NBER WORKING PAPER SERIES

TECHNOLOGY ADOPTION AND PRODUCTIVITY GROWTH: EVIDENCE FROM INDUSTRIALIZATION IN FRANCE

Réka Juhász
Mara P. Squicciarini
Nico Voigtländer

Working Paper 27503
http://www.nber.org/papers/w27503

NATIONAL BUREAU OF ECONOMIC RESEARCH
1050 Massachusetts Avenue
Cambridge, MA 02138
July 2020

We thank Sandy Black, Bruno Caprettini (discussant), Michael Huberman, Markus Lampe, Jan de Loecker, Joel Mokyr, Tomasso Porzio and numerous seminar audiences at Bocconi University, Cologne University, Leuven University, Lund University, Montreal University, Namur University, Yale University, UCLA, and participants at the 2019 SED meetings, at the 1stWorkshop of Economic History in Bologna, at “The Transnational History of French Industrialisation Before 1914” and the IGC-Stanford conference on Firms, Development and Trade 2019 for helpful comments and suggestions. We thank Gaia Dossi, Johanna Gautier, Lorine Labrue, Marie Michaille, Simon Margolin, Alberto Mola, and Sebastian Ottinger for excellent assistance throughout the construction of the dataset, Guillaume Daudin for kindly sharing data, and Eugene White for sharing his expertise of hyperinflation during the French Revolution. Financial support from the National Science Foundation (Grant # 1628866) is gratefully acknowledged. The views expressed herein are those of the authors and do not necessarily reflect the views of the National Bureau of Economic Research.

Technology Adoption and Productivity Growth: Evidence from Industrialization in France
Réka Juhász, Mara P. Squicciarini, and Nico Voigtländer
NBER Working Paper No. 27503
July 2020
JEL No. F63,N23,O14

ABSTRACT

We construct a novel dataset to examine the process of technology adoption during a period of rapid technological change: The diffusion of mechanized cotton spinning during the Industrial Revolution in France. Before mechanization, cotton spinning was performed in households, while production in firms only emerged with the new technology around 1800. This allows us to isolate the firm productivity distribution of new technology adopters. We document several stylized facts that can explain the well-documented puzzle that major technological breakthroughs tend to be adopted slowly across firms and – even after being adopted – take time to be reflected in higher aggregate productivity: The productivity of firms in mechanized cotton spinning was initially highly dispersed. Over the subsequent decades, cotton spinning experienced dramatic productivity growth that was almost entirely driven by a disappearance of firms in the lower tail. In contrast, innovations in other sectors (with gradual technological progress) shifted the whole productivity distribution. We document rich historical and empirical evidence suggesting that the pattern in cotton spinning was driven by the need to re-organize production under the new technology. This process of 'trial and error' led to widely dispersed initial productivity draws, low initial average productivity, and – in the subsequent decades – to high productivity growth as new entrants adopted improved methods of production and organization.

Réka Juhász
Department of Economics
Columbia University
420 West 118th Street
New York, NY 10027
and NBER
rj2446@columbia.edu

Mara P. Squicciarini
Bocconi University
Department of Economics
Via Roentgen, 1
Milan 20136
Italy
mara.squicciarini@unibocconi.it

Nico Voigtländer
UCLA Anderson School of Management
110 Westwood Plaza
C513 Entrepreneurs Hall
Los Angeles, CA 90095
and NBER
nico.v@anderson.ucla.edu

A data appendix is available at http://www.nber.org/data-appendix/w27503

1 Introduction

The diffusion of innovation is at the core of aggregate productivity growth in the long run. Despite its importance for economic development, understanding the determinants and effects of technology adoption has proven difficult. As a consequence, the literature faces a number of open questions. For example, many technologies that ended up being widely adopted – such as hybrid corn seed in agriculture (Griliches, 1957) or by-product coke ovens in the iron and steel industry (Mansfield, 1961) – were slow to diffuse across firms.[1] This slow adoption is particularly puzzling given that new technology can provide a substantial boost to firm productivity (Bloom, Eifert, Mahajan, McKenzie, and Roberts, 2013; Giorcelli, 2019). There is also a second, well-documented puzzle: When major innovations such as information technology (IT) or electricity spread across firms, the widely expected boost in aggregate productivity proved hard to document in the actual data. This prompted Robert Solow to remark in 1987 that "[...] what everyone feels to have been a technological revolution, a drastic change in our productive lives, has been accompanied everywhere, including Japan, by a slowing-down of productivity growth, not by a step up. You can see the computer age everywhere but in the productivity statistics."[2]

A natural lens to study aggregate effects of technology adoption is the firm productivity distribution – an approach that has gained prominence over the last decade (c.f. Syverson, 2011). However, applying this framework to technology adoption is difficult for numerous reasons: The use of specific technology by firms is rarely directly observed, and even if it is known, new and old technologies typically coexist within narrowly defined sectors, or even within firms. In addition, the productivity distributions under the old and new technologies are not independent – a firm's productivity with the old technology can affect its propensity to adopt innovations. These factors render it difficult to isolate aggregate productivity growth among adopters of the new technology. One approach to tackle these challenges is the use of randomized control trials (RCTs), which provide clean identification of the effects of technology at the firm level (Bloom et al., 2013; Atkin, Chaudhry, Chaudry, Khandelwal, and Verhoogen, 2017; Hardy and McCasland, 2016). However, the relatively small sample size and short time horizon do not allow for a systematic analysis of the firm productivity distribution.

This paper bypasses the typical limitations by exploiting a unique historical setting – the adoption of mechanized cotton spinning in France during the First Industrial Revolution. Mechanized cotton spinning had been invented in Britain and – if operated efficiently – promised huge productivity improvements. We collect novel firm-level data from historical surveys covering mechanized cotton spinning and two comparison sectors – metallurgy and paper milling – at two points in time,

---

[1] The more general observation that technology is often slow to diffuse is attributed to Rosenberg (1976). See Hall and Khan (2003) and Hall (2004) for surveys of the literature on technology diffusion.

[2] New York Times, July 12, 1987, p. 36

around 1800 and in 1840. Importantly, in 1800, mechanized cotton spinning technology had only recently been adopted in France. Four decades later, the technology had reached maturity (Pollard, 1965). Thus, the time period that we study encompasses both the initial phase of adoption and the period when the new technology had widely spread.

Our empirical strategy relies on a number of features of the historical setting. First, before the emergence of the new technology, cotton spinning was performed in home production with hand-operated spinning wheels. Firms – or let alone factories – did not exist in cotton spinning prior to its mechanization. The new technology – the famous spinning jenny – required the organization of production in cotton mills. Thus, all cotton firms that we observe in the data operated mechanized spinning.[3] This allows us to isolate the productivity distribution specific to the new technology and to examine its evolution over time. Second, we document that entrepreneurs that set up mechanized cotton spinning firms typically had a background in banking and finance as opposed to handspinning, suggesting that productivity under the new and old technologies were not systematically related. Third, we show that the vintages of capital in mechanized cotton spinning stayed approximately the same throughout our sample period. This allows us to separate the long-run productivity effects of *adopting* a major new technology and optimizing its operation from subsequent improvements in this technology that arrived externally.

We document three main findings for mechanized cotton spinning firms: 1) we observe a highly dispersed productivity distribution in the initial period (1806) relative to 1840; 2) we estimate that the mechanized cotton spinning industry underwent a substantial (82%) increase in firm productivity between 1806 and 1840 *after* mechanization had already been adopted; 3) this aggregate productivity growth in mechanized cotton spinning had a strong lower-tail bias: productivity growth in this sector was largely driven by the disappearance of lower-tail firms.

We compare the evolution of the firm productivity distribution in cotton spinning to that observed in our two comparison sectors – metallurgy and paper milling. Importantly, in these sectors, production was already organized in firms before the Industrial Revolution (because of their reliance on water power and high-fixed-cost machinery). Technological progress in these sectors was more gradual and took the form of integrating new capital vintages into existing production setups – as opposed to the radical shift from home-based to factory-based production in cotton spinning. We find that the whole productivity distribution shifted to the right in the comparison sectors.

To rationalize these findings, we build on a mechanism that has been emphasized by historians and back it with new empirical evidence: Adopting mechanized cotton spinning required firms to

---

[3] It is possible that in some occasions, the enumerators included workshops that used the old spinning technology. However, such workshops had a limited number of employees since the old technology did not benefit from increasing returns (which is reflected by its typical home-production setup). All our results hold when we exclude firms with fewer than 10 employees, some of which may have been workshops.

learn best-practice methods along multiple dimensions. This is consistent with a setting in which firms learn about the optimal use of multiple inputs or tasks that in turn exhibit complementarities in the production function. We show that these features initially (when firms have little experience in the optimal performance of tasks) lead to a fat lower tail in the firm productivity distribution. Over time, as firms learn about the efficient use of multiple inputs (tasks), the lower tail disappears. We provide rich historical evidence consistent with this mechanism. Mechanization required the move to factory-based production, which represented an important organizational challenge to entrepreneurs: How should the layout of the mill be designed? How should machines be powered and how should the work flow be organized? How should workers – not used to the hierarchy and discipline of factory production – be recruited and managed? These organizational innovations proceeded via a process of trial and error, and the diffusion of organizational knowledge took time. As Allen (2009, p.184) writes: "The cotton mill, in other words, had to be invented as well as the spinning machinery *per se*."

We provide several pieces of evidence in line with the proposed mechanism. First, we show that the exit rate of firms in mechanized cotton spinning was substantially higher than in other sectors between 1800-1840. This is consistent with the idea that early adopters faced considerable uncertainty about best-practice methods in production. Coherently, we show that exiting firms were substantially less productive than those that survived. Second, using firm age, we show that cotton spinning firms that entered the market later had higher productivity. This finding supports our argument that knowledge about the optimal organization of mechanized cotton spinning diffused slowly over time. Moreover, the productivity advantage of younger firms is only a robust feature in cotton spinning around 1800. Younger spinning firms were *not* more productive in 1840; and in metallurgy, young firms were as productive as older ones in both periods.[4] This is consistent with the idea that later entrants in mechanized cotton spinning could draw from a better pool of organizational knowledge, which evolved over time and reached maturity around 1840. This process was muted in metallurgy, where firm-based production methods had been established much earlier, and organizational knowledge had spread already by 1800. Finally, we examine our data for patterns compatible with learning effects. We find evidence supporting the spatial diffusion of knowledge: Firms located closer to high-productivity firms were themselves more productive, and this relationship is strong only for cotton spinning firms and only during the initial period of technology adoption. We show, using a rich set of controls and placebo tests, that these results are unlikely to be driven either by firm selection into productive locations or by omitted variables.

Overall, our findings allow us to shed light on the two puzzles of slow adoption of major innovations and slow aggregate productivity growth. In combination with rich historical evidence, the highly dispersed initial productivity distribution points to information disparities across cotton

---

[4] Due to data limitations, we cannot conduct this exercise for paper milling.

firms: The organization of factory production evolved via a process of trial and error such that only the most productive adopters, those that 'stumbled' onto the efficient organization of factory production, survived. By 1840, information about the efficient organization of cotton mills had dispersed, leading to a much narrower distribution of firm productivity. Uncertainty about the optimal organization of production with a new technology can thus explain why *aggregate* productivity gains for technologies are initially small. Early adopters need to experiment with the efficient organization of production, and most of them will inadvertently operate the new technology inefficiently. Consequently, the potential benefits of the new technology materialize relatively slowly for the average firm. Our findings thus lend support to the view in the literature that the effects of disruptive technologies, such as electricity and IT, appear slowly in industry productivity "due to the need to re-organize the operation of the entire manufacturing facility to make effective use of this innovation" (Hall and Khan, 2003, p.8).

At the same time, potential adopters of a new technology expect that the knowledge about its optimal operation will improve over time. This creates incentives to delay entry. Indeed, we observe that later entrants in cotton spinning had significantly higher productivity than early adopters. This can help to explain the slow diffusion of major innovations, especially if they require a re-organization of production.

Our paper is closely related to a sizeable literature on technology adoption. The most developed strand of this literature explains the low rates of technology adoption in agriculture in developing countries.[5] Given its importance in driving long-run sustained growth, understanding technology adoption in manufacturing is arguably equally important. However, this strand of the literature is much smaller, perhaps due to the difficulty of observing technology use in manufacturing. For this reason, the majority of recent papers use RCTs to understand the determinants of technology adoption (c.f. Bloom et al., 2013; Hardy and McCasland, 2016).[6] In line with our results, some of the evidence from experimental settings points to the importance of organizational barriers (Atkin et al., 2017). We contribute to this literature by studying the full firm productivity distribution for one of the most famous innovations in history, both at the initial phase of technology adoption and once the industry had reached maturity. Interestingly, the mechanism found in this paper suggests that the complex nature of production processes in manufacturing relative to agriculture may be important. In cases where technology adoption requires a substantial re-organization of production, adoption may be slow and productivity effects may take time to materialize.

Second, theoretical and empirical research over the past decade has pointed to the importance

---

[5] See for example Foster and Rosenzweig (1995), Munshi (2004), Bandiera and Rasul (2006), Conley and Udry (2010), Duflo, Kremer, and Robinson (2011), Suri (2011), Hanna, Sendhil, and Schwartzstein (2014), BenYishay and Mobarak (2018), Beaman, Magruder, and Robinson (2014), and Emerick, de Janvry, Sadoulet, and Dar. (2016).

