Munich, Germany, and Ifo Institute for Economic Research, CESifo and IZA (e-mail: woessmann@ifo.de). Comments from Bob Allen, Davide Cantoni, Brad DeLong, Matthias Doepke, Bob Hart, John Komlos, Dirk Krueger, David Mitch, Uwe Sunde, Michèle Tertilt, three anonymous referees, and seminar participants at University of California-Berkeley, the universities of Oxford, Warwick, Humboldt/Berlin, Liverpool, Munich, Stirling, Dundee, and Swansea, IZA Bonn, Ifo Munich, Max Planck Jena, and the annual meetings of the Royal Economic Society (Surrey), the Economic History Society (Durham), and the German Economic Association (Magdeburg), as well as financial support by the Pact for Research and Innovation of the Leibniz Association, are gratefully acknowledged.

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of technological leadership from Britain to Germany in leading sectors at the end of the nineteenth century (e.g., David S. Landes 1969). But the role of education for catch-up during the first phase of the Industrial Revolution until the mid-nineteenth century is less clear, and thorough empirical evidence is missing for both phases, including the second phase until the end of the nineteenth century. The main existing evidence on the role of human capital during the Industrial Revolution refers to the technological leader country, Britain, where the established view is that formal education did not play a prominent role in the emergence of new industries (David Mitch 1999). However, surprisingly little attention has been paid to the role of education in the industrial catch-up of the technological follower nations—the whole world except Britain.

This paper provides evidence that initially better-educated regions within Prussia responded more successfully to the opportunities created by the outside technological changes from Britain. Based on several full population, factory, occupation, and school censuses conducted by the Prussian Statistical Office, we compile a historically unique micro-regional panel dataset of 334 Prussian counties that spans nearly the whole nineteenth century. In particular, we cover education and pre-industrial development indicators in 1816, before the start of the Industrial Revolution in Prussia (which is generally placed around the mid-1830s; e.g., Walther G. Hoffmann 1963; Richard Tilly 1996), as well as education and industrial employment shares toward the end of the first phase of industrialization in 1849 and during the second phase in 1882.

Using the education level observed before the onset of industrialization, which we argue had emerged from historical idiosyncrasies, as an instrument for education levels during industrialization, we find that basic school education is significantly related to industrial employment in both phases of the Industrial Revolution. Our database allows us to distinguish between industrialization in three industries: metals, textiles, and other industries (outside metals and textiles), such as rubber, paper, and food. It turns out that in the textile industry, where innovation was less disruptive and child labor more prevalent, formal education apparently played a minor role during both phases of industrialization. However, formal education appears to have played an important role in the metal and all other industries already in the first phase of the Industrial Revolution, and its importance increased further during the second phase. In line with technology-diffusion models, we find significant results for basic education in elementary and middle schools, but not for upper-secondary enrollment or higher education institutions. Our analyses are motivated by the idea that it may not be arbitrary that Prussia, the educational world leader at the time (Peter H. Lindert 2004), was particularly successful in industrial catch-up. The results suggest that Prussian educational leadership indeed translated into technological catch-up throughout the nineteenth century.

The main threat to empirical identification of the effect of education on industrialization arises from the fact that the process of industrialization may itself cause changes in the demand for education. This leads to possible endogeneity bias, the direction of which is not clear a priori. On the one hand, factory production may increase the demand for low-skilled labor, drawing children out of school into factory work. For example, Michael Sanderson (1972) suggests that the Industrial Revolution created new occupations with relatively low educational requirements, which would bias the education estimate downward. On the other hand, to the extent that the Industrial Revolution increased living standards, education may have become more affordable for broader parts of the population. In addition, Galor and Omer Moav (2006) argue that at least during the second phase of industrialization, the new industrial technologies increased the demand for human capital, which would bias the education estimate upward.

We aim to identify the effect of education on industrialization in the face of simultaneity among the two by using education in 1816, *before* industrialization in Prussia, as an instrument for education at the two later periods. This instrument is not affected by changes in the demand for education that emerged *during* industrialization and thus isolates a part of the variation in education that is not determined simultaneously with industrialization. Under the assumption that pre-industrial schooling is not correlated with other measures that are themselves related to subsequent industrialization, this instrumental-variable (IV) specification estimates the causal effect of education on industrialization in Prussia. We test this assumption and corroborate the validity of the IV specification by showing its robustness against an unusually rich set of covariates indicating the state of economic development before the onset of industrialization. Our results are also validated when using distance to Wittenberg as an alternative instrument which yields historically plausibly exogenous variation in education across Prussia due to Protestants' urge for literacy to read the Bible (Becker and Woessmann 2009).

To further address concerns that any pre-existing omitted variables might drive the cross-sectional findings, we also report results of panel data models that pool our three periods of observation (1816, 1849, and 1882). Results confirm the effect of education on industrialization, and county fixed effects rule out that the findings simply capture unobserved heterogeneity across the counties. While we are confident that our identification strategy—the combination of depicting idiosyncratic historical factors that underlie the historical variation in education, controlling for a rich set of observable factors that make counties heterogeneous, and providing fixed-effects panel evidence—corroborates that pre-existing educational differences provide plausibly exogenous variation, the exclusion restriction is ultimately untestable. Pre-industrialization schooling levels may still be correlated with unobserved conditions that later interact with the propensity to industrialize. Identification by using a lagged measure of the potentially endogenous variable as an instrument cannot prove that there is no persistent omitted variable, and thus cannot establish causality beyond doubt.

Still, several additional aspects of our framework facilitate empirical identification as they introduce exogeneity into the emergence of industrial technologies in Prussia. First, the Industrial Revolution is characterized by production techniques that had not been available before. The new modes of production created a new sector, mechanized industry. This distinguishes analyses of historical industrialization from analyses of agricultural advancement over time and from more general analyses of economic development. Second, most industrial technologies were first applied in Britain, making their advent exogenous from a Prussian perspective. They came as an exogenous "shock" (in the econometric sense of a matter determined outside the variation employed in the model) simultaneously to all Prussian counties once fundamental institutional reforms had freed up the Prussian economy in the first two decades of the nineteenth century. Third, by using micro-regional data to exploit within-Prussian variation, we can reduce the concern that fundamental differences in geography, and in such institutions as written law and the legal system, property rights, and administrative structures, determine the capacity for technological adoption because there is considerably less heterogeneity in institutional, cultural, and climatic background between Prussian counties than there is across countries. We therefore view the advent of the industrial technologies in Prussia as a historical experiment that came from Britain as an exogenous shock.

Our results inform a broader literature of empirical investigation of how schooling influences the incidence and pace of catch-up economic development. For example, Benhabib and Spiegel (2005) provide a series of modern time, cross-country regressions indicating that years of schooling are positively related to the rate of catch-up to total factor productivity. Using direct measures of cognitive skills, Eric A. Hanushek and Woessmann (2009) find high-level skills to be related to higher growth in particular in lagging countries. Diego Comin and Bart Hobijn (2010) document that large existing cross-country lags in the adoption of technologies can account for important differences in per capita income, and that successes in catch-up growth over the twentieth century involved a substantial reduction in the lags of technology adoption. The stylized growth facts suggested by Charles I. Jones and Paul M. Romer (2010, 238) imply that the dynamics of idea flows and technology are a leading candidate to understand modern catch-up growth. Based on Indian micro data, Andrew D. Foster and Mark R. Rosenzweig (1996) document the role of human capital in technical change during the Green Revolution. We extend this literature to analyze the role of education in technological catch-up during the Industrial Revolution in a historical perspective.

The remainder of the paper is structured as follows. Section I briefly places the analysis in a theoretical framework and provides historical background. Sections II and III introduce the empirical model and database, respectively. Section IV presents the results. Section V concludes.

I. A Leader-Follower Interpretation of Industrialization

A. *The Industrial Revolution and Catch-up to the New Technological Frontier*

The Industrial Revolution[1] refers to the period of industrialization characterized by profound technological change sparked by such inventions as the steam engine and mechanical spinning, their diffusion, adaptation, and improvement, the rise of the factory system, and accompanying social changes in households and markets (cf. Joel Mokyr 1999). Modern theory subdivides the Industrial Revolution into two phases: a first phase with skill-saving technological change and minimal educational requirements, and a second phase where technological change increases the demand for human capital as skills become necessary for production (e.g., Galor 2005).

[1] Because of the fundamental economic and social processes of change that occurred everywhere during the industrialization, it has become common to speak of an Industrial "Revolution" not only in the technological leader country Britain, but also in follower countries like Germany (e.g., Knut Borchardt 1973; Hans-Werner Hahn 2005).

In line with this argument, Mitch (1993, 307) concludes his seminal review by stating that "education was not a major contributing factor to England's economic growth during the Industrial Revolution," an argument that applies in particular to formal education and to the first phase of the British Industrial Revolution. Examples of similar assessments include Sanderson (1972), Roger S. Schofield (1973), Robert C. Allen (2003), and Gregory Clark (2005). As Mokyr (1990, 240) famously sums up, "If England led the rest of the world in the Industrial Revolution, it was despite, not because of, her formal education system." Countless reasons have been advanced for England's technological leadership, ranging from property rights, geography, culture, the biological spread of values, fertility limitation, capital deepening, imperial expansion, and a unique structure of wages and energy prices, up to historical accidents and pure chance (for references, cf., e.g., Galor 2005; Nico Voigtländer and Hans-Joachim Voth 2006; Clark 2007; Allen 2009). The very question of why England was first to industrialize may even be misconceived and unanswerable because of the uniqueness of the event and the stochastic character of the innovation process (Nicholas F. R. Crafts 1977).

Leaving these discussions aside, we focus instead on industrialization in follower countries. Classical studies such as Alexander Gerschenkron (1962) and Moses Abramovitz (1986) have argued that catch-up growth of initially backward countries is inherently different from growth in technological-leader countries (cf. Daron Acemoglu, Aghion, and Fabrizio Zilibotti (2006) for a modern exposition). For the rest of the world, the developments in Britain established an outside event that created new technologies and work organizations. Given the change was exogenous to follower countries, we suggest that the best way to frame the situation of the rest of the world at the time is a classical technological-follower model along the lines of Nelson and Phelps (1966).

A subsequent string of contributions, such as Finis Welch (1970); Theodore W. Schultz (1975); Richard A. Easterlin (1981); Crafts (1996); G. Nick von Tunzelmann (2000); Benhabib and Spiegel (2005); and Vandenbussche, Aghion, and Meghir (2006), stresses the leading role of the stock of human capital in the adoption of new technologies and in the ability to deal with changing conditions.[2] This is the link we test in this paper. The main catch-up hypothesis can take three different forms, from narrower to broader. The narrow form suggests that schooling facilitates industrialization; a broader form suggests that it facilitates the adoption of new technologies in general; and the broadest form suggests that it improves the ability to adapt to changing economic conditions. The question addressed in our empirical analysis is: Once the new technologies had been introduced in Britain, did human capital facilitate their adoption in follower countries?[3] Our empirical investigation

[2] Lars G. Sandberg (1979) argues that human capital was a leading factor in late nineteenth century Swedish catch-up. Based on a cross section of 16 countries, O'Rourke, Kevin Hjortshoj, and Jeffrey G. Williamson (1996) conclude that schooling mattered for catch-up in 1870–1913, but only modestly. Alan M. Taylor (1999) confirms this result for the same period with panel data for seven countries, but stresses the considerable limitation of historical cross-country education data. Peter Lundgreen (1973, 1976) provides a descriptive account of aggregate education levels in Prussia from 1864–1911.