[6] One notable exception is Giorcelli (2019), who exploits a historical natural experiment to identify the productivity effects of adopting modern management practices by Italian firms after WWII.

of firm dynamics for understanding aggregate productivity (Melitz, 2003; Syverson, 2011). A key insight of this literature is that – as there are large differences in productivity even within narrowly defined sectors – examining the entire distribution is critical for understanding aggregate productivity (Hsieh and Klenow, 2009). We apply this insight to the arguably most important structural break in economic history: The First Industrial Revolution, which saw unprecedented growth in manufacturing productivity (Crafts, 1985; Crafts and Harley, 1992; Galor, 2011). So far, productivity growth during this period has been studied mostly at the country level, or – in some cases – at the aggregate sectoral level. To the best of our knowledge, our paper is the first to study the contribution of firm dynamics to manufacturing productivity improvements during the Industrial Revolution. In addition, we examine the puzzle of the slow diffusion of major technological innovations through the lens of the firm-productivity literature: Our findings suggest that focusing on the entire distribution of firm productivity can help deepen our understanding of technology *adoption*.

Finally, our paper is related to a large literature that studies organizational changes brought about by the Industrial Revolution. The seminal work by Pollard (1965) documents important organizational innovations (in what we would call 'management' today) that took place in the first half of the 19th century.[7] Pollard (1965) argued that before the 19th century, the lack of knowledge about efficient management practices prevented firm scale from increasing. Our data allow a uniquely detailed look into the evolution of firm size during the First Industrial Revolution. The particularly large firm scale in cotton spinning, and the increase in firm size across all sectors, is consistent with the importance of organizational innovations during this period.

The paper is structured as follows. The next section describes the historical context. Section 3 describes the construction of our novel dataset from archival sources, while Section 4 presents and discusses our empirical results. Section 5 draws conclusions from our results for technology adoption during periods of major innovation.

2 Historical Background

Early nineteenth century France presents an ideal setting for our study of technology adoption. While England was the first country to industrialize, France was a close follower and structurally similar to England (Crafts, 1977; Voigtländer and Voth, 2006). The flagship inventions of the Industrial Revolution – most notably the spinning jenny – were developed in Britain. France adopted these widely during the first half of the 19th century and witnessed a similar acceleration in industrial output as Britain (Rostow, 1975).[8] By focusing on France, we thus study the effects of technology adoption in the context of an industrializing economy that was (at least initially)

---

[7] Subsequent research in this area is discussed in Mokyr (2010).

[8] Appendix A.1 provides a more detailed discussion of the Industrial Revolution in France.

mostly adopting technology developed elsewhere.

Our empirical analysis builds on three pillars that emerge from the historical context. First, the new cotton spinning technology entailed a move from home-based to factory-based production. This allows us to isolate the productivity distribution of adopters of the new technology. Second, we compare the productivity distribution in cotton spinning to two other sectors: metallurgy and paper milling. Production in these sectors was already organized in firms prior to the Industrial Revolution and experienced mostly incremental technological change that did not entail a drastic reorganization of the production process. Using these comparison sectors helps us to distinguish the effect of adopting a major new technology in cotton spinning from other trends at the time that may have affected productivity distributions more broadly. Third, we discuss the historical evidence for the mechanism that arguably explains our empirical findings: The move to large-scale factory-based production in cotton spinning required the development of best-practice methods for organizing production through a process of trial and error.

2.1 Mechanized Cotton Spinning

Development of Mechanized Spinning in Britain. Cotton textiles was the flagship industry of the First Industrial Revolution, contributing 25% of TFP growth in Britain during the period 1780-1860 (Crafts, 1985). Cotton spinning is the process by which raw cotton fiber is twisted into yarn. Traditionally, this task was performed mostly by women in their homes, using a simple spinning wheel (see the left panel of Figure A.10 in the appendix). With this old technology, each spinner was able to spin only one thread of yarn. The industry was rurally organized and generally centered around a local merchant-manufacturer who would supply spinners with the raw cotton, collect their output, take care of the marketing, and often also owned the spinning wheels (Huberman, 1996).

The breakthrough "macro-invention" in spinning was forged in Britain in the late 18th century, when James Hargreaves invented the spinning jenny. This made it possible to spin multiple threads simultaneously, as twist was imparted to the fibre not by using the workers' hands, but rather by using spindles (see the right panel of Figure A.10). The productivity effect of these innovations was enormous. Allen (2009) estimates that the first vintage of the spinning jenny alone led to a threefold improvement in labor productivity. Correspondingly, the price of yarn declined rapidly in the late 18th century (Appendix Figure A.1), especially for the highest-quality yarn, where prices declined from 1,091 pence per pound to 76 pence per pound in real terms between 1785 and 1800 (Harley, 1998).[9]

---

[9] Harley (1998) collected price data for three different qualities of yarn from British sources: 18, 40 and 100 count yarn (the count is an industry-wide standard that refers to the length per unit mass, implying that higher counts are finer). While all counts saw striking price declines (see Appendix Figure A.1), this trend was most pronounced for the finest, highest-quality varieties. Machine spinning had the largest impact on the fine high-quality yarn, which British hand-spinners had not been able to effectively produce and to which the water-frame and mule jenny (subsequent vintages of the machine introduced in the late 18th century) were well-suited. Our data include information on the

The mechanization of cotton spinning required production to be organized within factories for two reasons. First, the use of high fixed-cost inanimate power sources (such as water and steam) led to the concentration of production in one location.[10] Second, mechanized production increased the need for monitoring workers, who were now paid factory wages rather than for their home-produced output (Williamson, 1980; Szostak, 1989).[11] As production moved to factories, cotton spinners faced a set of new challenges in organizing production in factories effectively. We return to this issue in the next section.

Adoption of Mechanized Spinning in France. Mechanized spinning was adopted with some lag in France. Efforts to adopt the technology had begun with state support during the *ancien regime*, and by the beginning of our sample period, the technology was widely known in France (Horn, 2006).[12] Moreover, Chassagne (1991) shows that the production of the machinery for mechanized spinning was established in France by the beginning of our sample period.[13]

A number of features in this setting allow us to study how technology adoption affected productivity growth. First, mechanized spinning technology was only operated in firms, while the old technology relied on home production. This allows us to identify all producers that used the new technology, i.e., all *firms* observed in our data.[14] Consequently, we are able to isolate the productivity distribution for firms that used the new, mechanized technology.

Second, the sharp break in organizational requirements under the new technology rendered experience with the old technology effectively useless. Correspondingly, historical evidence suggests that most entrepreneurs who operated the new technology in France around 1800 did not have a background in the old technology. Table 1 presents information on the socio-economic background of entrepreneurs in mechanized cotton spinning for the early period of technology

---

type of yarn produced, allowing us to account for quality differences across firms.

[10] The initial spinning jenny was hand-powered, but newer vintages of machinery that used inanimate sources of power (the water frame and the mule) were rapidly developed and had become the standard by 1800.

[11] Huberman (1996, p. 11) describes the need for monitoring in mechanized cotton spinning: "If there were multiple breakages of yarn on the larger machines, the mule had to come to a complete stop to piece the broken threads. There was also doffing, when the reels were full of spun cotton, the mule had to be stopped and the reels removed. Finally, there was cleaning. At all times, the spinners could expend effort as they were motivated to and without proper supervision or incentives they could disguise how hard they could in fact work." This created a strong need for monitoring, so that even early hand-powered mules (a particular vintage of spinning machinery) were housed in the "garrets of cottages and later in sheds." (Huberman, 1996, p. 11).

[12] The first year of data used in our empirical analysis for cotton spinning is 1806. At this time, the large-scale expansion of the industry documented in Juhász (2018) had just begun.

[13] Spinning machinery was produced mainly domestically in France because of a ban on exporting British machinery until 1843 (Saxonhouse and Wright, 2004).

[14] We follow Mokyr (2010, p. 339) in defining factory-based production as "the precise circumscription of work in time and space, and its physical separation from homes." This definition is solely based on the *organization* of production; it does not rely on the use of machines or inanimate sources of power. This is important because it allows us to refer to 'factory production' even when our data do not include information on machines and/or power sources. In mechanized cotton spinning (but not in the comparison sectors), we observe the number of mechanized machines in use in both time periods, which gives us further confidence that our cotton spinning data only pick up production units that we can think of as firms.

adoption (1785-1815). Based on these figures, the vast majority of firm owners were "traders, bankers and commercial employees" (62.5%), while only a small faction (10.2%) came from the production side, i.e. "workers and mechanics," and three-quarters of this latter group were in fact highly skilled mechanics.[15] As we discuss in more detail below, the type of skills necessary for successfully running mechanized cotton spinning firms were very different from those required under the old cottage-industry technology.

Third, during our sample period, the vintages of capital in cotton spinning remained more or less unchanged. This implies that there was no additional leap in technology whose introduction might confound our findings.[16] We can confirm this in our data, because the firm survey in 1806 asked which vintage of capital firms used. We find that both the throstle and the mule-jenny (two vintages of capital) had been widely adopted in France. The next vintage to appear (the self-acting mule – a fully automated machine) did not spread until the 1840s, i.e., after our sample period ended (Huberman, 1996).

2.2 Comparison Sectors: Metallurgy and Paper Milling

We compare the evolution of the firm productivity distribution in mechanized cotton spinning to two other sectors: metallurgy and paper milling.[17] The key feature of both comparison sectors is that they had already organized production in firms since well before the Industrial Revolution. In metallurgy, firm production was mostly due to the reliance on high fixed-cost machinery such as the furnaces used both in smelting and refining. In paper milling, production was organized in firms because of the beating engine's reliance on water-power.[18]

Technological change in the two comparison sectors was introduced gradually and *within* the existing organization of production. The switch from charcoal to coal in metallurgy could be introduced by modifying a firm's existing machines and ovens. In paper milling, the mechanization of forming paper (one step in the production process) did not substantially alter the layout of the factory, or other parts of the production process. Moreover, the adoption of new technologies in both sectors was slow in France. Adoption began in the 1820s, and it was fairly modest until 1840. In metallurgy, the switch to coal was delayed because – in contrast to Britain – the relatively low price of charcoal kept the old technique profitable until the new technology's efficiency had risen

---

[15] It is possible that some merchant-manufacturers previously involved with handspinning are reported under the category "traders, bankers and commercial employees." However, Chassagne (1991, p. 274) clarifies that two-thirds of traders were general merchants and more specifically cloth and fabric merchants. This highlights the importance of marketing skills (as opposed to previous experience with handspinning) in setting up cotton spinning factories.

[16] This is not to say that there were no improvements of the existing technology, or that firms did not increase their capital intensity. In fact, machines were improved over time and the capital-labor ratio increased substantially; but this is arguably part of learning to use the new technology and working with it efficiently. In robustness checks, we show that our main result holds when we control for the capital-labor ratio of firms.

[17] Appendix A.2 contains a more detailed discussion of both comparison sectors.

[18] The beating engine breaks down the raw input vegetable matter into cellulose fiber. The production process is described in more detail in Appendix A.2.

(Allen, 2009). The new production processes using charcoal – coke smelting and the puddling process in refining – were both introduced around the 1820s in France and gradually adopted thereafter. In 1827 (in the middle of our sample period), there were only four French departments where iron was smelted with coke. The adoption of the puddling process was more widespread, with 149 puddling furnaces in use across 15 out of 86 departments (Pounds and Parker, 1957).[19]

In paper milling, the adoption of mechanized paper formation was similarly slow. While evidence on the adoption of mechanized paper-making is relatively scarce, our firm-level data from 1840 suggest that the technology had not been widely adopted. Only 10 (out of 348) firms explicitly mention having mechanized their production process, and only 42 firms report using steam power, which was necessary for the mechanized machine.

Given these features, the firm productivity distributions in metallurgy and paper milling reflect the same mix of old and new technology vintages that is typically observed in standard data sources. Our ability to observe two industries that were already organized as firms prior to the Industrial Revolution allows us to disentangle the effects of technology adoption in cotton spinning from other shocks that affected the productivity distribution of all industries simultaneously.

2.3 The Challenging Transition to Factory-Based Production in Cotton Spinning

The transition to large-scale factory-based production has been characterized as "one of the most dramatic sea changes in economic history" (Mokyr, 2010, p. 339). While cotton spinning was not the first sector to organize production in factories, the organizational changes during its industrialization went far beyond the experience made by other sectors.[20] By the time cotton spinning mills reached maturity around 1830 in Britain (Pollard, 1965), they were larger, with a finer division of labor and a greater concentration of capital than previous factories (Chapman, 1974). However, the biggest change was the development of *flow production* – the production of standardized goods in huge quantities at low unit costs by "arranging machines and equipment in line sequence to process goods continuously through a sequence of specialized operations" Chapman (1974, p. 470). It is this synchronisation of highly specialized machines that distinguishes the cotton spinning factory as a "fully-evolved factory" from earlier developments (Chapman, 1974, p. 471).