[3] Empirical evidence on the role of education in the Industrial Revolution is largely refined to the leader country Britain (cf. Mitch 1999), and even there suffers from severe data constraints. In particular, British studies have to rely mostly on proxying education by signatures in marriage registers for limited Parish samples, observed concurrent to but not before the Industrial Revolution in Britain (see online Appendix D). Exceptions of econometric studies of the role of education in industrialization outside Britain include Brian A'Hearn (1998) on Southern Italian textile factories

thus tests the narrow form of the catch-up hypothesis. Given that the narrow form is nested within the broader ones, we cannot discriminate between them, although below we discuss how certain aspects of our results are consistent with the different forms.

In the broadest form, the technology-diffusion models stress the role of education in creating the ability to adjust to changing conditions, thereby facilitating the adoption of new technologies.[4] It is conceivable that the direct (static) productive use of skills as well as entrepreneurial and scientific skills played a role in catch-up industrialization. However, in the follower-country context of rapid economic change from outside, basic general skills that open up logical thinking to understand the functioning of the world are particularly relevant in order to perceive and solve new problems. In this regard, the educational reforms that Wilhelm von Humboldt initiated in Prussia in 1808 to advance his humanistic educational ideal of an encompassing general education, and to implant the ability of rational thinking among the whole population, may be of particular relevance (see online Appendix D for details). In line with the leader-follower models, and because the average level of secondary and higher education was very low in the nineteenth century, we focus on basic education in this paper. In addition, these models predict that the adoption of new technologies, and thus industrialization, is a function of the *stock* of, rather than the *change* in, human capital.

Based on this theoretical framework, we would expect the role of education to be most important in sectors where the need to adapt to radical change was most intensive. Accordingly, the impact of education should be most pronounced in sectors that were newly created by the Industrial Revolution or where processes were transformed more radically. By contrast, it may be less relevant in the textile sector, where new technologies were built closely on previously available technologies so that innovation was more incremental and less disruptive. In addition, child labor was more prevalent in textiles than in other industries, and textile industrialization in Prussia was particularly slow and, in contrast to Britain, never a leading sector of industrialization (Friedrich-Wilhelm Henning 1995), possibly exacerbated by the availability of cheap import competition (see online Appendix D for specifics of the textile sector). While most existing British evidence focuses on the textile sector, our sectoral data allow us to look at differences across sectors.

B. *Institutional Reforms and the Emergence of Industrialization in Prussia*

Before the Napoleonic reign in 1806–1813, Prussia's institutional structure can be described as a stiffened absolutistic and feudal regime. A series of modernizing institutional reforms based on the ideas of the Enlightenment were enacted in response to the military defeat of Prussia in 1806.[5] These institutional reforms are

in 1861–1914, Joan R. Rosés (1998) on Catalan cotton factories in 1830–1861, and James Bessen (2003) on textile firms in Lowell, Massachusetts around 1842. Note that all these contributions focus on the textile sector and on a specific region, and that their interpretation may be affected by the endogeneity issues discussed in this paper.

[4] Online Appendix B provides a more detailed discussion of the type of education relevant for industrial catch-up. Online Appendix C presents a selection of historic concrete examples of how education was important for the adoption of British technologies in Prussia.

[5] A positive interaction between the institutional framework and education in promoting economic development has both been emphasized theoretically and been found in modern data (cf. Hanushek and Woessmann 2008).

sometimes described as a "revolution from above" and were "aimed at fostering private initiative through removing guild restrictions on trade as well as a sweeping set of anti-feudal land and labor reforms" (Timothy Lenoir 1998, 22). As Tilly (1996, 98) puts it, "the Stein-Hardenberg Reforms constituted an important, indeed, crucial, step forward in German industrialization." The most important institutional changes were the abolishment of serfdom, particularly for peasants, and the introduction of freedom of land tenure, which together created individual property rights in land and labor (e.g., Toni Pierenkemper and Tilly 2004); the introduction of freedom of occupational choice and of business establishment, which created freedom of trade (e.g., Henning 1995); improvements in equality before the law; emancipation of the Jews; introduction of substantial municipal self-government; and, in 1818, the abolishment of internal tariffs (followed by customs unions with other German states that culminated in the Zollverein in 1834).

The new order of Europe set up at the Congress of Vienna in 1815, after the defeat of Napoleon, thus establishes a landmark for the start of the possibility to industrialize in Prussia (e.g., Hubert Kiesewetter 2004). Once Prussia had opened up institutionally, all parts of Prussia were in principle exposed to the changes that had emerged in Britain. The reforms that were initiated under French occupation "were akin to an exogenous change in institutions unrelated to the underlying economic potential of the areas reformed" (Acemoglu et al. 2008, 2). An additional reason for the delay of industrialization in Prussia relative to Britain has been seen in the long span of revolution and war in Continental Europe from 1789 to 1815 (Landes 1998). Furthermore, Napoleon had established the Continental System that embargoed Britain from the continent between 1806 and 1814. Once this ban of trade with Britain was abolished, Prussia became able to copy British technologies (e.g., Joachim Radkau 2008).

When dating the inception of the Industrial Revolution in Prussia, most history scholars agree that the first phase of industrialization in Prussia started around the mid-1830s (e.g., Hoffmann 1963; Tilly 1996). The earliest chronological dating stems from Kiesewetter (2004) who argues that in a regional perspective, the defeat of Napoleon in 1815 may be viewed as the very earliest beginning of industrialization in some regions (see also Ralf Banken 2005). In line with the argument of the institutional divide above, this enables us to view school enrollment in 1816 as a measure of education observed before the onset of the Industrial Revolution in Prussia.

Prussian industrialization is generally subdivided into two phases, with the first one dating roughly between 1835 and 1850 and the second one in the second half of the nineteenth century. According to some observers, around 1850 the technological gap between Britain and Prussia "had been more or less closed" (Charles P. Kindleberger 1995, 231). In the second phase, the adoption of imitated, imported technologies was expanded toward more autonomous developments of industrial pioneers, for example, in the chemical industry and in electrical technologies (e.g., Hahn 2005). The German revolutions in 1848–1849 also establish a significant break. We thus view 1849, for which unique factory and education data are available, as a useful landmark toward the end of the first phase of industrialization in Prussia.

II. The Empirical Model

A. *Basic Setup*

The leader-follower relationships discussed above, as modeled by Nelson and Phelps (1966), and subsequent growth models (cf. Benhabib and Spiegel 2005), require a specification where the level of, rather than the change in, education affects economic development (cf. Alan B. Krueger and Mikael Lindahl 2001). Therefore, our basic model expresses industrialization *IND* toward the end of the first phase of the Industrial Revolution in 1849 (which, given that industrialization at the beginning of the phase was virtually zero, basically reflects the change in industrialization over the first phase) as a function of the level of education *EDU* and other explanatory factors *X*:

$$(1) \qquad IND_{1849} = \alpha_1 + \beta_1 EDU_{1849} + X'_{1849}\gamma_1 + \varepsilon_1,$$

where ε is a random error term and β is the coefficient of interest. We will estimate this model using the cross section of Prussian counties, effectively exploiting Sidney Pollard's (1981, 14) assessment that the Industrial Revolution was "a regional phenomenon" (cf. Gerd Hohorst 1980 and Kiesewetter 2004 for similar arguments for Germany). In addition to using indicators for industry as a whole as the dependent variable, we can also perform the analyses for three separate industries: textiles, metals, and the group of all industries outside textiles and metals. In addition to 1849, we also measure the level of industrialization at a later stage, during the second phase of the Industrial Revolution in 1882.

The main threat to empirical identification is that ordinary least squares (OLS) estimates of β may be subject to endogeneity bias. In particular, the process of industrialization may itself cause changes in the demand for education, giving rise to possible reverse causality. The estimated coefficient on education would be biased downward if factory production increased the demand for low-skilled labor and kept children out of school by drawing them into factory work. Thus, the British Industrial Revolution seems to have created new occupations with lower educational requirements than the existing ones (Sanderson 1972; cf. E. G. West 1978 for a discussion). But the estimated coefficient on education may also be biased upward if the Industrial Revolution increased living standards to the extent that education became more affordable for the broad masses, or if the new industrial techniques increased the demand for human capital. The latter is often argued at least for the second phase of industrialization (cf. Galor 2005). In sum, not even the direction of any possible bias, let alone its size, is obvious a priori.

B. *Obtaining Exogenous Educational Variation from Pre-industrial Education Levels*

To address the worry that education may be endogenous to industrialization itself, we suggest an instrumental-variable strategy, where education levels observed before the industrialization serve as an instrument for education levels during industrialization. Thus, in equation (1), we instrument education *EDU* in 1849 by education *EDU* before the Industrial Revolution in 1816:

$$EDU_{1849} = \alpha_2 + \beta_2 EDU_{1816} + X'_{1849}\gamma_2 + \varepsilon_2. \tag{2}$$

This first stage allows us to isolate that part of the variation in education in 1849, that can be traced back to pre-industrial variations in education. Such an approach is enabled by our unique panel dataset which includes education data *before* the Industrial Revolution. We can then follow the same Prussian counties during the two phases of the Industrial Revolution.

A fundamental point is that the Industrial Revolution is about new industrial technologies, both technical and organizational, which simply did not exist previously. Exogeneity comes from the fact that mechanized industrial production developed outside Prussia, in Britain. For the Prussian counties, its advent constituted a common exogenous shock (in econometric, not historical terms). We effectively have a preset distribution of education across the country and then observe what happens to the different counties when the shock of new technologies from Britain hits Prussia after it opens up through the institutional reforms of the Napoleonic era.

While we do not fully model the source of the variation in our instrument EDU_{1816}, it appears that, apart from the systematic variation due to distance to the Protestant hub Wittenberg used in an alternative specification (see online Appendix F), the educational variation that existed in Prussia in 1816 stems from an accumulation of idiosyncrasies of local rulers rooted deep in history that are exogenous to our topic of investigation. This can be best depicted by a number of examples of sources of substantial educational variation between neighboring counties, as evidenced by the four rectangles in Figure 1 which show an educational map of Prussia in 1816. In each case, historical peculiarities that are unlikely to be otherwise correlated with features relevant for later industrialization gave rise to significant and lasting differences in schooling.

For example, the counties in rectangle 1 constitute the area of Swedish Western Pomerania, which was governed by the Swedish kings from the Thirty Years' War until 1720 (although it was not a formal part of Sweden, but of the German Empire). But while the southern part (later called Old Western Pomerania) came to Prussia in 1720, the northern part (New Western Pomerania), divided by the river Peene, came to Prussia only in 1815. Sweden had difficulties enforcing a tax system in its territory, and thus somewhat neglected the financial equipment of its representatives. As a consequence, while the southern counties that had been part of Prussia for a century had enrollment rates of 72 percent to 77 percent in 1816, enrollment rates in the northern counties, which had just joined Prussia, were still as low as 17 percent to 34 percent.

Three further examples of other historical idiosyncrasies are discussed in online Appendix E. Together, the examples illustrate that a multitude of idiosyncratic sources had given rise to the cross-Prussian variation in education levels in 1816. While historical differences in rule had given rise to the variation in pre-industrial education levels, all counties are subject to the same Prussian rule after 1815. We

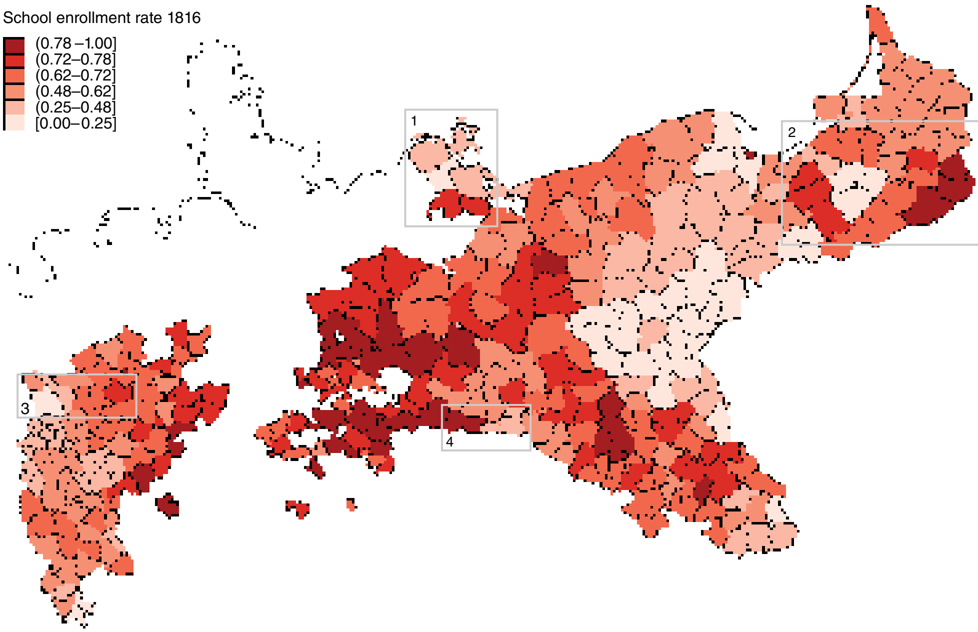

Figure 1. School Enrollment in Prussia 1816

Notes: County-level depiction based on the 1816 Population Census. Enrollment rates refer to enrollment in elementary and middle schools divided by the population aged 6 to 14. The delimiters correspond roughly to the tenth, twenty-fifth, fiftieth, seventy-fifth, and ninetieth percentile of the variable. See online Appendix A for data details. The four rectangles point out the four example regions referred to in the text.

thus view the variation in our instrument EDU_{1816} as exogenous to the error term of our model, corroborating instrument validity.

A potential remaining threat to this IV identification could still emerge if the instrument was correlated with the error term ε_1 of the industrialization model, through correlated idiosyncrasies or for other reasons. If pre-existing education were correlated with relevant omitted factors that drive subsequent adoption of industrial technologies, such as pre-existent institutional or geographical features, the IV estimate of the education coefficient might still be biased.

To address this remaining concern, we test whether our IV estimates are robust to including a set of indicators of pre-industrial development Y measured at the county level at the same time as pre-industrial education:

$$IND_{1849} = \alpha_3 + \beta_3 EDU_{1849} + X'_{1849}\gamma_3 + Y'_{1816}\,\mu_3 + \varepsilon_3. \quad (3)$$

Here, our particularly rich database containing pre-industrial development measures observed at the county level around 1816 comes into play, covering the spread of pre- and proto-industrial technologies such as looms, brick making plants, and watermills, urbanization, availability of resources for mining and weaving, measures of agricultural development including livestock counts and agricultural employment, measures of public infrastructure like buildings and paved streets, and access to navigable water measured by rivers and transport ships. While we control for proto-industrialization, it should be noted that industrialization itself, in the sense used in this paper of the new mechanized production techniques that had recently emerged in Britain, did not exist in Prussia in 1816 (as evidenced by the fact that the 1816 census does not list any industrial occupations, as in the 1849 census). We additionally check robustness to geographical controls, religion as a possible remaining cultural variation, and rounds of Prussian annexations (to proxy for possible remaining variation in institutional implementation).

We estimate the models both for the first (1849) and the second phase of industrialization (1882), where the latter depicts the full effect of education for both phases. To depict the impact of education on the progress of industrialization during the second phase (1849–1882), we estimate

$$IND_{1882} = \alpha_4 + \beta_4 EDU_{1882} + \lambda_4 IND_{1849} + X'_{1882}\gamma_4 + Y'_{1816}\mu_4 + \varepsilon_4, \tag{4}$$

which holds the level of industrialization already achieved in 1849 constant. This specification identifies the additional effect of education on industrialization during the second phase.

C. *Panel Data Models with County Fixed Effects*

In a further approach to identification, we use the panel structure of our data in order to account for fixed effects for each county. By combining the time periods for which there is relevant census data—1816, 1849, and 1882—we can estimate our basic model on a panel of 334 counties i observed at three points in time t:

$$IND_{it} = \alpha_i + \pi_t + \beta_5 EDU_{it} + X'_{it}\gamma_5 + \varepsilon_5. \tag{5}$$

By including county fixed effects α_i, this specification ignores any differences in levels that exist across countries. These fixed effects rule out any bias from unobserved initial heterogeneity that might still be omitted from the rich list of variables contained in equation (3), as long as these omitted factors are time-invariant. Identification in this model is achieved by testing whether counties in which education in later phases is higher *relative to the education level they had already reached earlier* experience additional industrialization *relative to the industrialization level they had already reached earlier*. To rule out that results are driven by average changes over time, we can also include time fixed effect π_t in the specification.

To account for the dynamic nature of the industrialization process that may contain correlation over time, the panel specification can be extended to include the lagged dependent variable among the controls:

$$IND_{it} = \alpha_i + \pi_t + \beta_6 EDU_{it} + \lambda_6 IND_{i,t-1} + X'_{it}\gamma_6 + \varepsilon_6. \tag{6}$$

Finally, to rule out reverse causation in the panel model, we can, again, instrument education EDU_t with its lagged value EDU_{t-1}, as in the cross-sectional specification of equation (2) above.

III. Prussian County-Level Data Spanning the Nineteenth Century

A. *Constructing a Panel Database*

The suggested empirical models require an unusually rich set of data. Not only do we need regional data on the levels of education and industrialization (as well as standard demographic and geographic controls) for two phases of industrialization, but also on the levels of education and general development at a point in time that predates the Industrial Revolution. To that extent, we have compiled a database for all Prussian counties for the years 1816, 1849, and 1882, effectively allowing us to observe micro-regional development throughout the nineteenth century.

The data originate from censuses conducted by the Prussian Statistical Office, founded in 1805, and are available at the county level in archives (see online Appendix A for details). The first released full-scale census is the population census in 1816, which, together with 1819 and 1821 surveys, provides us with data on education, demographics, and a host of development indicators. In 1849, the statistical office conducted not only another population census, but also a factory census that provides us with data on industrial employment. We are not aware that these data have been used at all before in microeconometric analyses. Finally, we add data from an occupation census in 1882 that provides detailed information on sectoral employment.

We structure our data by the 334 counties existent in 1849. Despite some changes in the administrative boundaries of counties between 1816, 1849, and 1882, we were able to link the data consistently over time, yielding a panel-structured database. Appendix Table A1 provides detailed descriptions of data sources and definitions for the variables employed in our analyses.

B. *Main Variables and Descriptive Statistics*

We measure industrialization toward the end of the first phase of the Industrial Revolution by factory employment as a share of total county population in 1849. In the factory census, the statistical office reports employment in 119 specific types of factories. We combine these into three industrial sectors: metalworking factories; textile factories;[6] and other factories (outside metals and textiles), such as those producing rubber, paper, food, wood, and wax.[7]

Our measure of industrialization in the second phase is manufacturing employment as a share of total county population in 1882. The sectoral classification is directly provided by the statistical office in the occupation census. A downside relative to the 1849 factory count is that the 1882 measure includes craftsmen and artisans who may not necessarily perform industrial work. Again, we subdivide the manufacturing sector into metals, textiles, and all manufacturing except metals and textiles. In both phases

[6] In the weaving factories, we exclude workers employed on hand-driven looms and only count mechanical looms, in line with a definition of industrialization as development toward machine-driven work.

[7] We have also experimented with excluding factories below a certain employment number from the analyses, such as factories with less than five or ten workers; our qualitative results were unaffected.

of industrialization, we can also calculate the county-level share of manufacturing workers in the occupied labor force, rather than in the total population.

Our education measure before the Industrial Revolution refers to 1816. It indicates the enrollment rate in elementary and middle schools, measured as the enrollment count in elementary and middle schools as a share of the population aged 6 to 14 years, which is the relevant school age in Prussian elementary and middle schools.[8]

The education measure in the first phase of the Industrial Revolution indicates the average years of primary (elementary and middle) schooling in the working-age population in 1849, constructed from school enrollment data available for 1816 and 1849.[9] Both enrollment and age-specific population data come from full population censuses.[10]

The education measure in the second phase is a measure directly referring to the education level of the working-age population, namely the adult literacy rate, available (for the first and only time) in the 1871 population census. It measures the share of those who are able to read and write among the population aged ten years or older. As discussed below, we also experiment with data on upper secondary enrollment and university location at the three points in time.

The 1816 census contains a wealth of additional information, including data on population demographics, religion, livestock, and occupations. We compile an extensive set of indicators of pre-industrial development from this and other sources, including indicators for pre-industrial production and endowment, natural resources, transportation infrastructure, urbanization and population density, and other historical patterns of development (see online Appendix A).

Table A2 in the online Appendix reports basic descriptive statistics for the variables used in our analyses. The education data reveal a relatively advanced educational development in Prussia throughout the nineteenth century. The average enrollment rate in elementary and middle schools is 58 percent in 1816 and increases to 80 percent in 1849. Still, there is enormous variation across counties, ranging from 3 percent to 95 percent in 1816 (cf. Figure 1) and from 33 percent to 99 percent in 1849. The average and distributional statistics of 1849 school enrollment and 1871 literacy are surprisingly similar.