Developing efficient cotton spinning mills meant solving organizational challenges along multiple dimensions. As Allen (2009) writes:

> "The spinning jenny, water frame and mule were key inventions in the mechanization of cotton spinning, but they were only part of the story. [...] the machines had to be spatially organized, the flows of materials coordinated, and the generation and distribution of power sorted out.

---

[19] We can also verify indirectly that the new coal-based technology was introduced slowly in metallurgy: Adopting coal required a switch from water to steam as power source (Pounds and Parker, 1957), and the latter is reported by firms in 1840. Only 16% of firms in metallurgy report using steam-power, implying that the vast majority of them still used the older charcoal-based technology.

[20] For example, metallurgy and paper milling, our comparison sectors, had already organized production in factories much sooner as we discussed above.

> A corresponding division of labour was needed. The cotton mill, in other words, had to be invented as well as the spinning machinery *per se*." (Allen, 2009, p.184)

Successful mill designs were observed and copied. Chapman (1970, p. 239) shows that early mills in England had a remarkably similar structure because entrepreneurs quite literally copied the original design of the Arkwright mills over and over again. Moreover, since few millwrights were qualified to build the power units of their mills, these were typically built by the same handful of engineers, qualified from experience Chapman (1970, pp. 239-240). It took time for design defects to be improved; for example, contemporaries were aware of ventilation problems in the Arkwright-style mills, but continued to use the same layout regardless (Fitton and Wadsworth, 1958, p. 98).

Beyond organizing the production process efficiently, the factory setting and the use of inanimate power itself produced a host of new, unanticipated challenges. For example, fire hazards were a particularly pressing issue in the case of cotton spinning because of the highly flammable cotton dust present during production (Langenbach, 2013). A process of trial and error eventually led to best-practice mill design that reduced fire hazards: Cotton textile mills introduced the so-called "fire-proof building" in Britain in the late 18th century, which entailed leaving no timber surfaces exposed by using cast-iron columns instead of wood (Johnson and Skempton, 1955). However, it quickly became apparent that fireproof mills were not indeed fireproof, because "steel or wrought iron, when heated, will fail by buckling or bending very much sooner than the equivalent beam of post or wood" (Boston Mutual Fire, 1908, p. 3). US textile mills developed what became known as "slow-burning mills" in the 1820s, recognizing that fires could not be prevented but their effects could be minimized by better mill design. Partly, this entailed moving back to using wood: "Timber posts offer more resistance to fire than either wrought-iron, steel, or cast iron pillars, and in mill construction are preferable in many respects (Boston Mutual Fire, 1908, p. 3). Chassagne (1991, p. 340) posits that early 19th century French mills consisted of multiple buildings and covered vast spaces (as opposed to building vertically) partly to minimize the fire hazard. Similarly, building structures needed to withstand the stress they faced from the vibrations of machines (Chassagne, 1991, p. 435). Iron rods with plates held beams to the masonry walls to prevent the vibrations of machines from shaking the walls apart (Langenbach, 2013).

Besides the need to develop the optimal mill layout and building structure, entrepreneurs faced a host of other challenges that stemmed from concentrating workers under one roof and implementing a division of labor. On the one hand, workers had to adapt to the discipline and economic hierarchy of factory work. Following instructions, showing up to work on time, or getting along with other employees was new to workers who largely had experience with a domestic system (Pollard, 1963). Huberman (1996) describes that monitoring worker effort was a huge problem in cotton spinning mills.[21] He estimates that it took two generations for efficient labor management practices to be developed. Once again, progress was made via trial and error. Firms in Britain initially experimented with dismissals, which led to disastrously high turnover rates, and later with replacing male with female spinners in the hope that the latter could be more easily disciplined. The industry finally settled on efficiency wages to motivate unobservable effort around 1830.

Managing teamwork efficiently became an issue when continuous flow processes were developed, which happened first in cotton spinning (Mokyr, 2010). Manufacturers did not have the experience, training, or access to knowledge to effectively manage labor or the mills in general. As Mokyr (2010) emphasizes:

> "[...] 'management' was not a concept that was known or understood before the Industrial Revolution. Military and maritime organization, the royal court, and a few unusual set-ups aside, the need for organizations in charge of controlling and coordinating large numbers of workers and expensive equipment was rare anywhere before 1750. British managers fumbled and stumbled into solutions, some of which worked and some did not." (Mokyr, 2010, p. 350)

In fact, Pollard (1965) argues that the lack of modern management techniques limited the size of firms. In his seminal book on the topic, he shows that large firm size (above 100-200 workers) was seen as undesirable:

> "up to the end of the eighteenth century at least ... management was a function of direct involvement by ownership, and if it had to be delegated ..., the business was courting trouble. This was a powerful argument against the enlargement of firms beyond the point at which an intermediate stratum of managers became necessary. [...] In the centuries preceding the Industrial Revolution, firms engaged in production were unable to cope with size, essentially because they could not cope with the problems of management which it involves." (Pollard, 1965, p. 23)

The fact that owners were directly involved in management in the late 18th century is also confirmed in our data. In the paper milling survey, we have information on the name of the owner and of the manager for 174 firms in the sample. In 135 of these firms (i.e., 78%), the owner and the manager were the same person in 1794.

In summary, the first generation of mechanized cotton spinners faced many organizational challenges all at once, along multiple dimensions. Developing efficient factory-based production proceeded via a process of trial and error, and it took decades for best-practice methods to emerge. According to Pollard (1965), the process was more or less complete by about 1830 in Britain: "a cotton mill was so closely circumscribed by its standard machinery, and there was so much less scope for individual design, skill or new solutions to new problems, by 1830, at least, ... that little

---

[21] As machines were not yet standardized, managers (overseers) lacked the technical information necessary to monitor effort. "[T]he operative spinner was firmly of the opinion that no two mules could ever be made alike. As a consequence, he proceeded to tune and adjust each of his own particular pair of mules with little respect for the intentions of the maker or the principles of engineering. Before very long, no two mules ever were alike" (Catling, 1970, quoted in Huberman, 1996, p. 59).

originality in internal layout was required from any but a handful of leaders" (Pollard, 1965, p. 90). The initial lack of knowledge about best practice along multiple dimensions is a crucial element in the discussion of our empirical findings.

3 Data Construction

Our analysis is based on a novel firm-level dataset constructed from handwritten historical industrial surveys. The data have a panel-like structure covering three industries: mechanized cotton spinning, metallurgy, and paper milling.[22] We observe firms in these sectors at two points in time: around 1800 and again in 1840. We are aware of no similar, firm-level panel data for any other country during the period of the First Industrial Revolution, including Britain. Below, we discuss the main features of the data and the variables used in the analysis.[23]

3.1 Industrial Surveys around 1800

Our data from the turn of the 19th century are based on three industry-specific surveys that were conducted by the French government. The survey for paper milling was implemented in 1794 during the French Revolution; it contains data on 593 firms. The survey for the other two sectors were conducted by the Napoleonic regime (in 1806 for cotton textiles, covering 389 firms, and in 1811 for metallurgy, covering 477 firms).[24] Examples of the original data for each sector are shown in Figures A.7, A.8, and A.9 in the appendix. Although these data have not been systematically used for quantitative analysis, the quality of French record-keeping in this period is well-known.[25] The period is referred to as the "Golden Age of French Regional Statistics" (Perrot, 1975), while Grantham (1997, p. 356) argues that "the quality equals that of any estimate of economic activity for a century to come." Though the surveys were conducted at different points in time, we refer to their date henceforth as 1800.

---

[22] In France, cotton spinning and weaving were generally not vertically integrated during this time period. Weaving, particularly in the early 19th century, was rurally organized implying less of an incentive to locate the workers in a common location, i.e, in a factory, and thus less of an incentive to vertically integrate the production processes. While this is true for the vast majority of cotton spinners, there were some examples of vertically integrated firms. We deal with integrated firms in the following way. In the 1806 survey – that covered all stages of production in cotton textiles, surveys were separately conducted for spinning and weaving (indicative of the lack of integration across these sectors in general). As such, if a firm is vertically integrated, we observe labor and output reported by activity and can thus estimate productivity only for their spinning activities. In the 1840 survey (for which we only observe total labor and revenues), only 7% of firms that spin cotton yarn report activities in both spinning and weaving. We follow the classification in Chanut, Heffer, Mairesse, and Postel-Vinay (2000) and use firms that report *only* cotton spinning.

[23] A more detailed description of the data (including sources) can be found in Appendix D.

[24] Bougin and Bourgin (1920) compiled an enormously rich overview of the metallurgy sector in 1788 using data from a wide variety of archival sources, including some recall data that was asked of firms in the 1811 survey. Unfortunately, as about 80% of firms do not report employment in Bougin and Bourgin (1920) for 1788, we cannot use the data in our baseline analysis, but we do use the data as a validation check on firm survival. Appendix D contains additional details.

[25] The only exception that we are aware of is Juhász (2018), who uses the data from 1806 on the mechanized cotton spinning industry.

3.2 Industrial Firm Census around 1840

Data for the the second period is based on the first industrial firm census in France, conducted in the years 1839-1847 and digitized by Chanut et al. (2000). For simplicity, we refer to these data as the '1840 census.' While this census covers all manufacturing establishments, we only use data for paper milling (348 firms), cotton spinning (528 firms), and metallurgy (839 firms).[26] Figure 1 shows the spatial distribution of firms around 1800 and in 1840 for the three industries that we study.

The different surveys contain remarkably rich information, although the exact set of variables varies from survey to survey. Here, we discuss only the variables used across all sectors, as well as additional, sector-specific variables when they are used in the empirical analysis. Our main variable of interest is labor productivity measured at the firm level and defined as the log of revenues per worker. We use this measure because it is consistently available across sectors and over time.[27] Additionally, we are interested in estimating firm survival across the different industries over time. Given the importance of these variables for our analysis, we discuss the key assumptions made in constructing these variables for each sector below.

3.3 Constructing Firm Productivity

We face two challenges in constructing consistent productivity measures across firms and across time. First, the surveys for the three sectors around 1800 report output quantity and some information on product-specific prices and product quality. The census in 1840 directly reports firm-specific revenues (but not output quantities). To render productivity measures comparable across time, we need to construct revenues for 1800. Second, workers are not consistently reported across all firms in 1800 in metallurgy and paper milling. We discuss how we deal with each of these issues in turn, below.

Estimating Firm Revenues in 1800

In cotton spinning, firms report the quantity of yarn spun (in kilogrammes) and the minimium and maximum count of yarn spun, which is the standardized measure of quality in the sector. We construct firm-level revenue by multiplying the quantity of firm-level output by the price of the average quality of yarn produced by the firm.[28] We use a schedule of prices for different counts of

---

[26] One potential concern with the 1839-1847 data is that firms with less than 10 workers may have been systematically under-reported (Chanut et al., 2000). This is mostly relevant for paper milling, where firm size is the lowest. In robustness checks, we show that our baseline results hold even when only using firms with at least 10 workers in both periods.

[27] Our revenue-based productivity measure reflects both product prices and quantities. It is thus potentially affected by changes in markups. However, this is unlikely to be quantitatively important because all three sectors in our analysis produced standardized, often intermediate products.

[28] The average is the (unweighted) minimum and maximum count of the yarn produced by the firm, which is the only information firms provide on the quality of yarn that they produce.

yarn reported by the French government.[29]

In metallurgy, the survey asks for the quantity of output produced (by product) as well as the price charged by the firm, by product type.[30] While product-specific output quantity is reported by all firms, the product-specific price is only reported by a subset of firms. We compute the average price for each product using the subset of firms where this information is available. We obtain firm revenues by multiplying product-specific firm output by the average price for each product and summing across products.

In paper milling, the survey does not report firm-specific output prices and it only reports the total quantity of paper products produced (in metric quintals). To construct revenues, we multiply firms' output quantity with the average price of paper products produced in that department as reported in the *Tableaux du Maximum*. We use the department-specific price in order to accurately capture the product mix produced by firms in this area. Given the highly imperfect nature of the price data, we construct sectoral price indices based on a variety of assumptions. In robustness checks, we use the country-wide sectoral prices.[31]

Finally, to compare revenues in the earlier periods and in 1840s, for all three sectors, we deflate revenue data using the producer price index (PPI) for respective years from Mitchell (2003).

Constructing Consistent Labor Variables

In cotton spinning, workers are consistently reported across both time periods and they include all labor (male, female and child) employed by the firm.

In metallurgy, respondents to the 1811 survey report both 'internal' and 'external' labor. Woronoff (1984, p. 138) describes external labor as only having very loose ties to the firm. These workers did not typically work at the location of the firm, their work was not supervised by the manager, and their identity was often not even formally known to the manager. They performed tasks such as driving, collecting charcoal for the firm, or performing other jobs in the forest without belonging to the firm hierarchy or reporting to superiors in the chain of command. These types of workers were highly unlikely to be considered formal salaried employees of the firm in the 1840 census. To construct a consistent measure of labor, our aim is thus to estimate internal employees of the firm in 1811 for the approximately 60% of the observations where only total labor is reported, with no indication of whether this total includes external labor. For these firms, we need an estimate of the size of their internal labor force. To this end, we use a nearest neighbor matching algorithm to determine whether firms that only report total labor are more likely to be reporting internal labor

---

[29] Source: AN F12/533. In robustness checks, we use a single sector-level price, which we define based on the average quality of yarn produced across all cotton firms.