Industrialization in 1849 as measured by the share of factory workers in total population is relatively low at 1.8 percent on average. Half of this is in industries outside metals and textiles, 0.6 percent in metals, and 0.3 percent in textiles. Across counties, the measure varies from 0.4 percent to 18.5 percent.[11] As a share of the

[8] As so-called *Mittelschulen* (middle schools) are only available in towns, they are not reported in the county-level data, but in separate town-level data, which we combined into the county-level data (see online Appendix A). To ensure that this is not driving our results, we also interacted our education variables with an indicator for those 154 counties that include at least one such town and find that results do not differ substantially between counties with and without middle school data (see row C of Table A5 in the online Appendix).

[9] We calculated average years of schooling in the adult population using data on school enrollment and population structure by age groups (cf. Robert J. Barro and Jong-Wha Lee 2001). Assuming that enrollment rates changed steadily over time, enrollment rates are interpolated between the observed 1816 and 1849 values in each county. Using the age profile of the 1849 population in each county (available in the brackets 17–19, 20–24, 25–32, 33–39, 40–45, and 46–60), we calculate the resulting average years of elementary and middle schooling for the population aged 17–60 in 1849.

[10] If we use the directly observed enrollment rate in 1849 instead of the constructed measure of years of schooling in 1849, qualitative results are the same (see Becker, Hornung, and Woessmann 2009).

[11] Given the skewness of the distribution of the dependent variables, we also estimated specifications using their logarithms, obtaining the same qualitative results.

occupied labor force, factory employment amounts to 2.8 percent. By 1882, 11.6 percent of the population (or 27.0 percent of the occupied labor force) are employed in manufacturing, combining 3.1 percent in metals, 3.9 percent in textiles, and 4.6 percent in other manufacturing sectors. All industrialization measures expose substantial regional variation (cf. Figures A1 and A2 in the online Appendix).

As a first descriptive indication of the associations among the education and industrialization variables, Table A3 in the online Appendix reports pair-wise correlations. The education measures at the different points in time are strongly related to each other. They are also significantly associated with the aggregate measures of industrialization at the two phases, most obviously in the industries outside metals and textiles. Industrialization is also strongly associated over time, with the correlations within each of the three sectors being much stronger than across sectors.

IV. Results

A. *The First Phase of Industrialization*

The first part of Table 1 reports OLS regressions across the 334 Prussian counties in 1849, toward the end of the first phase of industrialization. The dependent variable measures industrialization by employment in factories as a share of the total county population in 1849, which we can subdivide into three sectors: all factories outside metals and textiles, metal factories, and textile factories. We start with a parsimonious model that controls only for basic demographic and geographic measures, namely the shares of the population aged below 15 and above 60 and the size of the county area, each of which might be expected to be negatively associated with industrialization.

The results reveal that toward the end of the first phase of the Industrial Revolution, the share of factory workers is significantly positively associated with years of elementary and middle schooling.[12] When looking into the three sectors, this is particularly true for industries outside metals and textiles, and also marginally for the metal industry, whereas there is no such significant association of education with industrialization in the textile industry.[13] However, as discussed above, any such OLS association may be biased because part of the labor force in 1849 obtained their education during industrial times, so that years of schooling in the adult population in 1849 may be endogenous to industrialization in 1849, with the direction of the bias unclear.

To address this issue, the remaining columns of Table 1 report IV estimates that instrument years of schooling in 1849 by school enrollment in 1816, before the onset of the Industrial Revolution. The instrument is not affected by changes in the demand for education that emerged during industrialization, which came exogenously from the industrial leader Britain. Under the assumption that 1816 school

[12] Throughout the paper, standard errors are clustered at the level of the 280 units of observation in the 1816 data that we use below (see online Appendix A for details). Results are very similar when data are aggregated up to the 280 original counties (see row B of Table A5 in the online Appendix).

[13] Although the dependent variables of our models are proportions that vary between 0 and 1, predicted values of a linear regression may fall outside the [0,1] interval. We thus used the logarithm of the odds ratio of the sector share as an alternative dependent variable that is not subject to this problem. Results are qualitatively the same.

Table 1—Education and Industrialization in the First Phase of the Industrial Revolution

Dependent variable	OLS: Share of factory workers in total population 1849			
	All factories (1)	All except metal and textiles (2)	Metal factories (3)	Textile factories (4)
Years of schooling 1849[a]	0.177**	0.156***	0.059	−0.038
	(*0.077*)	(*0.045*)	(*0.045*)	(*0.034*)
Share of population < 15 years	−0.016	−0.043*	0.040	−0.013
	(*0.046*)	(*0.026*)	(*0.027*)	(*0.014*)
Share of population > 60 years	−0.092	−0.134**	−0.057	0.100***
	(*0.096*)	(*0.063*)	(*0.048*)	(*0.038*)
County area (in 1,000 km²)	−0.011***	−0.004***	−0.005**	−0.002**
	(*0.002*)	(*0.001*)	(*0.002*)	(*0.001*)
Constant	0.028	0.028**	−0.005	0.005
	(*0.020*)	(*0.012*)	(*0.010*)	(*0.006*)
Observations	334	334	334	334
R^2	0.103	0.140	0.035	0.063

Dependent variable	IV: 1st stage Years of schooling 1849	IV: 2nd stage Share of factory workers in total population 1849			
	(5)	All factories (6)	All except metal and textiles (7)	Metal factories (8)	Textile factories (9)
Years of schooling 1849[a]		0.132*	0.135***	0.045	−0.048
		(*0.077*)	(*0.044*)	(*0.046*)	(*0.033*)
School enrollment rate 1816	0.061***				
	(*0.001*)				
Share of population < 15 years	0.019**	−0.019	−0.044*	0.039	−0.014
	(*0.008*)	(*0.045*)	(*0.026*)	(*0.027*)	(*0.014*)
Share of population > 60 years	0.078***	−0.074	−0.126**	−0.052	0.104***
	(*0.016*)	(*0.094*)	(*0.062*)	(*0.047*)	(*0.038*)
County area (in 1,000 km²)	−0.001***	−0.011***	−0.004***	−0.005**	−0.002**
	(*0.0003*)	(*0.002*)	(*0.001*)	(*0.002*)	(*0.001*)
Constant	0.006*	0.031	0.029**	−0.004	0.006
	(*0.004*)	(*0.019*)	(*0.012*)	(*0.010*)	(*0.006*)
Observations	334	334	334	334	334
R^2	0.968	0.102	0.139	0.034	0.063
First-stage F-statistic	6,206.97				

Notes: [a] Coefficients multiplied by 100.
Standard errors (adjusted for clustering by 280 original counties) in parentheses.
***Significant at the 1 percent level.
**Significant at the 5 percent level.
*Significant at the 10 percent level.

Source: Data for Prussian counties from different censuses; see online Appendix A for details.

enrollment is not correlated with other measures that are themselves related to subsequent industrialization, these IV estimates depict the causal effect of education on industrialization in Prussia. We will address concerns with this assumption below.

Table 2—The Reduced-Form Effect of 1816 School Enrollment on Subsequent Industrialization

	All industries (1)	All except metals and textiles (2)	Metal industries (3)	Textile industries (4)
(A) End of first phase of Industrial Revolution (1849)	0.008*	0.008***	0.003	−0.003
(parsimonious model)	(*0.005*)	(*0.003*)	(*0.003*)	(*0.002*)
(B) End of first phase of Industrial Revolution (1849)	0.011**	0.007***	0.006*	−0.003
(model with controls for pre-industrial development)	(*0.005*)	(*0.003*)	(*0.004*)	(*0.002*)
(C) End of second phase of Industrial Revolution (1882)	0.043***	0.022***	0.029***	−0.008
	(*0.013*)	(*0.004*)	(*0.009*)	(*0.008*)
(D) Progress during second phase of Industrial Revolution	0.030**	0.018***	0.023***	−0.006
(1882, controlling for industrialization in 1849)	(*0.012*)	(*0.004*)	(*0.009*)	(*0.006*)

Notes: Coefficient on school enrollment rate 1816. Dependent variable in 1849: share of factory workers (in the respective industry) in total population. Dependent variable in 1882: share of manufacturing workers (in the respective industry) in total population. Models in row A control for the basic demographic and geographic measures of Table 1. Models in rows B–D control for the full set of control variables shown in Tables 3–5, respectively. Standard errors (adjusted for clustering by 280 original counties) in parentheses.

***Significant at the 1 percent level.

**Significant at the 5 percent level.

*Significant at the 10 percent level.

Source: Data for 334 Prussian counties from different censuses; see online Appendix A for details.

As the first stage (column 5) shows, 1816 school enrollment provides a powerful instrument for adult schooling in 1849.[14] The second-stage estimate for total factory employment in all industries is statistically significant (column 6). This effect is fully borne by the industries outside metals and textiles, whereas the estimate in the latter two sectors is not statistically significant. We will discuss the size of the estimates below.

The significantly positive association of pre-industrial school enrollment with industrialization in general, and industrialization outside metals and textiles in particular, is also evident in the reduced-form models (Table 2).

B. *Is Pre-existent Education Exogenous?*

For pre-industrial levels of education to be a valid instrument, we have to assume that there are no other features correlated with education in 1816 that also correlate with subsequent industrialization. In order to test this assumption, we extend our model with a host of indicators of pre-industrial development, testing whether the IV estimates are robust to their inclusion.

The indicator of pre-industrial development most often used in the literature is urbanization, as cities could only be supported where agricultural productivity was high, specialization advanced, and the transport systems were well developed (cf. Paul Bairoch 1988; Acemoglu, Johnson, and Robinson 2002). Thus, the first column of Table 3 adds the share of a county's population living in cities in 1816, defined by the Prussian

[14] The large partial *F*-statistic of the first stage is due to the fact that 1816 school enrollment enters the construction of the measure of 1849 adult schooling. If, instead, 1816 enrollment is used as an instrument for independently observed 1849 enrollment, the *F*-statistic is 69.7 (see Becker, Hornung, and Woessmann 2009).