[30] The survey includes the following products: iron of first quality, iron of second quality, iron of third quality, steel using the cementation process, natural steel, and pig iron.

[31] Additional details on the deflator used are discussed in Appendix D.4.

only or the sum of internal and external labor.[32] When our algorithm suggests that the firm is reporting internal and external labor together, we estimate the number of internal workers by using the mean proportion of internal labor from all firms that report both types (the internal labor share is 20%).

In paper milling, the vast majority of firms only reported male labor in 1794. We impute the total labor force by scaling male labor in 1794 by the proportion of male employees to the total labor force in 1840. The validity of this method hinges on the assumption that the proportion of male employees remained constant over time. We are able to check this using the subset of firms that report all types of workers in 1794. We find that the shares are remarkably consistent.[33] Moreover, we show that our results are also robust to using only male employees in both periods, which preserves the true variation in labor across firms.

3.4 Linking Firms over Time

It is possible to link firms over time given that all surveys report the name of the owner and the precise location of the firm up to the commune, which is the lowest administrative unit in France.[34] We use two pieces of information to link firms over time: First, we match firms by their owner names in a given location in the respective industry. Since the name of the owner may change even if the firm is the same, we also match by location in a second step: We match locations where there is *only* one firm in the respective sector in 1800 and where there is at least one firm active in the same sector in 1840. This turns out to be fairly common in the data. An obvious concern is whether this ‘local matching’ indeed identifies the same firm. This is likely, given a fortuitous feature across all three of our industries: their reliance on water power. Only a small number of locations in a particular commune will be suitable for setting up a water-powered mill, as rapid streamflow is needed to yield sufficient power. Moreover, the backwater created by one mill means that another mill cannot be located in close proximity. Consistent with this, Crafts and Wolf (2014) argue that agglomeration in the cotton textile industry was not observed until steam became the common source of power in Britain. Consequently, our ‘local matching’ arguably identifies firms that have the same location within communes. Whether these were owned by the same entrepreneur (or their descendants), or whether they had passed on to a different owner is not crucial for our analysis.

One way to validate the assumptions underlying ‘local matching’ is to examine how frequently communes with a single firm active in the sector in 1800 show up in 1840 with multiple firms

---

[32] The nearest neighbor matching uses capital, output and stage of production. The decision on which type of labor is being reported depends on whether the total labor of the firm examined is closer in absolute value to the internal labor force of the nearest neighbor match or the internal plus external labor force of the nearest match. These decisions are not generally close, as the average firm has 4 external employees for each internal one.

[33] The share of male workers is 2.26 in 1794 for the subset of firms ($n = 20$) that report all types of labor, while in 1840 it is 2.28 (among all firms).

[34] In bigger cities such as Paris, the *arrondissement*, or district, is also reported.

active in the same sector. If this occurs frequently in the data, it would suggest that in fact there are multiple suitable locations for production in that sector for a particular commune. This is not the case in our data: For the vast majority of single-firm communes that we identify in the initial period, there either continues to be one firm or no firms in the subsequent survey. It is exceedingly rare (6% of cases in both paper milling and cotton spinning, and 8% in metallurgy) across all three surveys for single firm communes to 'add' additional firms (despite the large increase in the number of firms active in the sector for metallurgy and cotton spinning). As an additional check on our methodology, it is also possible to compare firm survival in metallurgy to that reported in Woronoff (1984) for this sector over the period 1788-1811. If our strategy of 'local matching' led to too many firm matches over time, we would expect an exaggerated survival rate. The contrary is true: Our estimates of firm survival rates for the period 1811-1840 are well below (one half or less) those that we calculate for the period 1788-1811. This suggests that it is unlikely that we systematically overestimate firm survival.

3.5 Firm Survival Rates

Our main measure of firm survival is based on the combination of matching by owner name and 'local matching' that we described above. We define the survival rate as the percentage of firms from the initial period that survive into the later period. The numerator counts all firms that fulfill at least one of the following two conditions: a) the firm has the same owner in both periods; b) there is only one firm in the respective sector in the location in the initial period and *at least* one firm in the same sector in 1840. The denominator is the sum of *all* firms in the given sector in the initial period. Note that this rate does not adjust for the fact that the number of firms located in communes that have only one firm varies across the three sectors in our sample.[35] Thus, we may mechanically find higher survival rates in a sector where single-firm communes are relatively more frequent. To address this issue, we also construct the 'restricted sample' survival rate as a robustness check. This measure is based solely on single-firm locations. The numerator counts the number of communes that had only one firm in the respective sector, in both the initial period and in 1840 (indicating firm survival). The denominator counts the number of communes that had a single firm in the respective sector in the initial period and either one or no firm in 1840 (indicating firm survival and firm exit, respectively).[36] Relative to our main measure of firm survival, this restrictive definition adjusts for differences in the frequency of single-firm locations across sectors.

---

[35] Among the 593 firms in paper milling in 1794, 218 (36.8%) were the only firms active in their commune in this sector. For cotton spinning in 1806, the proportion is 25.4% (99 out of the 389 firms), and in metallurgy in 1811 , 69% (329 out of 477 firms).

[36] Based on this sample definition, we exclude firms that were the only ones in their commune in 1800, and where there was more than one firm in 1840. As discussed above, the number of these "uncertain" observations is very small across all sectors, which we consider a validation of our methodology.

4 Empirical Analysis

In this section, we use our data to study the effect of technology adoption in cotton spinning and in our two comparison sectors – metallurgy and paper milling. We begin by examining firm scale in the different sectors (measured by the number of employees). Next, we compare the evolution of the productivity distribution in cotton spinning with metallurgy and paper milling. Then, we propose and investigate a mechanism that can rationalize the observed patterns. Finally, we consider a set of alternative mechanisms that could account for the results and test them empirically.

4.1 The Evolution of Firm Scale

What did firms look like in 1800 across the three sectors, and to what extent did they undergo change during our study period? Table 2 provides an overview, reporting the evolution of firm size, measured by the number of workers. A few points stand out. First, as early as 1806, cotton spinning firms were strikingly large. The average spinning firm in this period had 63 employees (the median was 30). Recall that mechanization, which triggered the move to factory-based production, was invented only in the late 18th century. Moreover, the machines were only adopted sporadically across France prior to the 1800s. Consistent with these facts, the median firm in cotton spinning was three years old in 1806. Despite the recent introduction of factory-based cotton spinning in France, firms were already much larger than in the two comparison sectors, which had a much longer tradition of factory-based production: Firms in metallurgy (reported in 1811) had on average 20 workers; paper milling firms had on average 13 employees.[37] In sum, despite the late start in factory-based production in cotton spinning, the average firm in cotton spinning was operating at a scale that was large compared to other sectors.[38]

Table 2 also shows that all sectors underwent significant growth in firm size over the period 1800-1840. Average firm size doubled in cotton spinning and grew threefold in the other two sectors. In 1840, the average cotton spinning firm had 112 employees (median 72), while metallurgy and paper milling had 57 and 43 workers on average, respectively. Next, we examine the evolution

---

[37] One caveat with making this comparison is that the paper milling survey dates from 1794. Thus, firm size may have grown by 1806 – the year of the cotton spinning survey. In addition, we had to extrapolate the overall number of workers in paper milling in 1806 (including women and children – see Section SECTION (sub): Constructing Firm Productivity). However, it is unlikely that true firm scale would have been very different in 1806. This is because even in 1840, the average firm size in paper milling was only 43 (including women and children, which are reported in this year). We can thus be confident that paper milling firms in 1806 were substantially smaller than cotton firms.

[38] Granted, our data only cover two comparison sectors. However, these two sectors had a long tradition of factory-based production and relied on high fixed-cost capital as well as inanimate power sources. This makes it likely that metallurgy and paper milling firms had relatively large firm size, as compared to firms in other sectors around 1800 for which we do not have data. We can also use the 1840 Census, where we know the size of firms in *all* other sectors to gauge support for this assertion: The average firm size in cotton spinning in 1840 is in the 85th percentile of all firms, while both metallurgy and paper milling firms are in the upper tercile of the firm size distribution across all sectors. In addition, all three sectors belonged to the top 90th percentile in terms of the share of firms using "any power," where the 81 sectors in the census are ranked by the share of firms using inanimate power sources.

of firm productivity during this period.

4.2 The Pattern of Productivity Growth

We begin by examining average annual labor productivity growth. Column 1 in Table 3 shows that all three sectors experienced a significant increase in labor productivity. The largest productivity gains were achieved in cotton spinning (2.4% per year), followed by metallurgy (1.9%) and paper milling (0.7%).[39] Remarkably, the estimated productivity increase is largest in spinning, despite the fact that all firms in this sector already used the new technology in 1800. In other words, because we only compare firms that used mechanized cotton spinning, the observed productivity increase must be due to efficiency gains *within* the new technology. This is in contrast to the two comparison sectors, where innovations replaced older technology vintages in existing firms – most prominently, coal as an energy source in metallurgy, and the Foudrinier machine in paper milling (which mechanized the formation of paper). Thus, the labor productivity growth in those sectors reflect not only improvements in operating existing vintages, but they are driven also by productivity gains from the adoption of new technology vintages.

In which part of the productivity distribution were these gains concentrated? Figure 2 plots the distribution of labor productivity in the three sectors at the beginning and at the end of our sample period, illustrating our main results. The contrast between cotton spinning and our two comparison sectors – metallurgy and paper milling – is striking. In the latter, the entire productivity distribution shifted to the right between 1800 and 1840. In cotton spinning, in contrast, two features stand out. First, the initial dispersion in labor productivity was large in 1800 relative to that in 1840. Second, the productivity gains are almost exclusively concentrated in the lower tail – the lower tail disappeared over our sample time period, while increases in productivity at the upper tail were modest. Quantile regressions confirm this pattern. Table 3 reports these results for each of the three sectors, estimating regressions for productivity growth at different quantiles of the productivity distribution. Figure 4 displays the corresponding coefficients. In cotton spinning, the bias towards productivity growth in the lower tail is striking. Productivity growth at the 25th percentile is estimated to be twice as large as that at the 75th percentile (3.3% per year relative to 1.65%), and the difference is more than fourfold between the 10th and the 90th percentile (3.9% and 1.0%). In the comparison sectors, the differences are more modest across the different quantiles, and growth is concentrated in the upper tail: In both metallurgy and paper milling, the productivity growth at the 25th percentile is marginally *lower* than at the 75th percentile.[40]

---

[39] Given that we discount revenues using price indices, all our productivity calculations reflect price-adjusted revenue-based productivity. To obtain the growth rates between the two time periods (around 1800 and 1840), we regress log output per worker $\ln(Y/L)$ on a dummy for 1840 in each sector. This coefficient measures the percentage growth in output per worker over the entire time period between the respective survey years. We then annualize these values (and corresponding standard errors) by dividing by the number of years between the surveys in each sector.

[40] Owing to the detailed data on the quality of yarn spun by each firm, we are able to use quality-adjusted sector-level

Summing up, the results in this section show that *after* the adoption of the new technology in mechanized cotton spinning, the industry witnessed major increases in productivity that were driven by a disappearance of the lower tail of the productivity distribution. Over time, the firm productivity distribution became less dispersed. This is in contrast to the patterns observed in the comparison sectors, where mean productivity growth was more modest and occurred relatively evenly across the productivity distribution – if anything, with a slight bias towards the *upper* tail.

4.3 Proposed Mechanism: Learning About Best Practice in Factory-Based Production

What explains the lower-tail bias of productivity growth in mechanized cotton spinning? The historical narrative points to an important role of learning about the efficient organization of factory-based production and adequate handling of new machinery. As documented in Section 2, early adopters in cotton spinning needed to engage in trial and error along multiple dimensions. This involved the development of best-practice methods for operating the new technology efficiently and integrating it into other, similarly new aspects of factory-based production.

A Stylized Framework. We formalize this process in a simple stylized framework that gives rise to lower-tail biased productivity growth. We summarize the key features here; Appendix B provides further detail. The essential ingredients are: i) a production function that involves multiple *complementary* inputs (tasks); ii) independent, random draws in the efficiency associated with each input; and iii) the lower bound of each input's efficiency draw increases over time (i.e., very bad draws disappear).

Initially, strong complementarity across inputs implies that a low efficiency draw for only one input will decrease output substantially.[41] This gives rise to a fat lower tail of the productivity distribution. Over time, as knowledge about the best practice in organizing and handling each input diffuses through the economy, the lower bound for the efficiency draws increases. This leads to productivity growth concentrated in the lower tail. Intuitively, learning from other producers eliminates the worst efficiency draws for each input, while the best possible draws remain unchanged. Figure 3 provides an illustration of this mechanism for the case of a CES production function with three inputs. We choose the elasticity of substitution across inputs to be 0.5, indicating a strong degree of complementarity.[42] Efficiency in each of the inputs is drawn from a uniform distribution with support $[0, 1]$. Over time, the lower bound for each distribution increases to 0.1. The right

---

prices in 1800 for cotton spinning. Our data are less precise for the other sectors; however, this does not drive the observed differences. Panel B in Table A.4 in the appendix shows the quantile regression coefficients when we use the same sector-level price across all firms in cotton spinning. The magnitude of the lower tail bias is slightly smaller but remains striking. The difference in productivity growth between the 10th and the 90th percentile is 3.9% relative to 1.0%, and thus almost identical to our baseline results. In addition, using detailed data on physical machinery (number of spindles) available for the cotton spinning sector, we also show that our results are robust to estimating TFP, as opposed to labor productivity (see Panel C in Table A.4 in the appendix).