Table 3—Accounting for Pre-industrial Development

Dependent variable	Share of factory workers in total population 1849			
	All factories			
	(1)	(2)	(3)	(4)
Years of schooling 1849[a]	0.152**	0.145**	0.170**	0.153**
	(0.075)	*(0.072)*	*(0.066)*	*(0.066)*
Share of population < 15 years	0.068	0.059	0.045	0.054
	(0.048)	*(0.045)*	*(0.045)*	*(0.050)*
Share of population > 60 years	0.075	0.049	0.048	0.080
	(0.088)	*(0.084)*	*(0.074)*	*(0.075)*
County area (in 1,000 km²)	−0.010***	−0.009***	−0.008***	−0.006***
	(0.002)	*(0.002)*	*(0.002)*	*(0.002)*
Share of population living in cities 1816	0.020***	0.017***	0.017***	0.017***
	(0.006)	*(0.006)*	*(0.006)*	*(0.006)*
Looms per capita 1819		0.195***	0.181***	0.174***
		(0.049)	*(0.048)*	*(0.047)*
Steam engines in mining per capita 1849			0.046***	0.045***
			(0.006)	*(0.006)*
Sheep per capita 1816				−0.001
				(0.002)
Share of farm laborers in total population 1819				−0.056***
				(0.015)
Constant	−0.015	−0.012	−0.010	−0.010
	(0.020)	*(0.019)*	*(0.018)*	*(0.020)*
Observations	334	334	334	334
R^2	0.138	0.184	0.238	0.253

(*Continued*)

Statistical Office as having city rights and privileges (which applies for roughly 1,000 Prussian cities). While urbanization in 1816 is indeed significantly associated with subsequent industrialization, the estimated effect of education is hardly affected. Very similar results are obtained when measuring urbanization by the population share living in one of the 172 large or medium-sized cities, defined as having more than 2,000 inhabitants (not shown). Population density, measured as inhabitants per square kilometer, does not enter the model significantly or affect the education estimate.

By 1816, proto-industrial technologies were already emerging. To account for their possible impact, column 2 adds the number of looms per capita in 1819 as a leading pre-industrial technology. Looms in 1819 enter the model significantly but hardly affect the education estimate. Other indicators of pre-industrial technologies, such as the number of brick making plants and watermills per capita in 1819, do not enter the model significantly (not shown).

Several industries are highly resource dependent, such as those requiring coal for energy or specific metals for production. We are not aware of measures quantifying the availability or potential of mineral resources around 1816. However, we know the number of steam engines employed in mining in 1849. To the extent that actual resource exploitation, and in particular the use of steam engines, is endogenous to industrialization itself, using this measure to control for resource availability over-adjusts our specification. However, as column 3 reveals, if anything, the estimated

TABLE 3—ACCOUNTING FOR PRE-INDUSTRIAL DEVELOPMENT (*Continued*)

Dependent variable	Years of schooling 1849[a] (5)[b]	Share of factory workers in total population 1849			
		All factories (6)	All except metal and textiles (7)	Metal factories (8)	Textile factories (9)
Years of schooling 1849[a]		0.182**	0.124***	0.106*	−0.048
		(*0.080*)	(*0.046*)	(*0.058*)	(*0.029*)
School enrollment rate 1816	0.060***				
	(*0.001*)				
Share of population < 15 years	0.020***	0.050	−0.010	0.055	0.005
	(*0.008*)	(*0.050*)	(*0.022*)	(*0.038*)	(*0.018*)
Share of population > 60 years	0.083***	0.085	−0.056	−0.005	0.146***
	(*0.016*)	(*0.074*)	(*0.054*)	(*0.033*)	(*0.046*)
County area (in 1,000 km²)	−0.001**	−0.005**	−0.004***	−0.001	−0.0003
	(*0.0003*)	(*0.002*)	(*0.001*)	(*0.001*)	(*0.001*)
Share of population living in cities 1816	0.0001	0.020***	0.009***	0.006	0.005*
	(*0.001*)	(*0.007*)	(*0.003*)	(*0.005*)	(*0.003*)
Looms per capita 1819	0.006*	0.154***	0.021	0.057*	0.075*
	(*0.003*)	(*0.046*)	(*0.020*)	(*0.034*)	(*0.039*)
Steam engines in mining per capita 1849	0.002	0.043***	0.001	0.038***	0.004
	(*0.001*)	(*0.005*)	(*0.003*)	(*0.004*)	(*0.004*)
Sheep per capita 1816	0.0003	−0.0004	0.002**	−0.002*	−0.001
	(*0.0003*)	(*0.002*)	(*0.001*)	(*0.001*)	(*0.001*)
Share of farm laborers in total population 1819	−0.007**	−0.057***	−0.006	−0.018**	−0.033***
	(*0.004*)	(*0.017*)	(*0.010*)	(*0.007*)	(*0.012*)
Public buildings per capita 1821	0.130***	−0.290	0.068	−0.337**	−0.022
	(*0.037*)	(*0.283*)	(*0.169*)	(*0.160*)	(*0.127*)
Paved streets 1815 (dummy)	0.001*	0.003	0.003**	0.001	−0.001
	(*0.0003*)	(*0.002*)	(*0.001*)	(*0.002*)	(*0.001*)
Tonnage of ships per capita 1819	0.001	−0.032**	−0.004	−0.014*	−0.014***
	(*0.008*)	(*0.015*)	(*0.009*)	(*0.007*)	(*0.005*)
Constant	0.006	−0.010	0.009	−0.016	−0.003
	(*0.004*)	(*0.020*)	(*0.010*)	(*0.014*)	(*0.008*)
Observations	334	334	334	334	334
R^2	0.970	0.266	0.216	0.162	0.172
First-stage F-statistic	5507.59				

Notes: Instrumental-variable estimates, with years of schooling 1849 instrumented by school enrollment rate 1816.
[a] Coefficients multiplied by 100.
[b] First stage for columns 6 to 9.
Standard errors (adjusted for clustering by 280 original counties) in parentheses.
*** Significant at the 1 percent level.
** Significant at the 5 percent level.
* Significant at the 10 percent level.

Source: Data for Prussian counties from different censuses; see online Appendix A for details.

effect of education increases when steam engines in mining per capita are included, even though the latter is positively associated with factory employment. Another available proxy for mining is the number of fatalities in mining per capita in 1853, which, when used as an alternative to the steam engine measure, also enter the model significantly, but do not affect the qualitative result on education (not shown). Results are also robust when adding a dummy for the 53 counties with any mining incidence according to the steam engine and fatalities measures. Alternatively, we can exclude workers in iron, wire, brass, smelter of other metals, steel, and copper-hammer factories from our factory count, yielding similar results (not shown).[15]

In fact, any issues of access to mineral resources would only affect the result on education if the instrument, school enrollment before the onset of the industrialization, were significantly correlated with the geographical distribution of deposits of mineral resources. This seems quite unlikely, given that the resources of interest only became of real relevance during and because of the Industrial Revolution. In fact, school enrollment in 1816 is uncorrelated with the different indicators of later mining—the indicator for use of steam engines in mining in 1849, iron working factories in 1849, and mining in 1882—(all p values exceed 0.75), and there is even a slightly negative correlation with 1849 steam engines in mining per capita.

Another resource relevant in particular for the textile industry is wool, which we can proxy by the number of sheep in 1816. More generally, counts of different livestock in 1816 provide measures of agricultural development. However, such agricultural measures at the time may also proxy for a lack of development in terms of craftsmen, commerce, and other businesses. The latter aspect can also be captured by the share of farm laborers in the county population, available for 1819. The number of sheep per capita is unrelated to subsequent industrialization, whereas agricultural employment is negatively associated with subsequent industrialization (column 4 of Table 3). But again, neither affects the education estimate. As a measure of dependent labor, the share of servants in the total county population also enters the model negatively but leaves the education result unaffected (not shown). A host of additional livestock counts, such as the number of cattle, horses, pigs, oxen, bulls, and foals, are either insignificantly or negatively associated with subsequent industrialization, and none affects the education result (not shown).

Finally, public infrastructure in existence before the industrialization may have facilitated the adoption of industrial technologies. We obtained data on the number of public utility buildings in 1821. To account for transport infrastructure, we also obtained an indicator on whether paved interregional streets existed in the county in 1815, as well as a measure of the tonnage capacity of transport ships in 1819. These measures may also capture differential connectedness, such as trade access, of Prussian counties with the outside world, especially Britain. As is evident from column 6 of Table 3, none of these is significantly positively associated with later industrialization, and none affects the qualitative education result. The same is true when the length of navigable rivers is added as an alternative measure of transport infrastructure (not shown).

The size of the estimated effect of education on industrialization actually increases to 0.182 (relative to 0.132 in the base model) once the whole set of indicators of pre-industrial development is added to the model. Rather than mitigating the estimated effect of education on industrialization, accounting for pre-industrial development actually strengthens the education result. This suggests that the downward bias of a negative effect of industrialization on the demand for education dominates in the first phase of industrialization.

[15] Similarly, the 1882 census provides a subcategory for manufacturing industries in mining, steel-mill operations, and salt production. Our results below are robust to excluding workers in this subsector from our manufacturing variable, and also to including the subsector as an additional control.

Results of this preferred specification for the three industrial subsectors (columns 7–9) show strong evidence for a positive effect of education on industrial development outside the metal and textile industries during the first phase of the Industrial Revolution until 1849, and some evidence for a positive effect in the metal industry. By contrast, there is no evidence that education positively affected industrialization in the textile industry. This pattern of results is similarly visible in the reduced-form models (Table 2), confirming the association between pre-industrial education and industrialization outside textiles.

As should be expected, among the pre-industrial development controls, looms in 1819 are particularly relevant in predicting industrialization in textiles, whereas steam engines in 1849 mining are particularly relevant in predicting industrialization in metals. Having a paved street in 1815 is particularly relevant in predicting industrialization outside these two specific industries, in line with the view that connectedness with the outside world, and in particular with Britain, may have been particularly relevant in nontraditional sectors.

C. *The Second Phase of Industrialization*

Table 4 reports results of the model with pre-industrial development controls for the second phase of industrialization. Both OLS and IV estimates show a significant positive effect of literacy (measured in 1871) on total manufacturing employment in 1882. Again, 1816 school enrollment is a strong instrument for 1871 literacy in the first stage of the IV specification. The significant positive impact of education on industrialization is evident both in the industries outside metals and textiles and in the metal industry but (in the IV model), again, not in textiles. It seems that by focusing on the textile industry, a lot of the existing literature may have missed the important role of education in the Industrial Revolution (see online Appendix D for discussion).

We now turn to a discussion of the size of the estimated effect of education in the two phases. Our estimates suggest that in 1849, one additional year of average schooling led to a 0.18 percentage point higher per capita factory employment (equivalent to 0.32 percentage point higher per worker factory employment, see Section IVD). In the 1870s/1880s, a 10 percentage point higher literacy rate led to 1.4 percentage point higher per capita manufacturing employment (or 3.2 percentage point higher per worker manufacturing employment). This may not seem very much, as it suggests that only about one in three additionally educated workers went into industrial production in 1882, and much less in 1849. The majority of workers with basic education still worked outside the industrial sector.

However, estimated effect sizes are quite substantial viewed against the average level of industrialization reached at the time. In 1849, average per capita factory employment was only 1.8 percent (ranging from 0.4 percent to 8.5 percent from the first to the ninety-ninth percentile). A simple linear simulation would suggest that if all counties would have had only the education level of the first percentile county (1.9 rather than the actual 5.2 average years of schooling), per capita factory employment would have been 0.6 percentage points lower. In other words, in this thought experiment, industrial production in Prussia would have been a third lower if she had had such a low level of education.

Table 4—Education and Industrialization in the Second Phase of the Industrial Revolution

Dependent variable	OLS Share of manufacturing workers in total population 1882			
	All manufacturing (1)	All except metal and textiles (2)	Metal manufacturing (3)	Textile manufacturing (4)
Literacy rate 1871	0.215***	0.065***	0.121***	0.029***
	(*0.021*)	(*0.008*)	(*0.016*)	(*0.011*)
Share of population < 15 years	0.034	−0.043	0.223***	−0.146**
	(*0.080*)	(*0.033*)	(*0.052*)	(*0.057*)
Share of population > 70 years	−1.226***	−0.086	−1.837***	0.697**
	(*0.396*)	(*0.128*)	(*0.308*)	(*0.274*)
County area (in 1,000 km²)	−0.013***	−0.003*	−0.005*	−0.005
	(*0.005*)	(*0.002*)	(*0.003*)	(*0.004*)
Share of population living in cities 1816	0.041***	0.028***	−0.005	0.018*
	(*0.013*)	(*0.004*)	(*0.006*)	(*0.010*)
Looms per capita 1819	0.827***	0.049	0.076	0.701**
	(*0.306*)	(*0.043*)	(*0.071*)	(*0.311*)
Steam engines in mining per capita 1849	0.157***	−0.0003	0.168***	−0.011
	(*0.015*)	(*0.005*)	(*0.020*)	(*0.014*)
Sheep per capita 1816	−0.024***	−0.005***	−0.009***	−0.010***
	(*0.004*)	(*0.002*)	(*0.003*)	(*0.003*)
Share of farm laborers in total population 1819	−0.064	0.002	−0.036	−0.030
	(*0.052*)	(*0.016*)	(*0.029*)	(*0.042*)
Public buildings per capita 1821	−1.832***	0.020	−0.666**	−1.186***
	(*0.523*)	(*0.211*)	(*0.308*)	(*0.378*)
Paved streets 1815 (dummy)	0.003	0.006***	0.0004	−0.003
	(*0.006*)	(*0.002*)	(*0.004*)	(*0.004*)
Tonnage of ships per capita 1819	−0.018	0.022	−0.005	−0.035
	(*0.033*)	(*0.014*)	(*0.020*)	(*0.023*)
Constant	−0.028	0.005	−0.089***	0.056**
	(*0.036*)	(*0.015*)	(*0.022*)	(*0.024*)
Observations	334	334	334	334
R^2	0.684	0.660	0.599	0.436

(*Continued*)

Similarly, if all Prussian counties would have had a literacy rate of only 46 percent in 1871 (the first-percentile county) rather than the actual average 84 percent, then 1882 per capita manufacturing employment would have been 5.1 percentage points lower—close to half of the actual total per capita manufacturing employment of 11.6 percent. In sum, the variation in education that existed across Prussian counties can account for a substantial part of Prussian industrialization.

The estimates of Table 4 do not control for the level of industrialization already reached by the end of the first phase of the Industrial Revolution. To depict the effect of education on the progress of industrialization during the second phase, between 1849 and 1882, Table 5 adds the level of industrialization reached in 1849 as a control variable. In all three sectors, the 1849 share of factory workers in the sector enters significantly and strongly in predicting the 1882 employment share in the sector. Still, the significant positive impact of education on industrialization outside textiles remains, albeit slightly (but not statistically significantly) smaller. Thus, education affected

Table 4—Education and Industrialization in the Second Phase of the Industrial Revolution (*Continued*)

	IV				
Dependent variable	1st stage Literacy rate 1871	2nd stage Share of manufacturing workers in total population 1882			
		All manufacturing	All except metal and textiles	Metal manufacturing	Textile manufacturing
	(5)	(6)	(7)	(8)	(9)
Literacy rate 1871		0.136***	0.069***	0.093***	−0.026
		(0.036)	*(0.013)*	*(0.025)*	*(0.025)*
School enrollment rate 1816	0.315***				
	(0.038)				
Share of population < 15 years	−0.490***	−0.051	−0.038	0.192***	−0.205***
	(0.180)	*(0.095)*	*(0.034)*	*(0.051)*	*(0.072)*
Share of population > 70 years	5.300***	−0.802*	−0.109	−1.684***	0.992***
	(1.089)	*(0.440)*	*(0.133)*	*(0.306)*	*(0.274)*
County area (in 1000 km²)	−0.074***	−0.019***	−0.003	−0.007*	−0.009*
	(0.016)	*(0.006)*	*(0.002)*	*(0.004)*	*(0.005)*
Share of population living in cities 1816	0.028	0.038***	0.028***	−0.006	0.016*
	(0.031)	*(0.013)*	*(0.003)*	*(0.006)*	*(0.010)*
Looms per capita 1819	0.629***	0.897***	0.045	0.102	0.750**
	(0.215)	*(0.311)*	*(0.043)*	*(0.069)*	*(0.314)*
Steam engines in mining per capita 1849	0.092	0.161***	−0.001	0.169***	−0.008
	(0.057)	*(0.015)*	*(0.006)*	*(0.021)*	*(0.012)*
Sheep per capita 1816	0.038***	−0.021***	−0.005***	−0.008***	−0.008***
	(0.012)	*(0.005)*	*(0.002)*	*(0.003)*	*(0.003)*
Share of farm laborers in total population 1819	−0.291**	−0.087*	0.003	−0.044	−0.046
	(0.119)	*(0.052)*	*(0.016)*	*(0.032)*	*(0.039)*
Public buildings per capita 1821	3.292*	−0.876	−0.033	−0.321	−0.522
	(1.751)	*(0.632)*	*(0.227)*	*(0.414)*	*(0.407)*
Paved streets 1815 (dummy)	0.066***	0.010	0.005***	0.003	0.001
	(0.011)	*(0.006)*	*(0.002)*	*(0.004)*	*(0.004)*
Tonnage of ships per capita 1819	−0.023	−0.017	0.022*	−0.005	−0.035
	(0.145)	*(0.033)*	*(0.013)*	*(0.018)*	*(0.023)*
Constant	0.718***	0.057	0.001	−0.058*	0.114***
	(0.085)	*(0.054)*	*(0.019)*	*(0.030)*	*(0.041)*
Observations	334	334	334	334	334
R^2	0.643	0.666	0.660	0.592	0.408
First-stage F-statistic	69.85				

Note: Standard errors (adjusted for clustering by 280 original counties) in parentheses.
***Significant at the 1 percent level.
**Significant at the 5 percent level.
*Significant at the 10 percent level.

Source: Data for Prussian counties from different censuses; see online Appendix A for details.

industrialization not only during the first phase of the Industrial Revolution, but also the additional progress of industrialization during the second phase.

D. *Additional Robustness Tests*

As an alternative approach to identification, we use distance to Wittenberg, Germany as an instrument for education within Prussia because of Luther's urge for

Bible reading (Becker and Woessmann 2009). As reported in online Appendix F, the specification confirms our previous results.

To test whether Protestantism had a significant independent effect on industrialization, we can add the share of Protestants in a county to the model. Such a model is reported in columns 1 and 6 of Table 6. In line with Becker and Woessmann (2009), the Protestant share is not significantly associated with industrialization once the effect of education is controlled for. The next columns add the share of Jews, which is negatively associated with industrialization. This may depict the traditional role of the Jewish community in merchant occupations, outside industry. The effect of education is robust to the inclusion of the religious indicators.

To test whether it mattered how long a county had been part of the common institutional and legal framework of Prussia, columns 3 and 8 add the year when a county was annexed by Prussia. While later annexations tended to be more likely to industrialize during the second phase, accounting for this actually increases the estimated effect of education.

The county of Iserlohn, which was well-known as a leading industrial center worldwide in the first half of the nineteenth century for its large metalworking factories (evidenced, for example, by an Iserlohn-produced coat of mail on display in the Tower of London), is a significant outlier in metal factories during the first phase. In Iserlohn, 16.5 percent of the population worked in metal factories in 1849, whereas the next biggest share in any other Prussian county was 5.9 percent. The qualitative results on the impact of education on industrialization are unaffected when estimating the models without Iserlohn to ensure that results are not driven by this outlier (not shown).

To test whether our estimates are affected by local migration, we compute the average of the education variables for each county and its neighboring counties (defined as sharing a border). In some cases, children from one county might have enrolled in school in a neighboring county, so that this average might reduce measurement error in the education variables. The average education level also addresses the fact that the industrial labor force might have been recruited on a broader regional market, capturing regional migration in search of employment. As the results reported in columns 4 and 9 of Table 6 show, results are robust when using the regional average of the education variables. The point estimates even increase in size, suggesting that regional migration for school or work might indeed attenuate the previous findings.

As additional tests for migration, we can add indicators of the shares of the county population that were born in the respective municipality and that are of Prussian origin, both available for 1871 (not shown). The estimated effect of education is robust to the inclusion of these migration indicators and even increases in size, again, suggesting that, if anything, migration biases the estimated effect of home-county education downward.

All models so far measure industrial employment as a share of the total county population, which is unaffected by possible endogeneity of total employment. Columns 5 and 10 of Table 6 instead use the share of industrial employment in the occupied labor force as the dependent variable. The results suggest that one additional year of schooling resulted in an 1849 share of factory workers in the labor force that was 0.32 percentage points higher, and a 10 percentage point increase in the literacy rate resulted in an 1882 share of manufacturing workers in the labor

Table 5—The Progress of Industrialization between 1849 and 1882

Dependent variable	Literacy rate 1871	Share of manufacturing workers in total population 1882			
		All manufacturing	All except metals and textiles	Metal manufacturing	Textile manufacturing
	(1)	(2)	(3)	(4)	(5)
Literacy rate 1871		0.101***	0.060***	0.076***	−0.018
		(*0.036*)	(*0.012*)	(*0.024*)	(*0.020*)
School enrollment rate 1816	0.301***				
	(*0.037*)				
Share of factory workers in total population 1849[a]	1.183***	0.923***	0.370***	0.875***	1.767***
	(*0.312*)	(*0.168*)	(*0.128*)	(*0.210*)	(*0.475*)
Share of population living in cities 1816	0.009	0.024**	0.025***	−0.008	0.009
	(*0.031*)	(*0.012*)	(*0.004*)	(*0.005*)	(*0.008*)
Looms per capita 1819	0.443**	0.774**	0.043	0.063	0.602**
	(*0.203*)	(*0.302*)	(*0.042*)	(*0.048*)	(*0.264*)
Steam engines in mining per capita 1849	0.042	0.125***	0.0002	0.140***	−0.020*
	(*0.057*)	(*0.017*)	(*0.005*)	(*0.022*)	(*0.011*)
Sheep per capita 1816	0.038***	−0.019***	−0.005***	−0.006**	−0.007***
	(*0.012*)	(*0.004*)	(*0.002*)	(*0.002*)	(*0.002*)
Share of farm laborers in total pop. 1819	−0.225*	−0.046	0.003	−0.033	0.011
	(*0.116*)	(*0.050*)	(*0.016*)	(*0.030*)	(*0.035*)
Public buildings per capita 1821	3.528**	−0.575	−0.033	−0.021	−0.551
	(*1.661*)	(*0.604*)	(*0.226*)	(*0.402*)	(*0.344*)
Paved streets 1815 (dummy)	0.063***	0.009*	0.005**	0.003	0.002
	(*0.011*)	(*0.005*)	(*0.002*)	(*0.003*)	(*0.003*)
Tonnage of ships per capita 1819	0.014	0.011	0.023*	0.007	−0.009
	(*0.136*)	(*0.031*)	(*0.012*)	(*0.016*)	(*0.018*)
Observations	334	334	334	334	334
R^2	0.659	0.702	0.683	0.658	0.541
First-stage F-statistic	65.29				

Notes: Instrumental-variable estimates, with literacy rate 1871 instrumented by school enrollment rate 1816. Additional controls: share of population < 15 years, share of population > 70 years, county area (in 1,000 km²), and a constant. Column 1 reports the first stage for column 2.