[41] In the extreme case – a Leontief production function – output drops to the minimum efficiency draw, no matter how large the draws for the other inputs are.

[42] For simplicity, we normalize all inputs to be 1 in both periods.

panel of Figure 3 shows the resulting evolution of the firm productivity distribution over time: The initially fat lower tail disappears in the second period – intuitively, very bad draws that pull down output towards zero (even if all other draws are high) have been eliminated. The productivity pattern shown in Figure 3 is qualitatively similar to the one for cotton spinning shown in Figure 2. While this is not the only theoretical framework that gives rise to lower-tail bias in productivity growth, it is a simple setup that represents the key features of the historical evidence. In what follows, we use this stylized framework to guide our discussion of likely mechanisms.

Firm Survival Across the Sectors. The historical evidence discussed in Section 2 suggests that learning best-practice methods was an important dimension during the shift to factory-based cotton production. We now provide evidence that this mechanism can explain the observed firm productivity patterns. First, we examine firm survival across sectors. If early adopters of mechanized cotton spinning technology had to experiment with best-practice methods, we would expect initially low firm survival rates relative to the other two sectors. Experimentation was arguably costly. For example, the layout of the factory was to a large extent a sunk investment. Changes and extensions could of course be made, but at substantial cost. Thus, initial design flaws were hard to correct and likely led to exit. Indeed, we find evidence of substantially larger exit rates in cotton spinning relative to the other two sectors. Table 4 reports firm survival rates over our sample period, using the two measures defined in Section 3.5 in each of the three sectors. Based on our baseline measure, survival rates in spinning (7%) are slightly lower than in paper milling (9%) and much lower than in metallurgy (34%). Note that the paper milling survey was conducted in 1794, more than 10 years earlier than the cotton spinning survey (1806). If we adjusted for the longer horizon in paper milling, the implied survival rates for 1806-1840 would be significantly higher. This implies that the differences in survival rates between paper milling and cotton spinning are probably higher than reflected in Table 4.

Turning to the 'restricted sample' survival rates, the differences across the three sectors are even starker. By this measure, the survival rate in spinning is still about 7%, but it is much higher in the comparison sectors: 20% in paper milling and 49% in metallurgy. Recall that this second survival rate is based on single-firm locations. Thus, the low survival rate observed in cotton spinning means that many locations lost their (only) cotton mill. This is consistent with a mechanism in which entrepreneurs that invested in a cotton spinning mill with poor layout had to exit the market, and the structure of the mill was not subsequently used by other entrepreneurs in cotton spinning.[43]

Exiting Firms had Lower Productivity. In Table 5 we examine the extent to which firms that

---

[43] Lower survival rates in spinning could also be consistent with the fact that the industry moved towards steam power to a larger extent than other sectors and hence moved away from water power. However, note in Table A.1 that even in spinning, steam power seemed to be used *in addition to* water power: 66% of cotton spinning firms still used water power as a source in 1840. Moreover, cotton mills using steam power were somewhat less productive (see Table A.3), suggesting that in France firms did not face a strong profit incentive to move away from water power.

eventually exited the market by 1840 had lower initial productivity around 1800, as compared to surviving firms. This pattern is strong in cotton spinning, where churn was the highest: Exiting firms were 49% less productive than survivors, and this difference is highly statistically significant. Exiting firms were also less productive in the comparison sectors, but there, the pattern is less pronounced: exiting firms were about 15% less productive in both sectors, and this number is not statistically different from zero. Columns 2 and 3 in Table 5 also show that exiting firms were significantly smaller, both in terms of employees and output, and that this pattern is particularly pronounced in cotton spinning.

Overall, we find that exiting firms in cotton spinning were particularly unproductive compared to survivors, and – likewise – the survival rate was significantly lower than in other sectors. These findings – in combination with the widely dispersed productivity distribution in cotton spinning – are consistent with large organizational challenges and low initial guidance in switching to factory-based cotton spinning.

Age Profile of Firm Productivity. Next, we examine whether the age profile of firm productivity is consistent with a mechanism of learning best-practice methods. We expect younger firms to have higher productivity, because they had a larger set of previously established firms from whom they could learn. We exploit the richness of our data to test this in both 1800, when best practice mill design was still evolving, and in 1840, when according to Pollard (1965), the industry had reached maturity – at least in Britain. The 1806 survey in cotton spinning contains the year of foundation. This allows us to compute a dummy for 'young' firms, defined as below-median age (with the median age in 1806 being three years). We first examine whether firm age is systematically correlated with productivity in cotton spinning. Column 1 in Table 6 shows that the unconditional association is strongly positive: 'Young' firms were 58% more productive in 1806. This could be driven by mechanisms other than the one we examine. For example, new entrants may use the most recent vintage of capital and thus have higher physical productivity (Foster, Haltiwanger, and Syverson, 2008). To address this issue, we control for several important firm characteristics in columns 2-6 of Table 6. This include the vintage of machinery used (a binary variable for using different vintages of machinery), the capital intensity of the firm (measured as log spindles per worker), the number of workers in the firm, and the average quality (count) of the yarn spun. The coefficient of interest remains large and highly significant when we add these controls one-by-one.[44] The only control that notably changes the magnitude of the coefficient of interest is the quality of yarn. However, the quality of the yarn that a firm could spin partly reflected its level of learning, and is thus arguably also capturing our mechanism. This is because the quality of yarn that could be spun by a firm depended partly on the quality of the machine, and the precision of its operation. This, in turn, may have reflected improvements of the machinery

---

[44] We do not include all controls together because of multicollinearity concerns.

achieved by tinkering, and the acquired skill of the spinner, both of which are a central part of our learning mechanism.

Next, we turn to the productivity-age pattern in 1840. While the data for this second period are generally more comprehensive, we do not observe firm age. However, we can perform a similar – albeit weaker – test based on the comparison of surviving and entrant firms. Table A.6 in the Appendix reports the results, regressing log output per worker on an indicator for whether the firm was an 'entrant' in 1840 (as opposed to a surviving firm by our definition from Section 3.5). The coefficient on the 'entrant' dummy thus reflects the average productivity differential for firms that entered between the initial survey year (1806) and 1840. Best-practice mill design evolved over this period, and it had largely converged by 1840 (Pollard, 1965). Correspondingly, we find that 'young' firms were not more productive; the coefficient is in fact negative, but not statistically different from zero. This holds also when we control for the use of water power, steam power, any other power source (wind or animal power used by a small subset of firms), and for log employees. We perform an additional exercise in the appendix, using data on metallurgy firms in both periods (Tables A.7 and A.8). For this sector, in both periods, the best measure of firm age that we observe is a binary indicator of firm survival from 1788 to 1811, and for survival from 1811 to 1840 (the latter being the same procedure as for cotton spinning in Table A.6). Overall, the results do not point to younger firms in metallurgy having a strong productivity advantage: In 1811, 'young' metallurgy firms were only marginally more productive, and in 1840 'young' metallurgy firms were somewhat *less* productive.[45]

Spatial Diffusion of Knowledge. In what follows we shed light on *how* the learning process took place. The historical background discussed in Section 2 suggests that firms copied successful designs and setups of the production process from each other. To test this channel, we estimate whether a firm's own productivity was higher in the proximity of other high-productivity firms. We use the following specification:

$$ln(Y/L)_{ij} = \beta_0 + \beta_1 dist_{ij}^{p90} + FE_j + \epsilon_{ij} \ ,$$

where $ln(Y/L)_{ij}$ is labor productivity (log output per worker) for firm i located in department j; $dist_{ij}^{p90}$ is log distance to the closest firm (in the same sector) with productivity in the 90th percentile (in the distribution of *all* firms in the sector across France). Firms that are themselves in the top productivity decile are excluded from the sample to avoid introducing a mechanical relationship. Our preferred specification includes department fixed effects (FE_j) to absorb unobserved

---

[45] In metallurgy in 1811, 'young' firms are 22% more productive when no controls are added (as compared to almost 60% for the same specification in cotton spinning). Once we control for firm size (log employees) in column 2 in Table A.7, the productivity advantage disappears. Note that the metallurgy survey has sparser information on this dimension; firm size is the only control that can be added in 1811.

location fundamentals that may make all firms in a given region more productive, irrespective of local spillovers. Thus, the coefficient of interest β_1 reflects the extent to which firms in the same department benefit from being located closer to a high-productivity firm (which may be located in the same or in another department). We do not interpret these correlations as causal effects, but as evidence that is compatible with spatial spillovers of production knowledge. We estimate the specification separately for the three sectors, and in both time periods. Standard errors are clustered at the department level to account for spatial correlation.

Before presenting the results, we first examine the spatial distribution of high-productivity firms across our sectors and time periods. Figure A.2 plots the spatial distribution of cotton spinning, metallurgy, and paper milling firms, distinguishing those in the 90th percentile of the productivity distribution. Across all sectors and time periods, high-productivity firms are distributed relatively evenly across space. Unsurprisingly, some regions have a larger concentration of high-productivity firms than others. However, these do not affect our results because we exploit within-department variation in distance to high-productivity firms.

Figure 5 visualizes our baseline results on spatial diffusion, and Table 7 reports the corresponding regressions. To allow for direct comparability, we report the standardized beta coefficients of $dist^{p90}$ for all three sectors in the two periods. The estimated coefficient for cotton spinning in 1806 is negative, statistically significant and large in magnitude: A one standard deviation increase in distance to a high productivity firm in the sector is associated with a 0.81 standard deviation decline in labor productivity. The pattern is much weaker in the two control sectors in 1811 (metallurgy) and in 1794 (paper milling) – the coefficients are less than one-third in magnitude as compared to cotton spinning. In addition, in 1840, there is essentially no relationship between labor productivity and distance to top-firms in any of the three sectors. Thus, proximity to high-productivity firms mattered the most in cotton spinning in 1806, i.e., in the sector that saw the most dramatic change during industrialization, and in the period before knowledge about the optimal organization of production had spread widely. While this pattern is consistent with a learning mechanism, it could also be driven by a number of other forces. We turn to examining some prominent alternative explanations below.

While department fixed effects capture unobserved differences that vary at the department level, they cannot capture unobserved differences at a finer spatial level. To test for these, we use four approaches. First, we control directly for some prominent location fundamentals at the commune level such as the availability of fast-flowing streams (as a source of water power), proximity to coal (which matters for steam power), and the share of forest cover (which matters for access to charcoal – a major input in metallurgy).[46] Table A.9 in the appendix shows the results for

---

[46] The sources for these data are as follows. Data on the stream flow of rivers are from EURO-FRIEND (http://ne-friend.bafg.de/servlet/is/7397/). These data report water flow rates from thousands of geocoded collection points across France. Data on charcoal sources are from the highly detailed 'Cassini maps' produced in the late 18th century

specifications that control for all of these location fundamentals. The pattern of the coefficients of interest does not change, and the estimated magnitudes remain very similar. Moreover, the location fundamentals themselves are mostly small and statistically insignificant. This is probably driven by the fact that the department fixed effects already account for the most important spatial differences in location fundamentals. Second, our results could be affected by more general agglomeration externalities, as opposed to learning. In particular, our findings may be driven by high-productivity firms emerging (within departments) where the density of production is large due to agglomeration forces. We investigate this explanation directly by adding a control for the density of production at the commune level (measured as the log of total output in the sector, excluding a firm's own output). Table A.10 in the appendix shows that controlling for the local density of production barely affects our results: The estimated coefficient on distance to high-productivity firms in cotton spinning in 1806 decreases by about 10% to -0.74 (se 0.19), while the distance coefficients in the other sectors and in 1840 remain relatively small. The coefficient on local production density itself is generally small, positive, and never statistically different from zero.

Appendix Table A.11 presents our third approach to probe for unobserved location fundamentals. We conduct a placebo exercise that examines whether firm productivity in 1800 was also related to the distance to high-productivity firms that only emerged later, i.e., firms in the top-90th percentile of productivity in 1840. Reassuringly, the estimated coefficient in cotton spinning is close to zero and statistically insignificant. In other words, productivity in cotton spinning in 1806 was not related to high-productivity locations three decades later. This suggests that the large estimated coefficient in our baseline specification is not driven by persistent location fundamentals within departments.

Finally, we examine the extent to which the estimated distance coefficient in cotton spinning in 1806 may be driven by firm selection. It is possible that we estimate a large coefficient in cotton spinning in 1806 not because firms are learning from their high-productivity neighbors but rather because *ex-ante* high-productivity firms choose to locate near other high productivity firms. Given that we observe firms' age in cotton spinning in 1806, we can examine selection patterns, building on our findings from Table 6 that 'young' firms in cotton spinning were particularly productive. In Table 8, we show that our coefficient of interest is robust to controlling for log firm age (column 1) and to adding the interaction of firm age and distance to high productivity firms (column 2). This suggests that (conditional on department fixed effects) firm entry did not vary systematically with the location of high-productivity firms. A different, arguably more conservative approach is to estimate the coefficient of interest using only the subsample of firms that entered *before* the nearest high-productivity firm. The timing of entry of these firms rules out systematic selection. In column

---

that contain information on forest cover. These maps were geo-referenced by Vallauri, Grel, Granier, and Dupouey (2012). Finally, data on the location of coal deposits – both in France and near its borders – were geo-referenced from maps in Tarr and McMurry (1993) and Guiollard (1993).

3 of Table 8 we show that the coefficient on distance to high-productivity firms remains statistically highly significant, although it is somewhat smaller than in the baseline sample (-0.44, se 0.153). Columns 4 and 5 show that the coefficient of interest remains stable and statistically significant as controls for firm age and the interaction between firm age and distance to high productivity firms are added in this subsample.

In summary, the consistently larger distance coefficient estimated in cotton spinning in 1806, in combination with a series of robustness checks presented above, points to the spatial diffusion of knowledge as one mechanism through which learning across firms took place.

4.4 Robustness to Alternative Explanations

In the final part of this section we consider potential alternative mechanisms that could explain our results. Recall that we observe the lower-tail bias in productivity growth only in cotton spinning, and not in the other two sectors. This suggests that the mechanisms driving the effect are either specific to cotton spinning or they affect this sector differentially. Below, we consider some competing mechanisms that would fit this pattern.

Market Integration. Could increased market integration explain our results in cotton spinning? As the French economy became more integrated over time, it is possible that lower-productivity firms faced tougher competition and had to exit the market.[47] However, we do not observe a lower-tail bias in productivity growth in the two comparison sectors. Thus, for market integration to explain our results, it must have affected cotton yarn differently.

We first note that the pattern in Table 5 speaks against such a mechanism: If market integration increased particularly strongly in cotton spinning, we would expect even relatively productive firms to exit the market, because of an increased productivity threshold that allows for profitable production (Melitz, 2003). However, the contrary is true: Exiting firms in cotton spinning had a particularly *low* productivity, as compared to the other two sectors.

Second, data on market integration also speak against a confounding role of this channel. Cotton yarn (and textiles more generally) are high value-to-weight products, which makes them more easily tradable over long distances than iron or paper. This suggests that cotton spinners may already have faced tougher competition through more integrated markets in the early 1800s. Thus, we would not necessarily expect cotton spinning to be the most affected sector by increased market integration after 1800. Consistent with this reasoning, we present evidence for relatively high market integration in cotton yarn in the late 18th century. We use data in 1794 from Daudin (2010) on the number of districts across France that reported consuming cotton textiles, iron, or paper products from any district in a given department.[48] Intuitively, higher market integration means

---

[47] Market integration arguably increased during our sample period both for policy reasons such as the abolition of internal barriers to trade during the French Revolution (Daudin, 2010), and because of infrastructure improvements that reduced transport costs such as the introduction of railways in the late 1820s.

[48] Districts are administrative units that stayed in place for approximately five years, from 1790 to 1795 – with each

lower price differentials across departments, which in turn implies that highly productive areas could dominate the market throughout France. Consequently, we can infer high market integration from the data if we observe that a few (presumably highly productive) departments sold to many other departments, while the majority of departments produced no output, or did so only for local consumption. Figure A.3 shows that this pattern is particularly strong in cotton textiles. Many departments produced mostly for themselves if at all (these are the zeros and ones), while a few departments supplied cotton to a large number of districts. The top tercile of departments exported cotton textiles to 30 or more districts. In the two comparison sectors, there is less specialization and less evidence for market integration: Fewer departments report not supplying to anyone (particularly in paper), and the top decile of departments supplied only to 6 (paper) and 7 (iron) districts in total. This suggests that cotton textile firms were already competing in a bigger market than the comparison sectors around 1800.

The appendix presents two further robustness checks that probe the extent to which market integration may explain our results. We introduce two controls in our quantile productivity regressions (see the baseline results in Table 3). Table A.12 controls for market potential, and Table A.13 introduces region fixed effects.[49] We find that the lower-tail bias of productivity growth remains unique to cotton spinning when these controls are added. Controlling for market potential changes the coefficients of interest only marginally, while adding region fixed effects dampens the lower-tail bias in cotton spinning: productivity growth at the 10th percentile is now only twice as large as in the 90th percentile (as compared to a factor of almost 4 in the baseline regressions in Table 3). This suggests that a part of the pattern is driven by reallocation across regions, but not in a way systematically related to market potential.

Firm Size and Early Spinning Workshops. Another potential concern is that our results may be driven by the disappearance of small cotton spinning workshops. Smaller workshops using early vintages of spinning jennies and generally no inanimate sources of power may have been inherently different from the large-scale factories powered by inanimate power sources. While the move to factory-based production was swift, systematic differences of smaller cotton workshops could account for the lower-tail bias of productivity growth in this sector. Our data does not differentiate between these two types of firms (and we do not observe power sources in the 1800 data). However, we can examine the extent to which our results could be driven by these forces in a number of ways.

Our baseline sample includes all firms reported by the enumerators, which probably included smaller workshops in the initial period. One way to examine their influence on our results is to adopt a stricter definition of firms and use only those that have more than 10 employees. This

---

department including from a minimum of 3 to a maximum of 10 districts.

[49] Market potential is computed as the sum of inverse distance-weighted city population in 1800.

should exclude the majority of the smaller workshops that may only be organized as factory-based production along some but not all dimensions. Figure A.4 and Table A.14 show that the lower-tail bias in productivity growth is robust to using only larger firms. The magnitudes remain similar at most quantiles, while the lower-tail bias of productivity growth remains unique to cotton spinning firms. These findings also address the concern that smaller firms may have been under-sampled in 1840.

Finally, our results could also be driven by increasing firm scale. Recall, however, that this is unlikely, as all sectors witnessed an increase in firm scale. Indeed, as the results in Table A.15 show, controlling for the number of workers in each firm does not alter our findings.

Effects of the Napoleonic Blockade on the Cotton Spinning Sector. Juhász (2018) shows that temporarily higher trade protection from British competition shifted the location of the mechanized cotton spinning industry within France. To what extent does varying trade protection explain the lower-tail bias of productivity growth in cotton spinning? Given that our results hold within regions (see Table A.13), where the pattern of protection was very similar, this is unlikely. Figure A.5 presents further evidence that varying trade protection does not drive our results, by splitting the sample into firms in northern and southern regions in France (corresponding to the main dimension along which protection varied). The productivity distributions in the north and south are remarkably similar, and in both regions, productivity growth until 1840 is due to a disappearing lower tail.

Vintages of Capital and Capital Deepening. Another possible alternative mechanism is that productivity growth in cotton spinning was driven by incremental technological improvements of the mechanized machinery after 1800. This is unlikely for two reasons. First, as we discussed in Section 2.1, the vintages of capital in cotton spinning remained largely unchanged during our sample period. Second, it is unclear why the successive adoption of better capital vintages would be concentrated in the lower tail of the firm-productivity distribution. In fact, in our two comparison sectors – where new vintages became available – the whole distribution shifted to the right.

Finally, in Table A.16 we examine whether capital deepening can account for our results by controlling directly for the capital-labor ratio in the firm (measured as the number of spindles per employee). The lower-tail bias for productivity growth remains robust and similar in magnitude, suggesting that neither differential capital deepening, nor changes in the vintages of capital drive our results.[50] In sum, our results are unlikely to be driven exclusively by technological improvements over time that were accessible to all firms.

---

[50] Newer versions of the different machines on the market did have more spindles. However, we use the number of spindles per worker as our measure of the capital-labor ratio of the firm, as opposed to the number of machines per worker. Thus, the results in Table A.16 already capture the effect of new machines having more spindles.

4.5 Discussion

Our results shed light on two important puzzles in the literature on technology adoption. First, our findings speak directly to why the *aggregate* productivity effect of major technological breakthroughs such as IT and electricity may be hard to pin down in the data. Based on our results, the full effects of a new technology may take significant time to materialize, as firms need to learn how the new technology can be operated efficiently once the technology has been widely adopted. In our context, adopting mechanized cotton spinning required producers to reorganize production from households to factories. In other settings, the specific challenges may be different, but they are plausibly subject to similar mechanisms. For mechanized cotton spinning, we estimate that productivity for the average firm using essentially identical new production methods increased by about 82% until 1840, relative to when the technology was in its infancy in 1806. Put differently, observers estimating the productivity effect of switching from handspinning to mechanized spinning would significantly underestimate the long-run aggregate productivity gain if they only looked at the initial data around 1800.

Second, our results also shed light on the slow adoption of major new technologies. When there is uncertainty about how to operate a new technology efficiently, and the knowledge – once acquired via costly experimentation – is observable to competitors, firms face a strategic incentive to delay adoption. The high exit rates observed in cotton spinning relative to other sectors, alongside the higher productivity observed for younger firms in 1806, suggest that firms that entered later were at an advantage. If entrepreneurs understand the significant uncertainty they face when setting up a spinning mill at early stages of adoption, they have an incentive to delay the switch to the new technology in order to take advantage of the learning externalities generated by other early adopters.

5 Conclusions

The diffusion of innovation is at the core of aggregate productivity growth and thus of key importance for economic development. However, understanding the determinants and effects of technology adoption has proven to be challenging. Our results shed light on the process of technology adoption, by focusing on a unique historical setting: The adoption of mechanized cotton spinning in France during the First Industrial Revolution. Mechanized cotton spinning had been invented in Britain in the second half of the 18th century, and its adoption in France had begun before the turn of the century. If operated efficiently, mechanized cotton spinning promised huge productivity improvements.

To conduct our empirical analysis, we digitized firm-level data from historical surveys covering mechanized cotton spinning and two comparison sectors – metallurgy and paper milling – at two points in time, 1800 and 1840. Since in cotton spinning, production in firms only emerged with the new technology – the famous spinning jenny – any cotton ‘firm’ in the data must have operated mechanized spinning. This allows us to isolate the productivity distribution specific to the new technology and to examine its evolution over time. On the other hand, in the comparison sectors, production was already organized in firms before the Industrial Revolution because of their reliance on water power and high-fixed-cost machinery. Thus, the firm productivity distribution in these sectors reflects the typical mix of different vintages of technology.

We documented three main findings for cotton spinning firms: 1) we observe a highly dispersed productivity distribution in the initial period (1806); 2) the industry experienced substantial productivity growth, which exceeded the growth in the comparison sectors; 3) this aggregate productivity growth in cotton spinning was largely driven by a disappearance of lower-tail firms, while in the comparison sectors, the whole distribution shifted to the right.

To rationalize these findings, we presented rich historical evidence that at early stages of adoption, entrepreneurs in mechanized cotton spinning needed to learn about the most efficient way to operate the new technology along multiple dimensions. In particular, the move from household to factory production represented a crucial organizational challenge to entrepreneurs, and historical evidence suggests that many of the organizational innovations proceeded via a process of trial and error. We showed empirical evidence consistent with this. First, churn was much higher in cotton spinning, consistent with the notion that early adopters that did not stumble upon efficient production methods needed to exit the market. Coherent with this interpretation, exiting firms in cotton spinning were substantially less productive than those that survived. Second, in 1806 younger firms in cotton spinning were more productive, even when controlling for the vintage of their capital. This is consistent with the idea that later entrants could draw from a better pool of best-practice knowledge. Finally, we showed evidence consistent with the spatial diffusion of best-practice methods.

These findings shed light on two important questions in the economics literature: Why is the adoption of major innovations slow, despite their huge potential for efficiency gains? And why do aggregate efficiency gains take time to materialize?

In our setting, the highly dispersed initial productivity distribution points to information disparities across cotton firms: The organization of factory production evolved via a process of trial and error and only the most productive adopters, those that ‘stumbled’ upon the efficient organization of factory production, survived. By 1840, information about the efficient organization of cotton mills had dispersed, leading to a much narrower distribution of firm productivity. This suggests that uncertainty about the optimal organization of production with a new technology can explain why aggregate productivity gains are initially small. When technological change requires the reorganization of production, early adopters experiment with the efficient organization of production, and some of them will operate the new technology inefficiently. Consequently, the promised benefits of the new technology may materialize relatively slowly for the average firm. These findings are in line with the literature showing that the effects of disruptive technologies such as electricity and IT appear slowly in industry productivity “due to the need to reorganize the operation of the entire manufacturing facility to make effective use of this innovation.” (Hall and Khan, 2003, p.8).

At the same time, a lack of knowledge about organizing production reduces the expected productivity gains from switching to a new technology, and expectations that this knowledge will improve over time creates incentives to delay entry. This can help explain the slow diffusion of major innovations, especially if they require a re-organization of production.

References

Allen, R. C. (2009). *The British Industrial Revolution in Global Perspective*. Cambridge University Press.

Atkin, D., A. Chaudhry, S. Chaudry, A. K. Khandelwal, and E. Verhoogen (2017). Organizational barriers to technology adoption: Evidence from soccer-ball producers in pakistan. *The Quarterly Journal of Economics 132*(3), 1101–1164.

Bandiera, O. and I. Rasul (2006). Social networks and technology adoption in northern Mozambique. *The Economic Journal 116*, 869–902.