[a] Columns 1 and 2: all factories; column 3: all factories except metals and textiles; column 4: metal factories; column 5: textile factories.

Standard errors (adjusted for clustering by 280 original counties) in parentheses.

***Significant at the 1 percent level.
**Significant at the 5 percent level.
*Significant at the 10 percent level.

Source: Data for Prussian counties from different censuses; see online Appendix A for details.

force that was 3.2 percentage points higher. Results are very similar when using the population aged older than 16 (available in 1849) or the population aged 20 to 69 (available in 1882) as the denominator instead of the occupied labor force.

Results reported so far refer to basic education, measured by years of elementary and middle schooling and by literacy rates. On average, enrollment rates in upper secondary schools did not surpass 5 percent throughout our nineteenth century data, and a maximum of 8 universities existed on Prussian ground. When we add upper secondary enrollment rates and universities to our models, they do not enter significantly (mostly with a negative point estimate) and do not change the significant positive effects of

Table 6—Additional Robustness Specifications

Dependent variable	Share of all factory workers 1849 in				
	Total population				Occupied labor force
	(1)	(2)	(3)	(4)[b]	(5)
Years of schooling 1849[a]	0.153*	0.149*	0.184***	0.238**	0.324**
	(*0.084*)	(*0.082*)	(*0.071*)	(*0.118*)	(*0.142*)
Share Protestants 1816	0.002				
	(*0.002*)				
Share Jews 1816		−0.062**			
		(*0.032*)			
Year in which annexed by Prussia			0.001		
			(*0.017*)		
Observations	334	334	334	334	334
R^2	0.267	0.269	0.266	0.268	0.351
Dependent variable	**Share of all manufacturing workers 1882 in**				
	Total population				Occupied labor force
	(6)	(7)	(8)	(9)[b]	(10)
Literacy rate 1871	0.135***	0.104**	0.178***	0.142***	0.316***
	(*0.037*)	(*0.042*)	(*0.033*)	(*0.035*)	(*0.084*)
Share Protestants 1816	0.001				
	(*0.006*)				
Share Jews 1816		−0.284**			
		(*0.113*)			
Year in which annexed by Prussia			0.079***		
			(*0.028*)		
Observations	334	334	334	334	334
R^2	0.666	0.656	0.690	0.663	0.663

Notes: Instrumental-variable estimates, with years of schooling 1849 resp. literacy rate 1871 instrumented by school enrollment rate 1816. Additional controls: share of population < 15 years, share of population > 60 years (70 years in 1882), county area (in 1000 km²), share of population living in cities 1816, looms per capita 1819, steam engines in mining per capita 1849, sheep per capita 1816, share of farm laborers in total population 1819, public buildings per capita 1821, paved streets 1815 (dummy), tonnage of ships per capita 1819, and a constant. Standard errors (adjusted for clustering by 280 original counties) in parentheses.

[a] Coefficients multiplied by 100.

[b] In columns 4 and 9, years of schooling and literacy are measured as average of years of schooling/literacy of each county and its neighboring counties.

***Significant at the 1 percent level.

**Significant at the 5 percent level.

*Significant at the 10 percent level.

Source: Data for Prussian counties from different censuses; see online Appendix A for details.

basic education (not shown). This suggests that the basic follower mechanisms highlighted in Section I, which stress the role of basic education for technology diffusion, rather than higher skill or entrepreneurial channels, were most relevant for relative regional industrialization in Prussia in the nineteenth century.

Finally, Table 7 reports a set of geographical robustness tests. As is evident in Figure 1, Prussia in 1849 was divided into two separated parts: the Rhineland and

Westphalia to the West and the other provinces to the East. To ensure that results are not driven by this separation, columns 1 and 6 add a dummy for the Western parts. Results are qualitatively unaffected, and the Western dummy is insignificant. However, it is significantly negative in the estimation for industries outside metals and textiles and significantly positive for the metal industry (not shown), in line with the coal-driven industrialization in the Ruhr area. Still, the qualitative results on the effect of education remain unaffected also in the two subsectors.

To control for possible differences in counties with Slavic languages, columns 2 and 7 add an indicator for counties located in Poland today. While the indicator enters significantly negatively (although not outside metals and textiles, not shown), the qualitative results for the education effect remain the same. The same qualitative results are also obtained when including an indicator for the three predominantly Polish-speaking provinces: Prussia, Poznan, and Silesia.

As additional geographical robustness tests, columns 3 and 8 augment the model by distance to Berlin as the Prussian capital, distance to the closest province capital, and distance to London. The latter measure may capture effects of the geographical distance to Britain, where the new industrial technologies originated. As expected, industrialization is lower the further away a county is from London and from Berlin, and the closer it is to a province capital. However, none of these controls affects the qualitative result on the role of education in industrialization. The specification in columns 4 and 9 even adds a full geographical grid of latitude and longitude, again, leaving the education result unaffected. To account for the possibility that the distribution of land may have been correlated with both education and industrialization (see Galor, Moav, and Dietrich Vollrath 2009), columns 5 and 10 control for landownership inequality (available only in 1849; see also Becker, Francesco Cinnirella, and Woessmann 2010). While land ownership inequality is negatively associated with industrialization, results on education are unaffected. Finally, controlling for urbanization in 1849 does not alter our main findings (see row D of Table A5 in the online Appendix).

E. *Panel Estimation*

In order to implement the panel models of Section IIC, we combine our three observation periods (1816, 1849, and 1882) into one panel. As pointed out before, the definition of our main variables is not identical in the different periods. While 1849 industrialization is measured by factory employment as a share of total county population, in 1882 the numerator is employment in the manufacturing sector. As a measure of industrialization in 1816, we use employment in brick making plants, lime kilns, and glass kilns (collected in the 1819 Establishment Census) as a share of total county population, which is the available measure closest to proto-industrial employment in 1816.[16] Results are robust to assuming zero industrialization in 1816 throughout. To ensure that the measure of education has the same basic concept of a share in all three waves, our measure of 1849 education in the panel models is age-weighted school enrollment rather than years of schooling (which boils down to a linear transformation

[16] As the 1819 census only reports establishment counts but not employment counts, we scale up the establishment measure by the average factory size observed in our 1849 data.

of the latter), where the weights are again given by the adult age structure observed in 1849. Note that in the case of both industrialization and education measures, systematic level differences across the variable definitions over time will be captured by time fixed effects that can be included in the panel model. It seems fair to assume that any remaining measurement differences are not related to our relationships of interest, so that they will reduce statistical precision (when in the industrialization measure) or attenuate the coefficient estimates (when in the education measure).

Table 8 reports the results of the panel models. For comparison, the first two columns show pooled models without fixed effects. The next columns add, consecutively, county and time fixed effects. In all panel models, there is a robust significant effect of education on industrialization, and its size is hardly affected by model variations once basic controls are included.

Results are also robust to controlling for the lagged dependent variable. Column 6 first shows that the basic fixed-effect model holds when reducing the panel to the two time periods after the onset of the Industrial Revolution. Column 7 then reveals that the result is hardly affected by adding lagged industrialization among the controls, so that only the change in industrialization during each phase is used as the outcome.

The final two columns report the two stages of an IV model that instruments education by its lag, which proves a powerful instrument. The effect of education on industrialization is confirmed in the second stage, although precision and point estimate are reduced in this model. Note, however, that this specification effectively excludes most of the variation of interest. As is well-known, estimating IV models in panels with fixed effects is very demanding and stretches our data and analysis quite far, so that such results can be somewhat sensitive to model specifications.

The panel analyses with county fixed effects confirm our previous results. They show that the cross-sectional results are not driven by pre-existing level differences across counties in the propensity to industrialize. Given that the point estimates are very close to the cross-sectional specifications of Tables 4 and 5, the latter results cannot be driven by time-invariant omitted factors. The IV strategy combined with the rich set of pre-industrial controls apparently ensure that they do not suffer from first-order bias due to unobserved heterogeneity across counties driving both pre-industrial education levels and subsequent industrialization.

V. Conclusion

To test whether leader-follower models that stress the role of education in technological catch-up have a bearing for the Industrial Revolution, this paper analyzed the role of education in industrial catch-up across Prussian counties over the nineteenth century. We interpret the situation as an "historical experiment," where the industrial technologies came as an exogenous shock to Prussia once the fundamental institutional reforms of the early 1800s had unleashed the potential for economic change. Although historical commentary sometimes argues that education played a prominent role in the emerging Industrial Revolution, positive evidence on this is virtually nonexistent. Sound empirical evidence, mostly restricted to textile industries in the industrial leader Britain, rather suggests no role for education, at least during the first phase of industrialization.

Table 7—Geographical Robustness Specifications

Dependent variable	Share of all factory workers in total population 1849				
	(1)	(2)	(3)	(4)	(5)
Years of schooling 1849[a]	0.185**	0.174**	0.168**	0.184**	0.169**
	(*0.082*)	(*0.077*)	(*0.077*)	(*0.079*)	(0.077)
Western part	0.002				
	(*0.003*)				
Polish parts		−0.006***			
		(*0.002*)			
Distance to Berlin (in 1,000 km)			−0.013**		
			(*0.006*)		
Distance to next province capital (in 1,000 km)			0.025		
			(*0.016*)		
Distance to London (in 1,000 km)			−0.012***		
			(*0.003*)		
Latitude (in rad)				−0.042	
				(*0.032*)	
Longitude (in rad)				−0.038**	
				(*0.016*)	
Landownership inequality					−0.067**
					(*0.031*)
Observations	334	334	334	334	334
R^2	0.269	0.286	0.303	0.294	0.270

Dependent variable	Share of all manufacturing workers in total population 1882				
	(6)	(7)	(8)	(9)	(10)
Literacy rate 1871	0.137***	0.129***	0.112***	0.130***	0.119***
	(*0.035*)	(*0.036*)	(*0.034*)	(*0.033*)	(*0.038*)
Western part	0.006				
	(*0.008*)				
Polish parts		−0.018**			
		(*0.007*)			
Distance to Berlin (in 1,000 km)			−0.075***		
			(*0.014*)		
Dist. to next province capital (in 1,000 km)			0.164***		
			(*0.041*)		
Distance to London (in 1,000 km)			−0.045***		
			(*0.011*)		
Latitude (in rad)				−0.292***	
				(*0.096*)	
Longitude (in rad)				−0.110**	
				(*0.045*)	
Landownership inequality					−0.402***
					(*0.115*)
Observations	334	334	334	334	334
R^2	0.668	0.678	0.718	0.698	0.670

Notes: Instrumental-variable estimates, with years of schooling 1849 resp. literacy rate 1871 instrumented by school enrollment rate 1816. Additional controls: share of population < 15 years, share of population > 60 years (70 years in 1882), county area (in 1000 km²), share of population living in cities 1816, looms per capita 1819, steam engines in mining per capita 1849, sheep per capita 1816, share of farm laborers in total population 1819, public buildings per capita 1821, paved streets 1815 (dummy), tonnage of ships per capita 1819, and a constant. Standard errors (adjusted for clustering by 280 original counties) in parentheses.