Beaman, L., J. Magruder, and J. Robinson (2014). Minding small change among small firms in Kenya. *Journal of Development Economics 108*, 69–86.

BenYishay, A. and A. M. Mobarak (2018). Social learning and incentives for experimentation and communication. *The Review of Economic Studies 86*, 976–1009.

Bloom, N., B. Eifert, A. Mahajan, D. McKenzie, and J. Roberts (2013). Does management matter? Evidence from India. *Quarterly Journal of Economics 128*(1), 1–51.

Boston Mutual Fire (1908). *Report No. 5: Slow-Burning or Mill Construction*. Boston Manufacturers Mutual Fire Insurance Co. 3rd ed., rev. and enl. Boston: The Company. .

Bougin, H. and G. Bourgin (1920). *L’Industrie Sid’erurgique en France au D’ebut de la R’evolution*. Paris: Imprimerie Nationale.

Catling, H. (1970). *The Spinning Mule*. David & Charles, Newton Abbott.

Chanut, J.-M., J. Heffer, J. Mairesse, and G. Postel-Vinay (2000). Editions de l’école des hautes études en sciences sociales, Paris.

Chapman, S. (1970). Fixed capital formation in the british cotton industry, 1770-1815. *The Economic History Review 23*(2), 235–253.

Chapman, S. D. (1974). The textile factory before arkwright: A typology of factory development. *Business History Review 48*(4), 451–478.

Chassagne, S. (1991). *Le coton et ses Patrons: France 1760-1840*. Editions de l’Ecole des Hautes Etudes en Sciences Sociales.

Conley, T. G. and C. R. Udry (2010). Learning about a new technology: Pineapple in Ghana. *American Economic Review 100*, 35–69.

Crafts, N. F. R. (1977). “industrial revolution in england and france: Some thoughts on the question, ’why was england first?”’. *Economic History Review 30*(3), 429–441.

Crafts, N. F. R. (1985). *British Economic Growth During the Industrial Revolution*. Oxford: Oxford University Press.

Crafts, N. F. R. and K. Harley (1992). Output Growth and the British Industrial Revolution: A restatement of the Crafts-Harley View. *Economic History Review 45*, 703–730.

Crafts, N. F. R. and N. Wolf (2014). The location of the UK cotton textiles industry in 1838: A quantitative analysis. *Journal of Economic History*.

Daudin, G. (2010). Domestic Trade and Market Size in Late-Eighteenth-Century France. *The Journal of Economic History 70*(3), 716–743.

Duflo, E., M. Kremer, and J. Robinson (2011). Nudging farmers to use fertilizer: Theory and experimental evidence from Kenya. *American Economic Review 101*, 2350–90.

Emerick, K., A. de Janvry, E. Sadoulet, and M. H. Dar. (2016). Technological innovations, downside risk, and the modernization of agriculture. *American Economic Review 106*, 1537–1561.

Fitton, R. S. and A. P. Wadsworth (1958). *The Strutts and the Arkwrights, 1758-1830: A study of the early factory system*. Manchester University Press.

Foster, A. D. and M. R. Rosenzweig (1995). Learning by doing and learning from others: Human capital and technical change in agriculture. *Journal of Political Economy 103*, 1176–1209.

Foster, L., J. Haltiwanger, and C. Syverson (2008). Reallocation, Firm Turnover, and Efficiency: Selection on Productivity or Profitability? *American Economic Review 98*(1), 394–425.

Galor, O. (2011). *Unified Growth Theory*. Princeton University Press.

Giorcelli, M. (2019). The Long-Term Effects of Management and Technology Transfers. *American Economic Review 109*(1), 1–33.

Grantham, G. (1997). The French cliometric revolution: A survey of cliometric contributions to French economic history. *European Review of Economic History 1*(3), 353–405.

Griliches, Z. (1957). Hybrid Corn: An Exploration in the Economics of Technological Change. *Econometrica 25*(4), pp. 501–522.

Guiollard, P.-C. (1993). *Les chevalements des houillères françaises*. Pierre-Christian Guiollard.

Hall, B. H. (2004). Innovation and diffusion. NBER working paper 10212.

Hall, B. H. and B. Khan (2003). Adoption of New Technology. *NBER Working Paper 9730*.

Hanna, R., M. Sendhil, and J. Schwartzstein (2014). Learning through noticing: theory and experimental evidence in farming. *Quarterly Journal of Economics 129*, 1311–1353.

Hardy, M. and J. McCasland (2016). It Takes Two: Experimental Evidence on the Determinants of Technology Diffusion. Working Paper.

Harley, C. K. (1998). Cotton textile prices and the Industrial Revolution. *The Economic History Review 51*(1), 49–83.

Horn, J. (2006). *The Path Not Taken: French Industrialization in the Age of Revolution, 1750-1830*. Cambridge MA: MIT Press.

Hsieh, C.-T. and P. J. Klenow (2009). Misallocation and Manufacturing TFP in China and India. *Quarterly Journal of Economics 124*(4), 1403–1448.

Huberman, M. (1996). *Escape from the Market*. Cambridge University Press.

Johnson, H. R. and A. W. Skempton (1955). William strutt's cotton mills, 1793-1812. *Transactions of the Newcomen Society 30*(1).

Juhász, R. (2018). Temporary Protection and Technology Adoption: Evidence from the Napoleonic Blockade. *American Economic Review 108*(11), 3339–76.

Langenbach, R. (2013). Better than Steel? Part 2: Tall Wooden Factories and the Invention of "Slow-burning" Heavy Timber Construction. Article URL accessed June 20, 2020.

Mansfield, E. (1961). Technical change and the rate of imitation. *Econometrica 29*, 741–766.

Melitz, M. J. (2003). The Impact of Trade on Intra-Industry Reallocations and Aggregate Industry Productivity. *Econometrica 71*(6), 1695–1725.

Mitchell, B. R. (2003). *International historical statistics. Europe, 1750-2000*. Palgrave Macmillan.

Mokyr, J. (2010). *The Enlightened Economy: An Economic History of Britain 1700-1850*. Yale University Press.

Munshi, K. (2004). Social learning in a heterogeneous population: technology diffusion in the Indian Green Revolution. *Journal of development Economics 73*, 185–213.

Perrot, J.-C. (1975). *L'ăge d'Or de la Statistique Régionale Française (An IV-1804)*. Paris: Société des Etudes Robespierristes.

Pollard, S. (1963). Factory Discipline in the Industrial Revolution. *The Economic History Review 16*(2), 254–271.

Pollard, S. (1965). *The Genesis of Modern Management: A Study of the Industrial Revolution in Great Britain*. Harvard University Press.

Pounds, N. and W. Parker (1957). *Coal and Steel in Western Europe: The Influence of Resources and Techniques on Production*. Bloomington: Indiana University Press.

Rosenberg, N. (1976). Factors affecting the diffusion of technology. *Explorations in Economic History 10*(1), 3–33.

Rostow, W. W. (1975). *How it All Began: Origins of the Modern Economy*. Methuen and Co., London.

Saxonhouse, G. R. and G. Wright (2004). Technological evolution in cotton spinning. In D. Farnie and D. Jeremy (Eds.), *The Fibre that Changed the World: The Cotton Industry in International Perspective, 1600-1990s*, pp. 129–152. Oxford University Press.

Suri, T. (2011). Selection and comparative advantage in technology adoption. *Econometrica 79*, 159–209.

Syverson, C. (2011). What Determines Productivity? *Journal of Economic Literature 49*(2), 326–365.

Szostak, R. (1989). The Organization of Work: The Emergence of the Factory Revisited. *Journal of Economic Behavior and Organization 11*(3), 343–358.

Tarr, R. S. and F. M. McMurry (1993). *New Geographies: Second Book*. Macmillan Company.

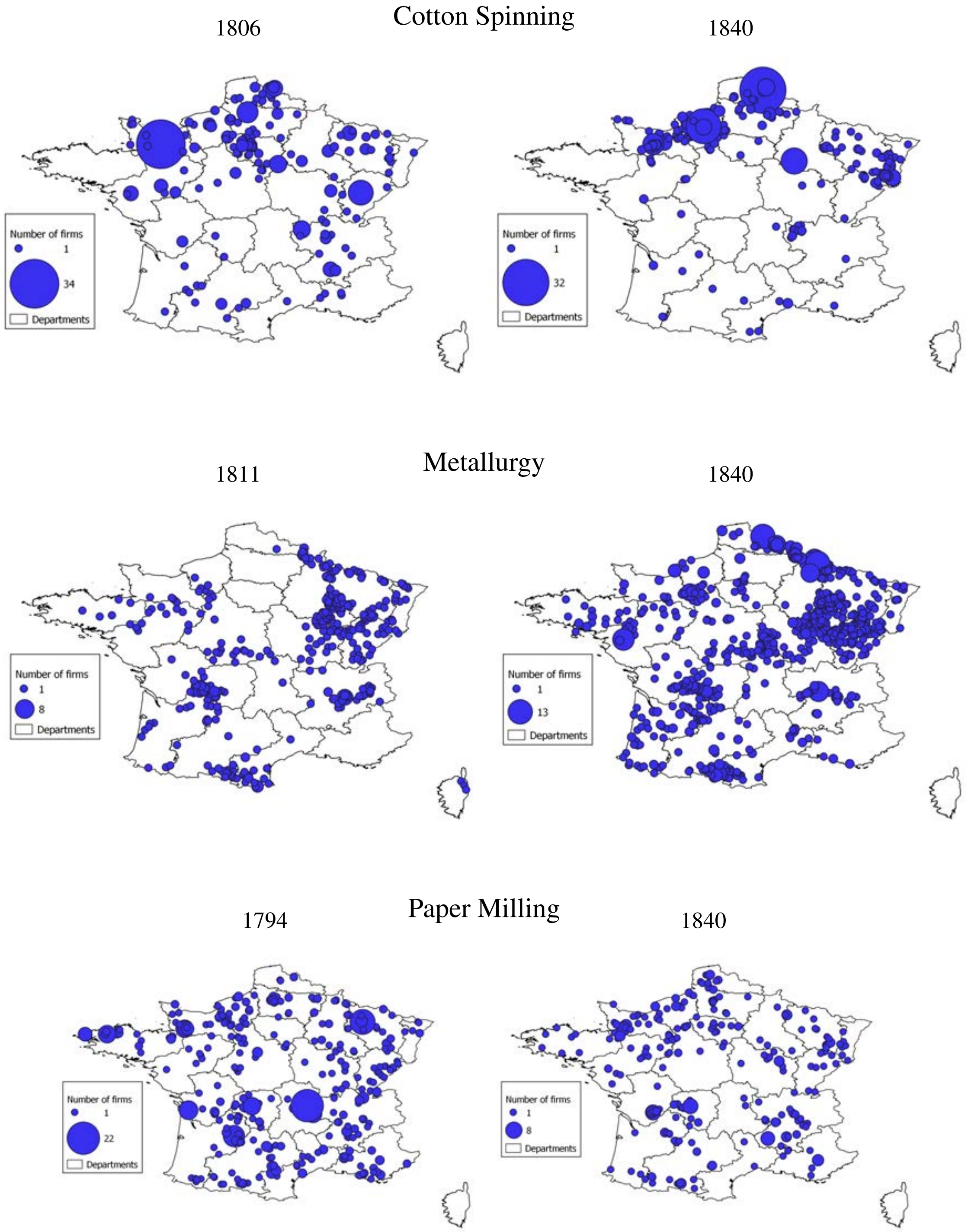
Vallauri, D., A. Grel, E. Granier, and J.-L. Dupouey (2012). *Les Forets de Cassini. Analyse Quantitative et Comparaison Avec les Forets Actuelles*. Marseille: WWF/INRA.

Voigtländer, N. and H.-J. Voth (2006). Why England? Demographic Factors, Structural Change and Physical Capital Accumulation during the Industrial Revolution. *Journal of Economic Growth 11*, 319–361.

Williamson, O. (1980). The Organization of Work: A Comparative Institutional Assessment. *Journal of Economic Behavior and Organization 1*(1), 5–38.

Woronoff, D. (1984). *L'industrie sidérurgique en France pendant la Révolution et l'Empire*. Paris: École des hautes études en sciences sociales.

FIGURES



Cotton Spinning

1806

1840

Metallurgy

1811

1840

Paper Milling

1794

1840

Figure 1: Spatial Distribution of Firms Across France in the Three Sectors

Note: The figure shows the spatial distribution of firms in cotton spinning (top), metallurgy (middle), and paper milling (bottom). Dots indicate the number of firms per commune.