[a] Coefficients multiplied by 100.

*** Significant at the 1 percent level.

** Significant at the 5 percent level.

* Significant at the 10 percent level.

Source: Data for Prussian counties from different censuses; see online Appendix A for details.

By contrast, we find that education had a significant effect on aggregate industrialization in both phases of the Industrial Revolution in Prussia. The aggregate result conceals important sectoral differences though. We find no such effect in the textile industry in either phase, possibly due to substantial path dependence that made change in this sector slow and incremental rather than disruptive, in particular in Prussia. But the effect of education is substantial during both phases in the bulk of industry, outside of textiles. Industrial development in the nontextile sectors, which experienced more radical change or were even newly created, depended on the availability of an educated population that was earlier aware of the productive potential of new technologies and more capable of adjusting to change. Some regions lacked these skills necessary to adopt the new industrial technologies from and catch up to Britain. Quantitatively, the variation in education levels that existed across Prussian counties can account for a substantial part of Prussian industrialization. A simple linear simulation suggests that if all Prussian counties had had only the education level of the first percentile county, industrialization in Prussia would have been lower by more than one-third both in 1849 and in 1882.

The catch-up hypothesis can take different forms, with schooling facilitating industrialization, or the adoption of new technologies more broadly, or the ability to adapt to changing economic conditions in the broadest sense. Our evidence ultimately tests the narrow form and does not directly discriminate it from the broader ones. However, two aspects of our results provide some, admittedly speculative, indication on the relative merits of the different forms. First, the fact that we find effects in some industries but not in others speaks against a too literal interpretation of the narrow hypothesis that schooling spurs industrialization in any circumstance. The cross-industry pattern suggests that schooling is most relevant where technological change is most disruptive. Second, the fact that we find effects for basic education but not for further education runs counter to standard expectations of pure models of technical adoption. While we do not provide direct evidence on the effect of education on the ability to adapt to change, our result patterns thus appear consistent with the broadest form of the catch-up hypothesis.

Our results also inform a broader understanding of how schooling affects catch-up economic development. The pattern of sectoral differences suggests that schooling facilitates catch-up in particular when sectors emerge all new, but not necessarily when change is incremental. A sound base of schooling may therefore be of particular relevance for those developing economies today that try to develop industrial sectors that are new to their country. In addition, the importance of basic education in the Prussian setting indicates particular relevance of the general basic education implemented by Humboldt which aimed at creating independent rational thinking and self-responsible action among the broad masses. This indicates that a curriculum that fosters the ability to learn how to learn may be more fertile for catch-up growth of contemporary developing countries than a curriculum focused on rote learning.

Historically, our results suggest that without her internationally outstanding education system before the onset of the Industrial Revolution, Prussia would probably not have been able to be a successful industrial follower, to the extent that she managed to take over technological leadership from Britain in many sectors by the end of the nineteenth century (cf. Landes 1969). Economic history may in

Table 8—Panel Fixed Effects Specification

	OLS				
	Pooled		County fixed effects		
	All three periods (1816, 1849, 1882)				
	(1)	(2)	(3)	(4)	(5)
Education	0.179***	0.103***	0.105***	0.101***	0.088***
	(0.011)	*(0.008)*	*(0.018)*	*(0.023)*	*(0.021)*
Share of young population		−0.303***	−0.042		0.011
		(0.063)	*(0.057)*		*(0.065)*
Share of old population		−1.925***	−2.143***		−1.665***
		(0.073)	*(0.113)*		*(0.185)*
County fixed effects	No	No	Yes	Yes	Yes
Time fixed effects	No	No	No	Yes	Yes
Observations	1,002	991	991	1,002	991
Counties	334	334	334	334	334
R^2 (within)	0.663	0.825	0.831	0.805	0.834
R^2 (overall)	0.344	0.654	0.629	0.694	0.658

	OLS		IV	
			1st stage	2nd stage
	County fixed effects			
	Two industrialization periods (1849, 1882)			
	(6)	(7)	(8)	(9)
Education	0.130***	0.114***		0.049*
	(0.022)	*(0.021)*		*(0.030)*
Share of young population	0.155*	0.131	0.166	0.137
	(0.093)	*(0.083)*	*(0.206)*	*(0.091)*
Share of old population	−2.592***	−2.388***	−2.358***	−2.400***
	(0.278)	*(0.284)*	*(0.611)*	*(0.261)*
Industrialization (lagged)		0.648**	0.975***	0.729***
		(0.310)	*(0.304)*	*(0.138)*
Education (lagged)			1.373***	
			(0.094)	
County fixed effects	Yes	Yes	Yes	Yes
Time fixed effects	Yes	Yes	Yes	Yes
Observations	668	668	668	668
Counties	334	334	334	334
R^2 (within)	0.862	0.871	0.836	0.866
R^2 (overall)	0.560	0.623	0.745	0.569
First-stage F-statistic			211.21	

Notes: Panel estimations of 334 Prussian counties for the three periods 1816, 1849, and 1882. Dependent variable: industrialization (except for column 8, where it is education). See text for definition of variables in each period. Standard errors (adjusted for clustering by 280 original counties, also across time periods) in parentheses.
***Significant at the 1 percent level.
**Significant at the 5 percent level.
*Significant at the 10 percent level.

Source: Data for Prussian counties from different censuses; see online Appendix A for details.

fact be more in line with catch-up models of economic growth than was previously thought. In terms of the adoption of new technologies (rather than their subsequent use in production when they have become standard), human skills may have been a complement to new technologies not only starting with the early twentieth century, as shown by Claudia Goldin and Lawrence F. Katz (1998), but even earlier. Education played a much larger role, both in the first and the second phase of the Industrial Revolution outside Britain, than most assessments based on the current state of empirical evidence seemed to suggest. Four reasonable causes for the differing findings between Prussia and Britain are inferior British data, specifics of the textile sector, differences between leader and follower countries, and Humboldt's specific ideals in Prussian education (see online Appendix D for greater detail). Their relative importance opens a range of interesting questions for future research.

Appendix

Table A1—Data Descriptions and Sources

Variable	Source	Description
Education measures		
School enrollment rate 1816	Population census 1816	Enrollment in elementary and middle schools divided by population aged 6 to 14
Years of schooling 1849	Population census 1816/ Schooling census 1849	Average years of elementary and middle schooling in the adult population, constructed from school enrollment rates in 1816 and 1849 (see text for details)
Literacy rate 1871	Population census 1871	Population older than 10 with ability to read and write divided by total population older than 10
Share of factory workers in total population 1849		
All factories	Factory census 1849	Employment in factories divided by total population
All factories except metals and textiles	Factory census 1849	Employment in factories other than metal and textile factories divided by total population
Metal factories	Factory census 1849	Employment in metal factories divided by total population
Textile factories	Factory census 1849	Employment in textile factories divided by total population
Share of all factory workers in occupied labor force	Factory census 1849	Employment in factories divided by total occupation count
Share of manufacturing workers in total population 1882		
All manufacturing	Occupation census 1882	Employment in manufacturing divided by total population
All manufacturing except metals and textiles	Occupation census 1882	Employment in manufacturing other than metals and textiles divided by total population
Metal manufacturing	Occupation census 1882	Employment in manufacturing of metals divided by total population
Textile manufacturing	Occupation census 1882	Employment in manufacturing of textiles divided by total population
Share of all manufacturing workers in occupied labor force	Occupation census 1882	Employment in manufacturing divided by total occupation count

(*Continued*)

TABLE A1—DATA DESCRIPTIONS AND SOURCES (*Continued*)

Variable	Source	Description
Basic demographic and geographic measures		
Share of population < 15 years	Population census 1849, Occupation census 1882	Population younger than 15 divided by total population
Share of population > 60 (70) years	Population census 1849, Occupation census 1882	Population older than 60 (70) divided by total population
County area (in 1,000 km²)	Population census 1816	Total area of the county in 1000 km², excluding expanse of water
Pre-industrial development		
Share of population living in cities 1816	Population census 1816	Population living in a town having city rights divided by total population
Looms per capita 1819	Establishment census 1819	Sum of looms on different fabrics divided by total population
Steam engines in mining (per 1,000 inhabitants) 1849	Factory census 1849	Steam engines employed in mining per 1,000 inhabitants
Sheep per capita 1816	Population census 1816	Sheep (*Landschafe*) divided by total population
Share of farm laborers in total population 1819	Establishment census 1819	Domestic workers (*Dienstboten*) in agriculture divided by total population
Public buildings per capita 1821	Population census 1821	Public buildings for state or public purpose divided by total population (not including churches)
Paved streets 1815 (dummy)	Calculated following Königliches Handelsamt zu Berlin (1847)	Dummy = 1 if county had access to one or more paved streets (*Chaussee*)
Tonnage of transport ships (in 4,000 pounds) per capita 1819	Establishment census 1819	Total tonnage capacity of river transport ships (in 4,000 pounds) divided by total population
Additional demographic and geographic measures		
Distance to Wittenberg (in 1,000 km)		Distance of county's capital to Wittenberg in 1,000 km
Share Protestants 1816	Population census 1816	Lutherans and reformed Protestants divided by total population
Share Jews 1816	Population census 1816	Jews divided by total population
Year in which annexed by Prussia (divided by 1,000)		Year in which county became part of Prussia divided by 1,000
Western part		Dummy = 1 if county in provinces Rhineland or Westphalia
Polish parts		Dummy = 1 if county located in Poland today
Distance to Berlin (in 1,000 km)		Distance of county's capital to Berlin in 1,000 km
Distance to next province capital (in 1,000 km)		Distance of county's capital to closest province capital in 1,000 km
Distance to London (in 1,000 km)		Distance of county's capital to London in 1,000 km
Latitude (in rad)		Latitude (in rad)
Longitude (in rad)		Longitude (in rad)
Landownership inequality 1849	Population census 1849	Ratio of land holdings greater than 600 Morgen to total number of land holdings

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