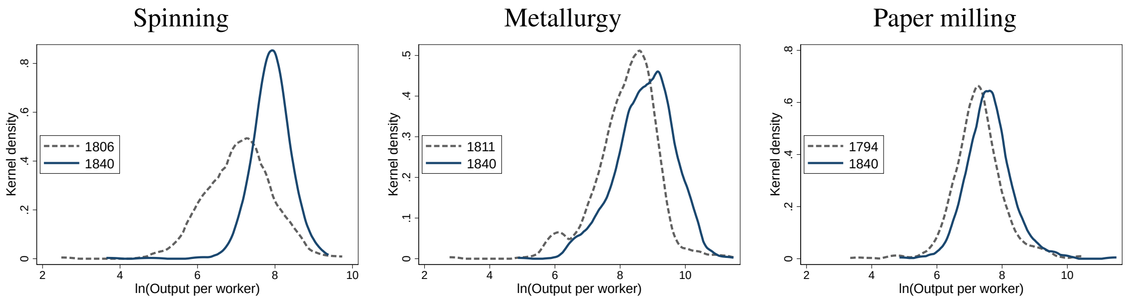


Figure 2: Changes in the Productivity Distributions in the Three Sectors

Note: The figure shows the distribution of ln(output per worker) for the three sectors at the beginning of our sample period (around 1800) and in 1840. Productivity growth in spinning was mainly due to a disappearing lower tail. In contrast, in metallurgy and paper milling, the whole distribution shifted to the right.

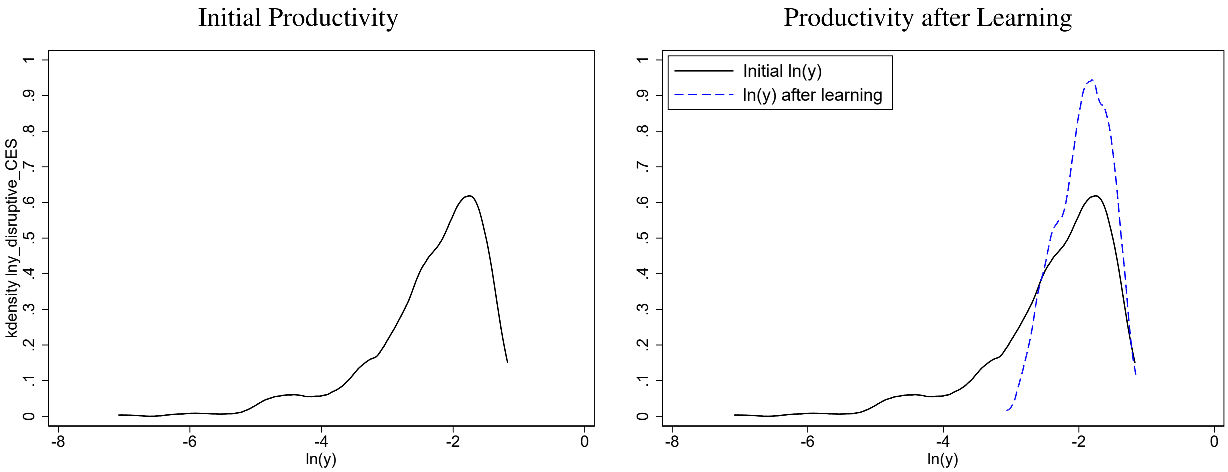
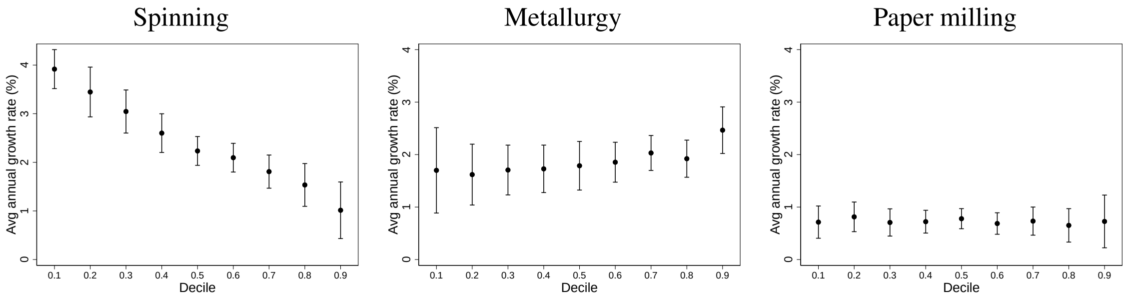


Figure 3: Simulated Productivity Distributions before and after Learning

Notes: Example with a CES production function that has three inputs (all normalized to 1). The elasticity of substitution is 0.5. The efficiency of each input is a random draw from an independent, uniform distribution with support $[0, 1]$. Left panel shows the initial productivity distribution. Right panel shows the change in productivity when the lower bound for each distribution increases to 0.1.

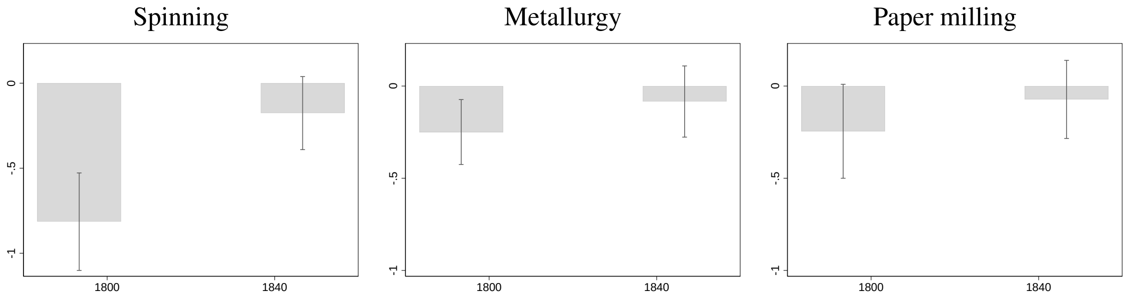

Spinning

Metallurgy

Paper milling

Figure 4: Productivity Growth at Different Parts of the Distribution

Note: The figure visualizes the results of quantile regressions for growth in ln(output per worker) for the three sectors estimated at each decile. Productivity growth in spinning was concentrated in the lower tail of initial firm productivity. In contrast, in metallurgy and paper milling, productivity growth is relatively even across the distribution.


Spinning

Metallurgy

Paper milling

Figure 5: Proximity to most productive firms

Note: The figure shows the standardized beta coefficients of $dist^{p90}$ at the beginning of our sample period (around 1800) and in 1840 for the three sectors. $dist^{p90}$ measures the log distance to the closest firm (in the same sector) with productivity in the 90th percentile. The dependent variable is log(output per worker). All regressions include department FE. Standard errors clustered at the department level.

TABLES

Table 1: Occupation and Background of Owners of Mechanized Cotton Spinning Firms

Panel A: Owners active between 1785-1815	
Nobility or administrator pre-1789	10.2%
Traders, bankers and commercial employees	62.5%
Industrialists	9.5%
Workers and mechanics	10.2%
Liberal profession	6%
Other	3.5%

Notes: Data are from Chassagne (1991, p.274). The author collected data on the owners of firms from a variety of archival sources described in more detail in Chassagne (1991, p. 274). The sample covers N = 185 firms.

Table 2: Summary Statistics: Firm Scale in the Three Sectors

Sector	year	(1) mean	(2) sd	(3) median	(4) 10perc	(5) 90perc	(6) N
Cotton Spinning	1806	63	(101)	30	4	150	372
	1840	112	(148)	72	28	210	528
Metallurgy	1811	20	(23)	11	4	46	457
	1840	57	(114)	22	7	135	839
Paper Milling	1794	13	(19)	11	5	23	550
	1840	43	(58)	19	5	112	348

Notes: The table reports statistics on the number of workers in the three sectors covered by our analysis. The year of the first survey varies across the sectors, while information in 1840 is available for all sectors. Data sources: see Section 3.

Table 3: Annual Productivity Growth (in %) at Different Parts of the Distribution

	(1)	(2)	(3)	(4)	(5)	(6)
	Average	At the following quantiles:				
		0.1	0.25	0.5	0.75	0.9
Spinning (1806-1840)	2.420***	3.917***	3.293***	2.234***	1.651***	1.014***
	(0.154)	(0.204)	(0.229)	(0.151)	(0.167)	(0.297)
Metallurgy (1811-1840)	1.949***	1.700***	1.776***	1.787***	2.025***	2.465***
	(0.185)	(0.415)	(0.271)	(0.236)	(0.187)	(0.226)
Paper milling (1794-1840)	0.734***	0.713***	0.681***	0.779***	0.759***	0.726***
	(0.111)	(0.157)	(0.137)	(0.098)	(0.137)	(0.256)

Notes: The table reports the average annual productivity growth (in %) between the initial sample period (around 1800) and 1840 for the three sectors. The number of observations underlying these estimates is reported in Table 2, col 6. Robust standard errors in parentheses. Notation for statistical significance: *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Table 4: Survival rates across sectors

Period	Spinning 1806-1840	Metallurgy 1811-1840	Paper milling 1794-1840
Survival rate	7%	34%	9%
Number of firms	389	477	593
Restricted sample survival rate	6.5%	49%	20%
Number of firms	93	303	218

Notes: The “survival rate” is defined as the percentage of firms from the initial period that survive to the later period based on matching either by name or location (see Section 3.5 for detail). The “restricted sample survival rate” adjusts for the fact that different sectors have single firm communes to a varying degree. It is based on the subset of firms located in communes that have only one firm in the initial period and that either do not show up in the 1840 data or they show up with only one firm.

Table 5: Productivity of Exiting Firms Relative to Surviving Firms

	(1)	(2)	(3)
Dependent variable	log(Y/L)	log L	Log Y
Spinning (exit = 1)	-0.506***	-1.043***	-1.548***
	(0.153)	(0.221)	(0.258)
Metallurgy (exit = 1)	-0.139	-0.439***	-0.578***
	(0.087)	(0.089)	(0.097)
Paper milling (exit = 1)	-0.179	-0.151	-0.331*
	(0.150)	(0.131)	(0.172)

Notes: The dependent variables are log(output per worker) in col 1, log(total labor) in col 2, and log(output) in col 3. Exit is a dummy variable equal to one for firms that existed in the initial period and that exited the market by 1840. In cotton spinning, there were 340 firms in 1806 with information on output and labor, and 314 of these had exited the market by 1840. In metallurgy, there were 457 firms with data to compute productivity in 1811, and 292 had exited the market by 1840. In paper milling, there were 520 with information on output and labor in 1794, and 473 of these had exited the market by 1840. Robust standard errors in parentheses. Notation for statistical significance: *** p<0.01, ** p<0.05, * p<0.1.

Table 6: Productivity and firms' age profile, 1806 – cotton spinning

Dependent variable: log(Output per worker)

	(1)	(2)	(3)	(4)	(5)	(6)
Young firm	0.575***	0.374***	0.543***	0.493***	0.608***	0.534***
	(0.088)	(0.079)	(0.083)	(0.085)	(0.086)	(0.085)
(log) Yarn quality		0.673***				
		(0.074)				
Low-tech spindles			-0.626***			
			(0.087)			
High-tech spindles				0.481***		
				(0.086)		
(log) Workers					0.107***	
					(0.025)	
(log) Spindles per worker						0.336***
						(0.070)
R^2	0.11	0.32	0.20	0.18	0.14	0.17
N	340	323	340	340	340	340

Notes: Young is a dummy variable equal to one for firms with below-median age (with the median age in 1806 being three years). Low-tech spindles and high-tech spindles are binary indicators equal to one for firms are using the earliest (jenny) and latest (mule jenny) vintage of machinery respectively. Robust standard errors in parentheses. Notation for statistical significance: *** p<0.01, ** p<0.05, * p<0.1.

Table 7: Effect of distance

Dependent variable: log(Output per worker)

	Spinning		Metallurgy		Paper milling	
	1806	1840	1811	1840	1794	1840
	(1)	(2)	(3)	(4)	(5)	(6)
Dist to p90 (1800)	-0.814^{***} (0.143)		-0.249^{***} (0.088)		-0.245^{*} (0.128)	
Dist to p90 (1840)		-0.176 (0.106)		-0.084 (0.097)		-0.073 (0.106)
Department FE	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.56	0.15	0.37	0.27	0.29	0.42
N	290	471	377	746	456	312

Notes: Dist to p90(1800) and Dist to p90(1840) measure the log distance to the closest firm in the same sector with productivity in the 90th percentile in 1800 and in 1840, respectively. The number of observations in these specifications is smaller than the full sample size as all firms that belong to the 90th percentile are excluded. Standard errors (clustered at the departmental level) in parentheses. Notation for statistical significance: *** p<0.01, ** p<0.05, * p<0.1.

Table 8: Testing for Spatial Selection of New Firms in Cotton Spinning in 1806

Dependent variable: log(Output per worker)

	Spinning 1806				
	(1)	(2)	(3)	(4)	(5)
			Only firms entering before high productivity firms		
Dist to p90 (1800)	-0.791^{***} (0.136)	-0.845^{***} (0.129)	-0.439^{***} (0.153)	-0.393^{**} (0.153)	-0.481^{**} (0.196)
Firm Age	-0.046 (0.085)	-0.203 (0.135)		-0.153 (0.133)	-0.388^{*} (0.205)
Firm Age* Dist to p90 (1800)		0.237 (0.203)			0.365 (0.258)
Department FE	Yes	Yes	Yes	Yes	Yes
R^2	0.56	0.57	0.66	0.66	0.67
N	284	284	176	176	176

Notes: Dist to p90(1800) is the log distance to the closest firm in cotton spinning with productivity in the 90th percentile in 1806. Standard errors (clustered at the departmental level) in parentheses. Notation for statistical significance: *** p<0.01, ** p<0.05, * p<0.1.